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RAPORT CERCETARE 3

**Studiu numeric privind aspectele
energetice și de confort pentru un sistem de
ventilare**

**Numerical study on energy and comfort
aspects for a ventilation system**

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LIST OF ABBREVIATIONS AND ACRONYMS

Symbol	Term	Measurement unit
h	- entalpy	$[kJ/kg]$
w	- speed	$[m/s]$
s	- area	$[m^2]$
ρ	- density	$[kg/m^3]$
c_p	- specific heat at constant pressure	$[J/kg \cdot K]$
φ	- relative humidity	$[\%]$
x	- moisture content	$[g_{apa}/kg_{aer}]$
$\dot{m}$	- masic flow	$[kg/s]$
$\dot{V}$	- volumic flow	$[m^3/s]$
V	- volume	$[m^3]$
ε	- evaporative efficiency	$[-]$
q_t	- total heat	$[J]$
q_s	- sensible heat	$[J]$
q_l	- latent heat	$[J]$
L	- length	$[m]$
l	- width	$[m]$
h	- height	$[m]$
IEQ	- Indoor Environmental Quality	
IAQ	- Indoor Air Quality	

1 STRUCTURE OF THESIS

1.1 ISSUES

Students spend much of their time in classrooms.

Schools have the highest occupancy rate compared to any other building.

In over 90% of cases there is no ventilation system to ensure air quality in classrooms.

It is vital to have an indoor climate that does not affect students' comfort, health, or intellectual performance.

The CO₂ concentration exceeds the recommended ASHRAE limit to be maintained or below 1000ppm.

Finding a system that solves the problems of air quality in schools, as well as the problems of thermal discomfort in the summer season is crucial.

2 OBJECTIVES

2.1 ABOUT ISSUES

Analysis of several ventilation systems with applicability in educational institutions.

Clear definition of problems for each type of system.

Propose a solution to improve air quality in educational buildings.

2.2 OPTIMIZING AND ANALYSIS OF THE SOLUTION

Numerical modeling, energy performance.

Economic calculation.

2.3 VALIDATION OF THE ANALYSIS

Validation on an experimental stand where the pre-defined performance improvement solutions will be applied.

Occupant noise protection analysis.

Testing solutions: heat recovery from exhaust air, daily time schedule (not just hourly), indoor CO₂ management, reduced energy consumption.

3 RESEARCH REPORT 3 – NUMERICAL STUDY ON ENERGY AND CONFORT ASPECTS FOR A VENTILATION SYSTEM, CASE STUDY, EXPERIMENTAL STAND 2 – HUMIDITY SENSITIVE GRILES + REVERSIBLE FAN + TRANSFER GRILES

3.1 DESCRIPTION OF THE ANALYSIS CLASSROOM

3.1.1 P&ID Diagram and ventilation system

A. Ventilation system description

The main ventilation system is an assembly consisting of a reversible fan (can insert or evacuate air from the classroom) of the axial type, mounted at the top of the window in front of the course room, the air can be introduced or discharged through it. At the bottom of the entrance doors of the classroom, located behind the classroom diagonally with the fan, the transfer grids are mounted to let the vicious air come out of the classroom or to get cleaner air from the corridor. The maximum airflow rate of the fan is 600 m³ / h. The fan is also equipped with an automatic closing flap, when the fan is not on, the grid will close. Both the fan and transfer grilles are painted in the color of the carpentry (brown) in order not to stand out and not to spoil the layout of the course room. The introduction of fresh air into the classroom is done by means of a double deflection grid, the latter having the role of controlling and guiding the air both horizontally and vertically in order not to disturb the occupants of the course rooms. Noise reduction was made using a specially designed and created noise attenuator for this type of fan and classroom. Noise reduction was satisfactory, Inside the classroom is a noise below the limit imposed by norms.

The secondary ventilation system consists of the hygro-adjustable grilles mounted in the upper part of the window carpentry frame. On each window, two grids with a maximum flow rate of 50 m³ / h were installed, resulting in a maximum total flow of 300 m³ / h in the classroom. This type of ventilation system has no energy consumption and does not require maintenance. Each grid is equipped with an actuator handle in which the closed, open or automatic position can be set. Automatic operation means opening and closing the grid depending on the humidity inside it. When students enter the room, the relative humidity will increase, so the grid will open to allow fresh air to enter the room as they leave the classroom, the humidity decreases or the grids will close so as to maintain a humidity average preset in the working area.

The main feature of this type of hybrid ventilation system plus hygro-adjustable grids is that in winter when the outside temperatures are very low, the ventilator can be used in the direction of evacuating the air from the course hall, the introduction of fresh air through the hygroregulable grids respectively from the school corridor. In spring-autumn season when warmer temperatures can be successfully used Introducing fresh air from the outside.

B. Description of monitoring and control system

It consists of an assembly of electronic elements to measure, monitor, display, control and control the ventilation system. There are three distinct main elements connected between a connection box: the remote control, the recorder and the time programmer. The remote is designed to turn the system off and on, to select how that fan operates to enter or evacuate the air in the classroom. It comes with a button that adjusts 5 fan speeds. Confirmation of the remote control is done by a red red LED. The recorder has the role of monitoring, displaying, controlling the fan according to the level of carbon dioxide inside. It records the main parameters of air quality: temperature, relative humidity and carbon dioxide. We can view these parameters on its display. The presence of the system is by a green LED. The time scheduler helps us to create different ventilation strategies, depending on a well-defined time schedule and set in correlation with student-supported classes or can be programmed to work only in recreation. Almost any programming configuration is possible. The time program is displayed by the display attached to the programmer, the operation is done by the red red LED. All the measurement and control elements described above are interconnected by means of a link box inside which we find the electrical and electronics parts..

C. Description of lighting system

The lighting installation is made up of 9 led bodies apparently mounted at the ceiling symmetrically divided over the entire surface of the ceiling. The length of the luminaire is 1.2 m. The features of each lamp are: 43W electrical power, 4,400 lumens, color temperature 4000 Kelvin, and a CRI80 color rendering index. They provide a degree of illumination in the useful plan of 550 lux.

D. P&ID Diagram

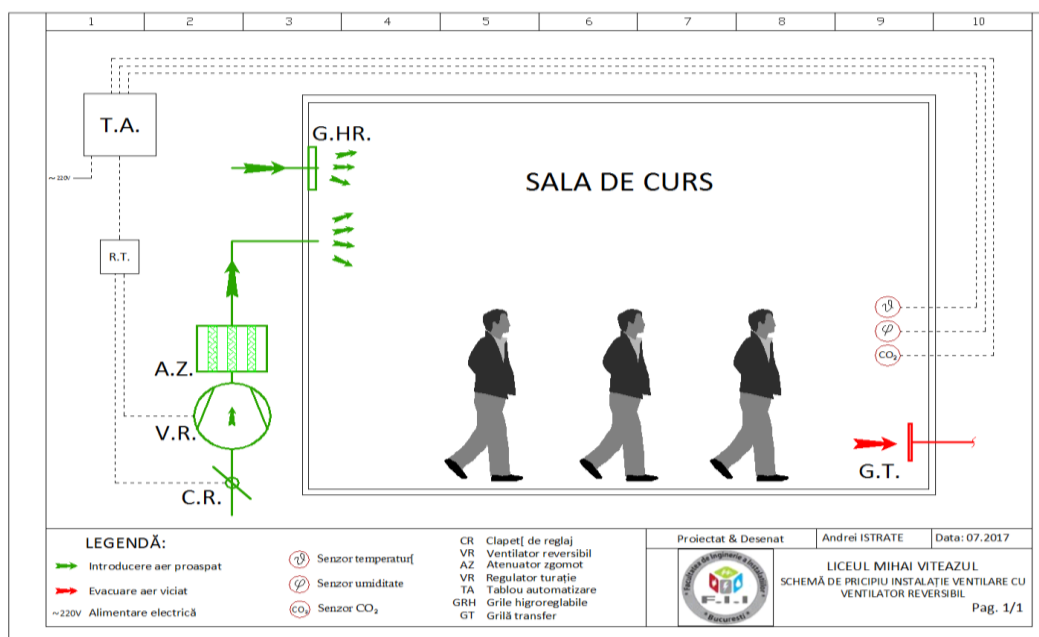


Fig.1: Piping and instrumentation diagram

3.1.2 Classroom description

A. Representation

The classroom is located in the Mihai Viteazul National College in Sectorul 2, Bucharest, one of the most famous high schools. The classroom is located on the 1st floor, in the middle of the building, with the windows facing the west side.

The walls are made of brick, the dimensions of the course are: length 9m, width 6.8m, height 4.9m resulting in an area of 61.2 m² and a volume of 300 m³. The glazed surface is made up of three windows double-glazed windows with wooden carpentry with a crescent top and a rectangular bottom of 1.5 m width. In the classroom there are 34 wooden benches grouped two by two plus the chair of the teacher. The entrance door is double-sided and has a total width of 1.3m..

B. Plan

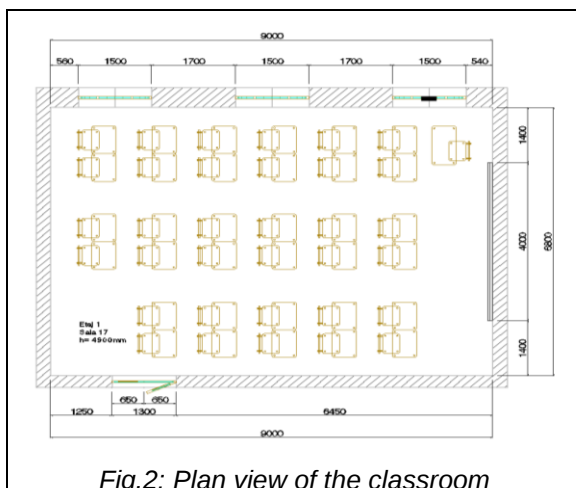


Fig.2: Plan view of the classroom

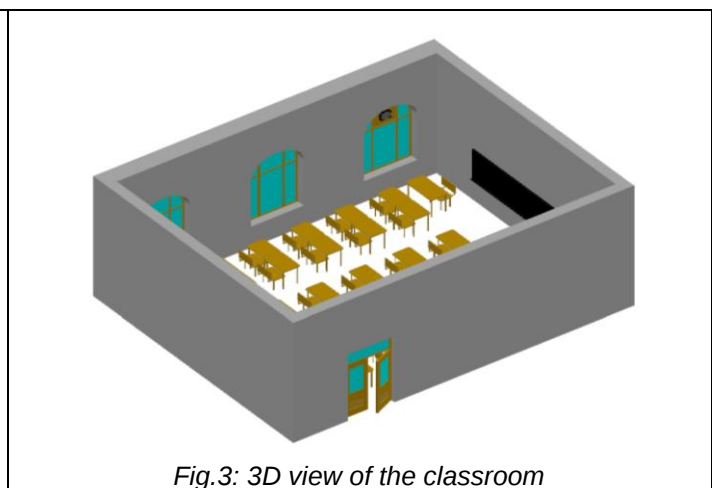


Fig.3: 3D view of the classroom

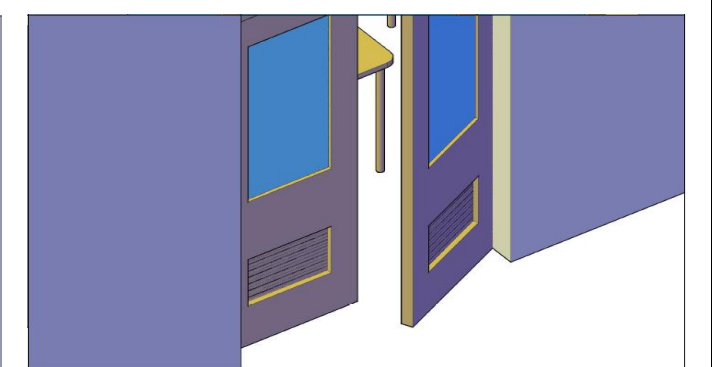
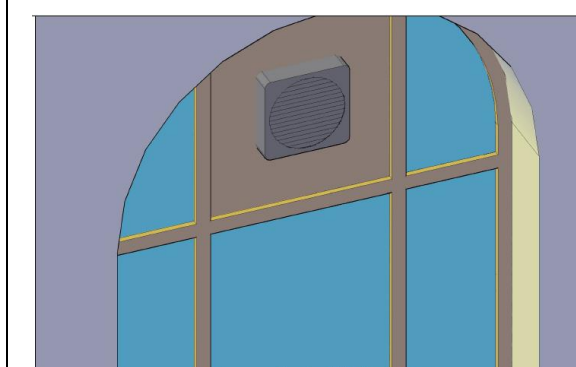


Fig.4: 3D details of the classroom

3.1.3 Final assembly system results

A. Representation

The ventilation system is an assembly consisting of a reversible fan (can insert or evacuate air from the course room) of the axial type, mounted at the top of the window in front of the course room, the air can be introduced or discharged through it. At the bottom of the entrance doors of the classroom, located behind the classroom diagonally with the fan, the transfer grids are mounted to let the vicious air come out of the classroom or to get cleaner air from the corridor. The introduction of fresh air into the classroom is done by means of a double deflection grid, the latter having the role of controlling and guiding the air both horizontally and vertically in order not to disturb the occupants of the course rooms. Noise reduction was made using a specially designed and created noise attenuator for this type of fan and classroom. Noise reduction was satisfactory, Inside the classroom is a noise below the limit imposed by norms. The secondary ventilation system consists of hygro-adjustable grilles mounted in the upper part of the window carpentry frame. On each window, two grilles were mounted. This type of ventilation system has no energy consumption and does not require maintenance.

B. Reprezentative images



Fig.5: Final system assembly representation

3.2 ENERGY MODELING OF THE BUILDING IN THE DESIGN BUILDER CALCULATION PROGRAM

3.2.1 General information about Design Builder software.

DesignBuilder is a user-friendly modeling interface where virtual building models can be introduced. This program can provide a number of building features such as:

- Hourly, monthly, daily energy consumption;
- CO2 emissions;
- Comfort conditions (variation of interior and exterior parameters)
- Natural lighting
- Dimensioning HVAC systems (calculation of heat / cold demand).

The most common uses of DesignBuilder are:

- Calculation of energy consumption of buildings;
- Evaluation of facade features (appearance, architecture, overheating, glass surface / wall surface ratio);
- Reduce electricity consumption due to the use of natural lighting;
- Analysis of the distribution of natural lighting by simulations of solar radiation;
- Viewing the site and shading of the building;
- Equipment dimensioning. Calculation of heating / cooling requirements;
- Detailed simulation and design of HVAC systems and natural ventilation, including analysis of indoor air impact and room air velocity using CFD (Computational Fluid Dynamics);
- Energy models for ASHRAE 90.1 and LEED;
- Economic studies on investment costs, lifetime costs and utility costs;
- Energy certification reports for the UK, Ireland, France and Portugal;
- Optimization of design by introducing multiple variables;
- Consultancy for design;
- Educational tool for learning energy simulations for engineering and architecture.

DesignBuilder's energy modeling type is approved by the UK Government and is part of the Building Performance 2000's energy performance calculation methodology. It is approved by the UK, Ireland and Jersey and serves both energy certifiers and those who want to optimize the design of a building.

DesignBuilder uses EnergyPlus as a dynamic simulation engine to generate data.

EnergyPlus the United States Department of Energy simulation program and is used for building modeling: heating, cooling, lighting, ventilation and other energy-using. This program has multiple simulation capabilities: less than one hour, modular systems, photovoltaic systems, thermal comfort, etc.

DesignBuilder has been developed around the EnergyPlus software and allows the introduction of many building materials from its own database: glazed surfaces, shadows, wall types, floor types, floor types, partition walls, etc. Scenarios the values of the internal energy inputs, the values of the releases, the basic dimensions (preintroduction) are taken from the ASHRAE standards and can be customized according to the project and the destination of the building. Also, the calculation algorithms for energy consumption analysis can be modified according to the materials used (eg: "Conduction Transfer Function" is used, and "Finite Difference" is used to take PCM implementation into consideration).

After opening the program, you can create a new project. The case presented is an already introduced project, used as a model for this documentation.

In figure 6 it can be seen that in the center there is the drawing of the classroom studied, which was introduced manually. On the left side of the picture you can see the building component (zonation). This is done hierarchically (from the whole building, to each floor, then to each area and eventually to each building element).

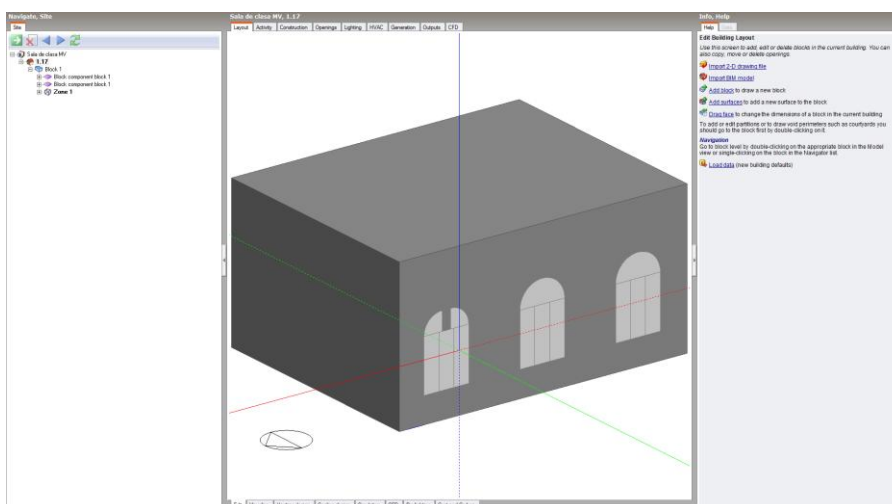


Fig.6 – DesignBuilder interface. Home page

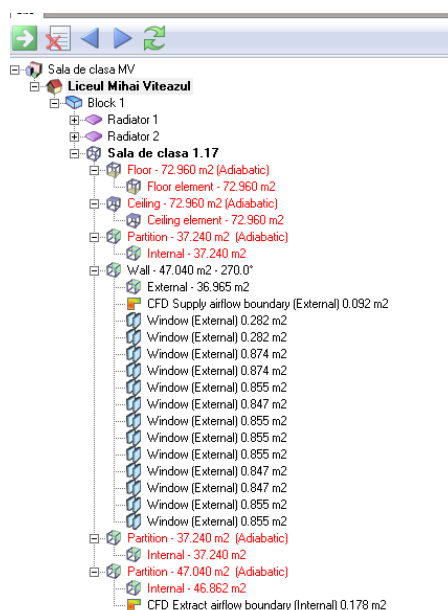


Fig.7 – Zoning of the building

At the top of Figure 6, you can see the data entry bar (Figure 8) where you can see the following tabs in turn: Layout: where you can view the component of the area and draw it.

- **Activity:** where you can enter calculation parameters for each area (type of area (heated / unheated), occupancy level, employment scenario, type of clothing, type of activity, hot water consumption, winter indoor temperature calculation, summer indoor temperature, guard temperatures, humidity control, fresh air flow rates per person and m2, releases from indoor heat sources); these inputs can be chosen from their own database or can be customized;

- **Construction:** where you can enter types of exterior walls, interior walls, terrace, planes, geometry, level of infiltration; Thermal bridges are taken into consideration and can become private layers or can be chosen from their own databases;

- **Openings:** where types of exterior / interior glazing, joinery types, shading times, shadow operation scenarios, door types can be entered;

- **Lighting:** Where to enter the type of lighting, the energy consumption per m2 and 100lux, the lighting scenario;

- **HVAC:** where the type of mechanical ventilation system, heat recovery, free-cooling, heating, cooling, humidity control, domestic hot water, ventilation etc. can be entered, respectively the technical data corresponding to the systems; for this tab you can choose the "simple" or "detailed" type to run simulations from the simplest to the most complex;

- **Outputs:** where the zone outputs are set;

- **CFD:** where CFD data is entered.

The information in these tabs can be changed for each hierarchical area. If the option is entered in a higher hierarchical area, the change applies to all lower hierarchical areas.

The information that can be entered into these tabs will be detailed in the following subchapters.

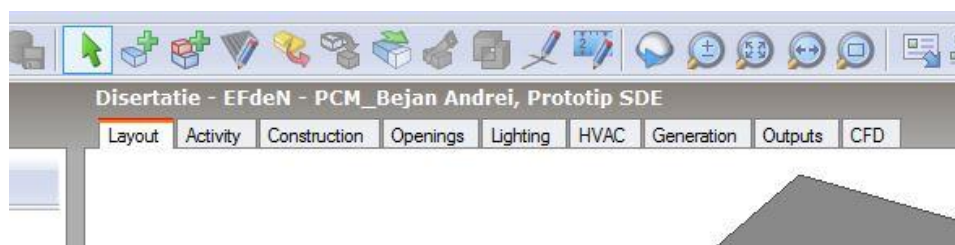


Fig.8 – Input bar

At the bottom of Figure 6 you can see the dynamic and stationary simulation bar (Figure 9) where you can see the following tabs:

- **Edit:** is the mode of editing the energy simulation model;

-
- Visualize: is the 3D rendering mode of the model; here you can also study natural lighting and shading;
 - Heating design: for making simulations for the dimensioning of heating equipment and finding the thermal load for heating; reports can be obtained in the form of graphs or tables; graphs can be detailed depending on the time period;
 - Cooling design: for designing simulations for cooling equipment sizing and finding thermal load for cooling; reports can be obtained in the form of graphs or tables; graphs can be detailed depending on the time period;
 - Simulation: where the annual energy consumption simulations, indoor comfort, etc. are performed; you can analyze the annual consumption according to the time step, the variation of the interior temperatures, etc.
 - CFD: where CFD analyzes are performed;
 - Daylighting: in which simulations of natural lighting are realized;
 - Cost and carbon: showing investment costs, maintenance and operating constants, and CO2 emissions to lifetime calorific value.

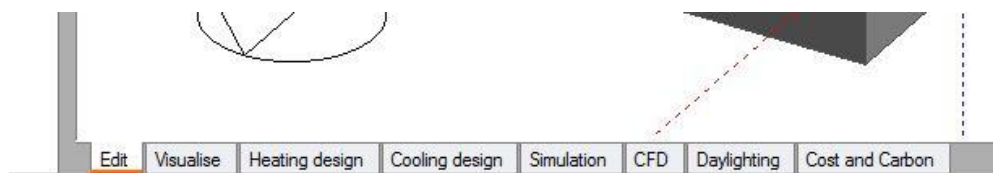


Fig.9 – Simulation bar

3.2.2 Entering building data in the DesignBuilder software

Thermal zoning of the building. Visualize.

The energy modeling of the building starts with the introduction of its thermal zones. A thermal area means a room or several rooms that have the same thermotechnical characteristics, orientation, installations, etc.

Thermal area with specific surface and volume characteristics was introduced. The orientation of the building is given by the left-down arrow of the images (this indicates the North).

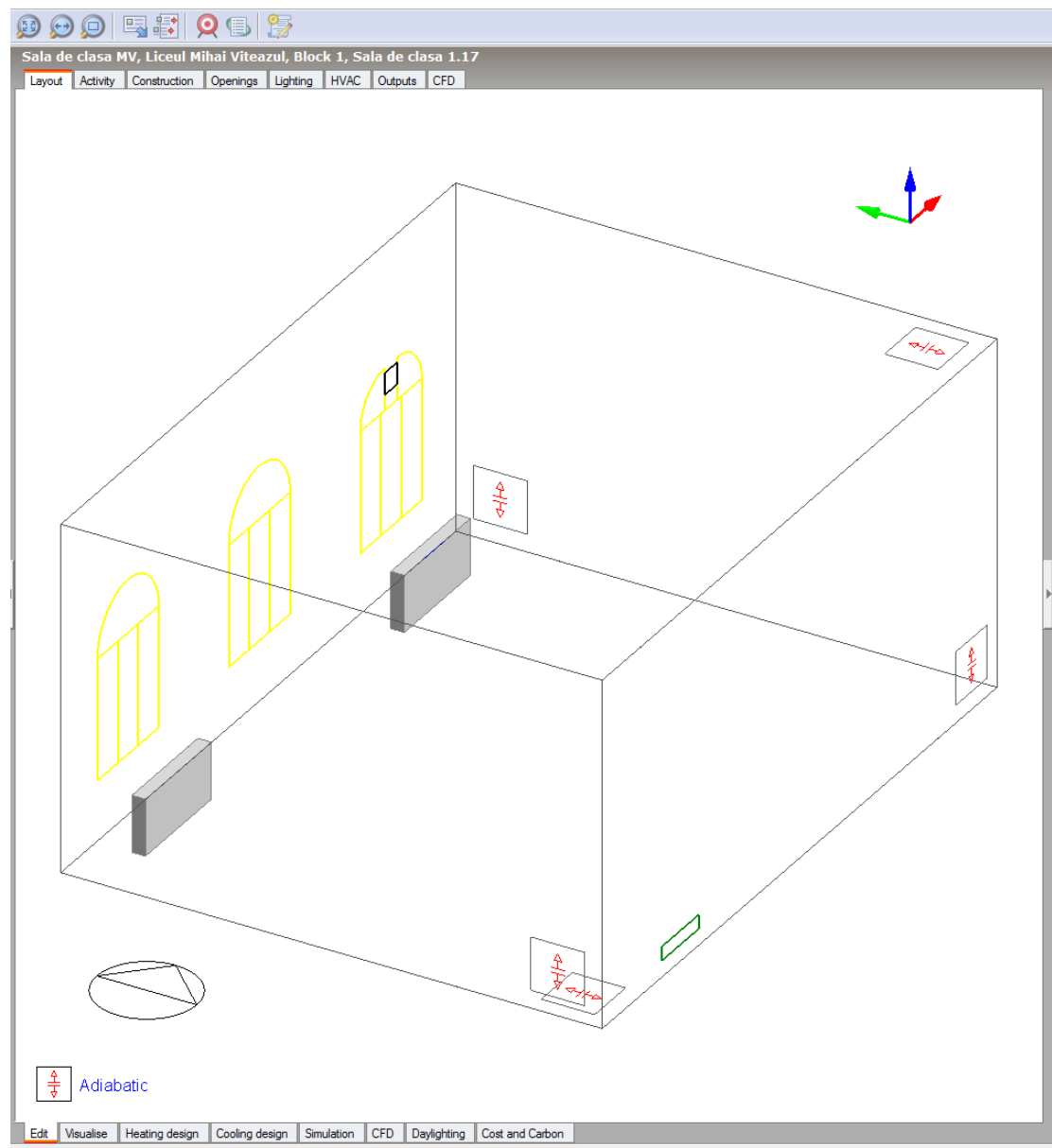


Fig.10 - Building modeling of the building (zoning)



Fig.11 - Drawing toolbar (zoning)

We can see how to draw the building in DesignBuilder. In the top right corner are the view options of the input plane (in this case, "Plan", in Figure 12 is "Axonometric" for 3D viewing).

We can see the toolbar where you can find the drawing tools: add new block, draw partitions (to create a new partitioned area within the previous partition), place construction line, measure length, angle or area, zoom in / out, and other zoom buttons, change the position of the building, make rotations, etc.

The 3D rendering with the resulting model is found in Figure 13.

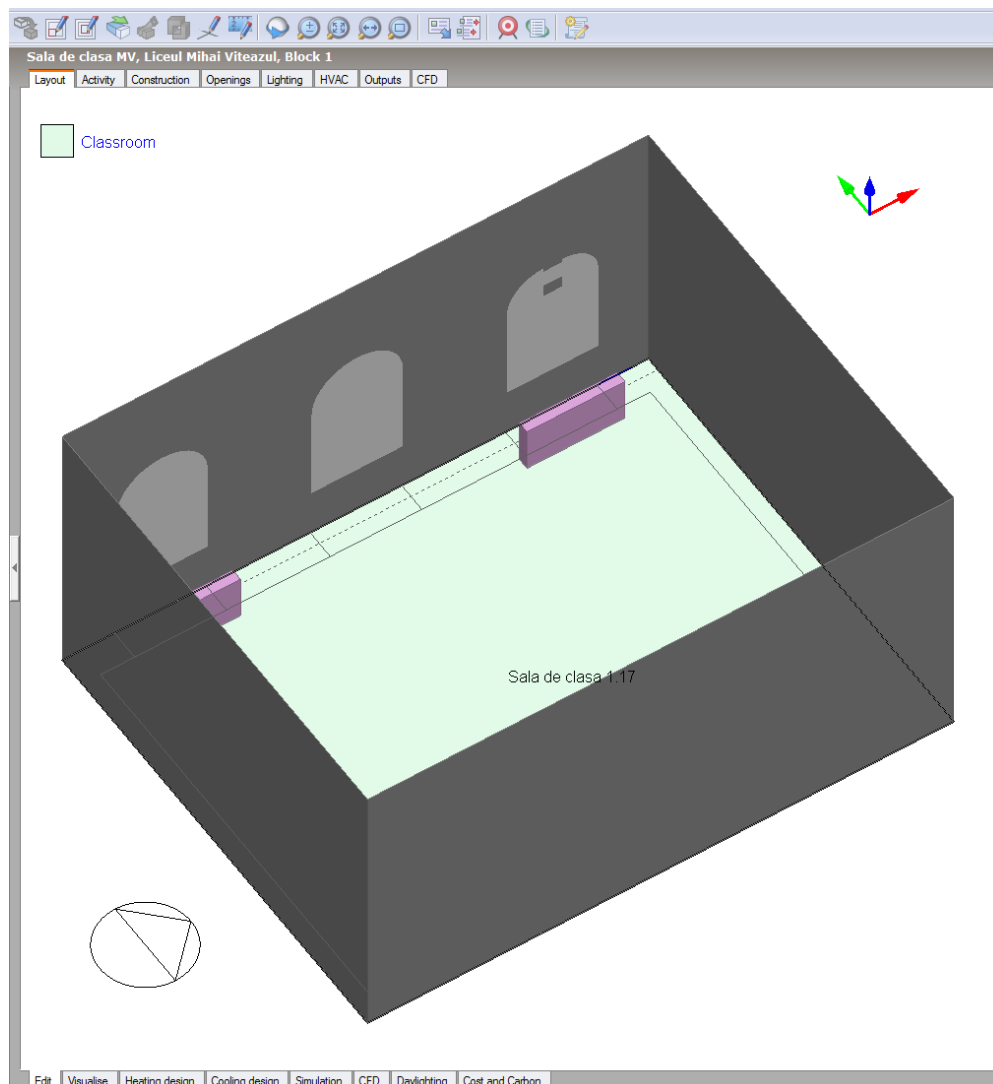


Fig.12 – Thermal zoning

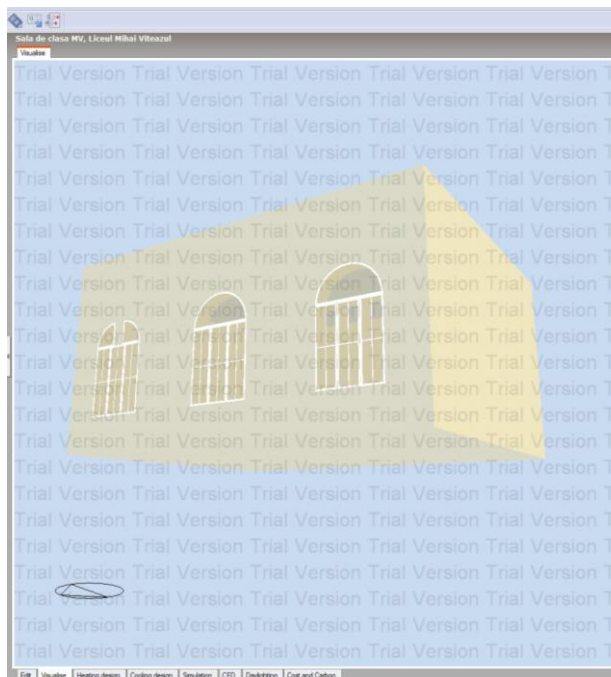


Fig.13 – Randaring of classroom

To enter doors, windows, gaps, grids, select the wall that you want to make the change (Figure 14). At that time a new toolbar (Figure 115) appears at the top of the window where the above elements can be depicted. The insertion of these elements can be done depending on the axes and certain Point Snaps which can be seen in left-bottom.

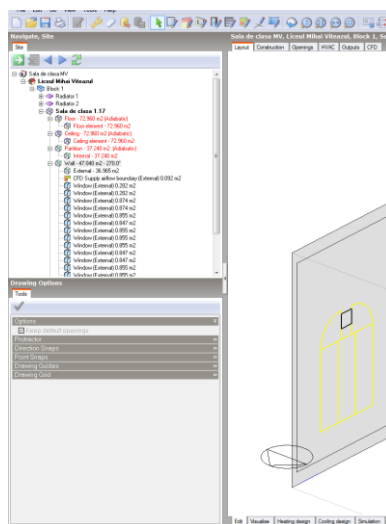


Fig.14 - Insertion of the gaps



Fig.15 – Bar introducing gaps

3.2.3 Introduction of the thermo-technical characteristics of the inertial building elements

After the thermal zoning of the building was introduced, the room inertial types were introduced in the "Construction" tab: external walls, ceiling, ground floor - figure 16. Here too and the characteristics of the partition walls.

For each building element, layers, types of materials, thicknesses, and a thermal bridge coefficient were introduced - Figure 17. The figures presented in this chapter are relevant for defining the outer wall layers.

Also in the "Construction" tab were the air infiltration rates through the tire elements according to the room.

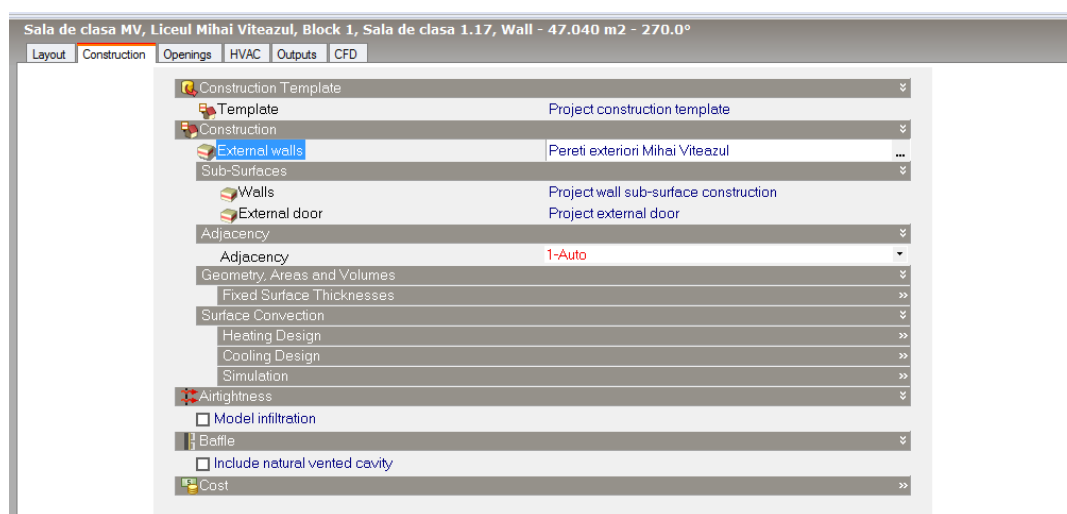


Fig.16 – Defining elements for the building envelope

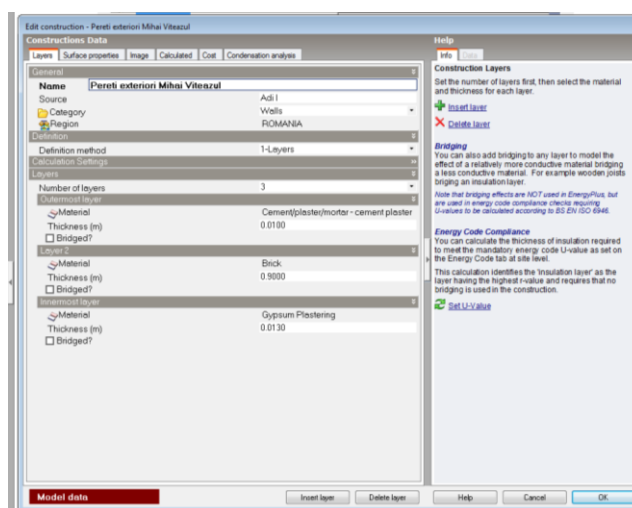


Fig.17 – Define the types of layers for exterior walls

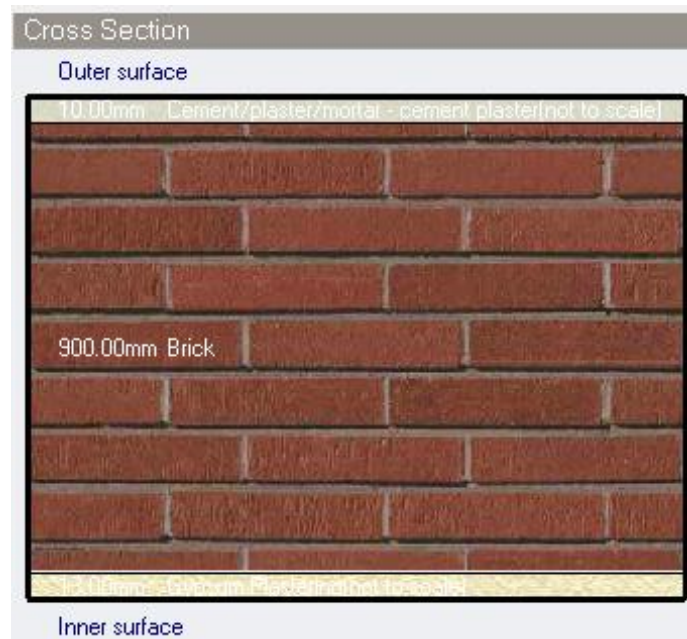


Fig.18 – Section through the outer wall

3.2.4 Introduction of types of glazed surfaces, shades and doors

After the room inertial elements were introduced into the energy model, the non - ineral elements of the tire were introduced.

For the vitreous elements of the outer tire and for those in the greenhouse and inside, three-layer, low-E, Argon U = 0.8 W / m2K glazed units were used.

For room exterior elements, shade systems have been used that have been externally mounted to limit solar radiation penetration as much as possible. Also, a type of control was used for this according to the intensity of the solar radiation and the outside temperature.

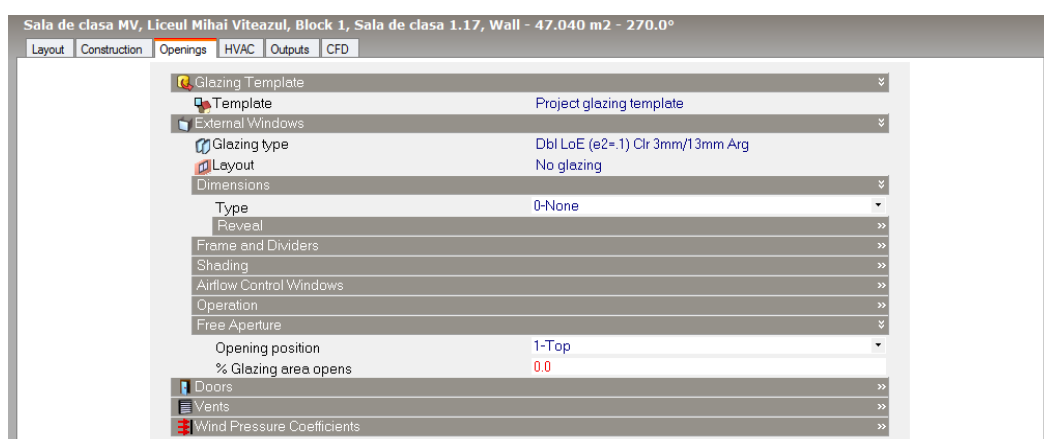


Fig.19 - Defining the types of glazed surfaces, shades, doors

3.2.5 Entering types of activities and indoor comfort parameters.

Scenarios

After the room elements were introduced, the room type, occupancy level, occupancy scenarios, type of activity, water consumption, summer indoor temperature, indoor winter temperature and indoor heat output were entered for each room.

Next, the values entered in the calculation model (the Activity tab) calculation area will be shown - figure 20.

The type of area is "Standard" because it is a heated room.

The occupancy level chosen is 0.4248 persons / m² because there are 25 students in classroom and the area of classroom is 61 m².

The employment scenario is shown in Figure 21. Also, the "Staing / Walking / Light Office Work" activity was chosen to determine the interior heat and humidity releases from the occupants.

The level of clothing is set to 1 clo for winter and 0.5 clo for the summer.

The consumption of water introduced in the defined area and type of occupation, respectively 0.14 l / m²/day.

The temperature set in the classroom is 22°C for heating.

The fresh air flow is calculated automatically depends of the day, orientation, speed of wind...etc.

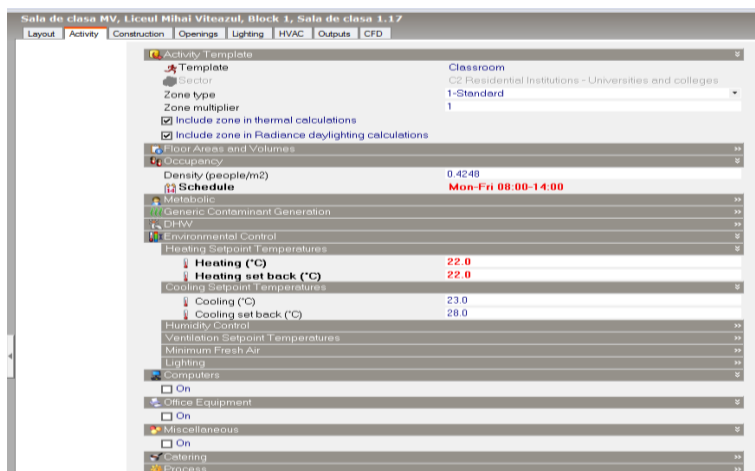


Fig.20 – Definition of activities, employment scenarios, temperatures

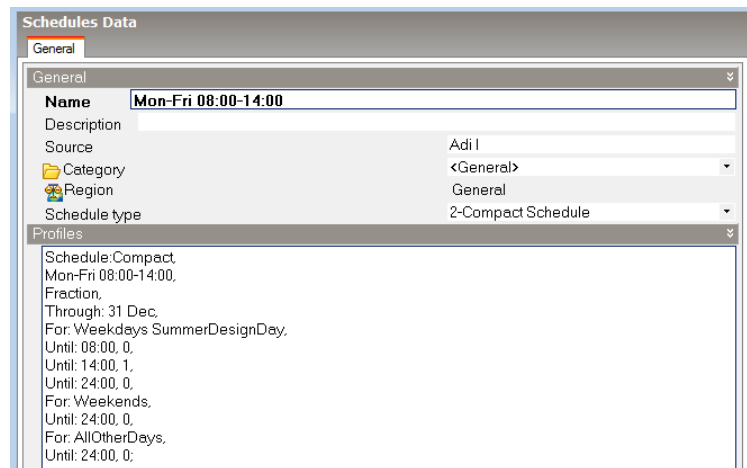


Fig.21 – Employment scenario.

3.2.6 Introduction of HVAC systems.

After the types of room elements, types of activities, comfort interior parameters, occupancy scenarios, types of lighting systems have been defined, the types of HVAC systems specific to the building - Figure 22. If you want to introduce complex HVAC systems, enter the Edit / Model Options menu (or press F11) and choose "Compact" or "Detailed" from the "HVAC" section. In this case, the option chosen was "Simple". From this window you can set different ways of calculating and approaching the model.

For the classroom, the following features of the HVAC system were introduced:

- radiant heating
- natural ventilation calculated automatically
- a working scenario is the occupation scenario (Figure 20);
- heating system based on boiler an average 0.85 for heating 0.85; a heating scenario is shown in Figure 22 (where 1 means the normal set temperature and 0.5 guard temperature).
- a heating scenario is shown in Figure 23 (where 1 means the normal set temperature and 0.5 guard temperature).
- a working scenario is the occupation scenario (Figure 20)

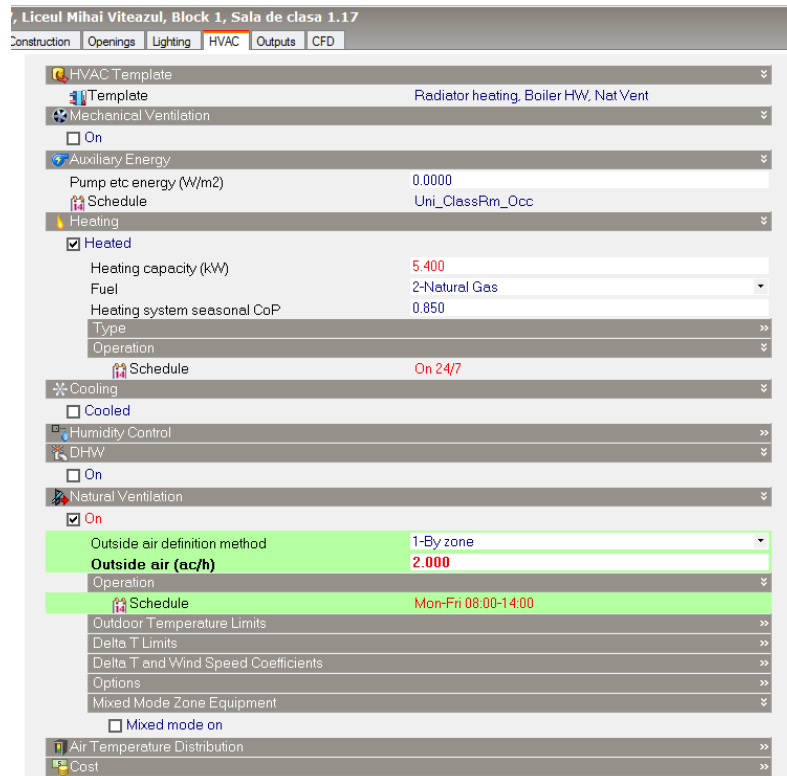


Fig.22 – Defining of HVAC systems

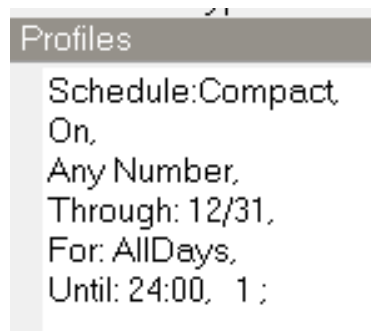


Fig.23 – Scenarios for heating

3.2.7 Simulation results

As mentioned above, at the bottom of the DesignBuilder interface there is a simulation bar. By accessing any of the existing tabs in this bar, the first step to take is to set the duration for simulations, simulation settings, and other similar data.

Here are some of the main simulations that can be made using DesignBuilder.

By accessing the "Heating design" option, the program calculates the heating system sizing and obtains a series of results such as: interior comfort, heating, etc.

By accessing the "Cooling design" option, the program calculates the cooling system sizing and obtains a series of results such as: indoor comfort temperatures, cooling requirements, etc.

By accessing the "Simulation" option, the program calculates energy consumption calculations and obtains a series of results such as: indoor comfort temperatures and their

variation over different periods of time, energy consumption broken down by utilities over different periods of time, etc.

When one of the types of analysis (Heating design, Cooling Design or Simulation) is accessed, a bar with several tabs appears on the top. By accessing "Analysis" / "Steady-state" you can see graphical data or results table. By accessing "Summary" you can see the simulation report. Also, a toolbar where you can resume the simulation or export it to a file where data can be processed more easily (eg Excel) is shown at the top of the screen.

In the bottom left-hand side, simulation indentation, the "Display Options" section shows where you can change the time periods, the simulation output data types, etc.



Fig.24 – Data export bar and resume simulations

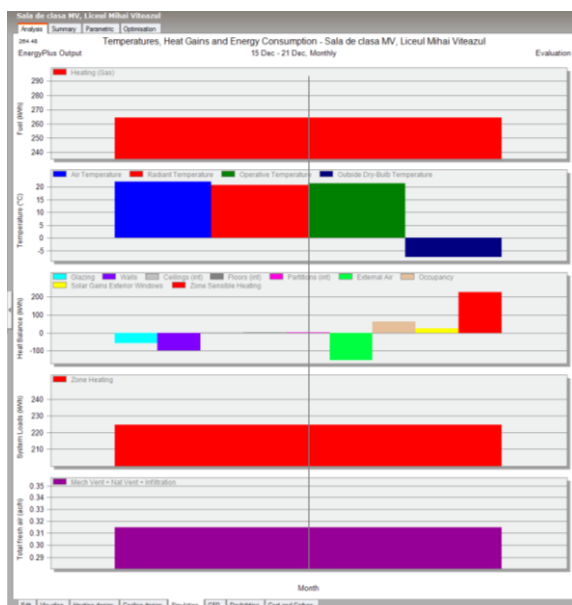


Fig 25 Quantity results

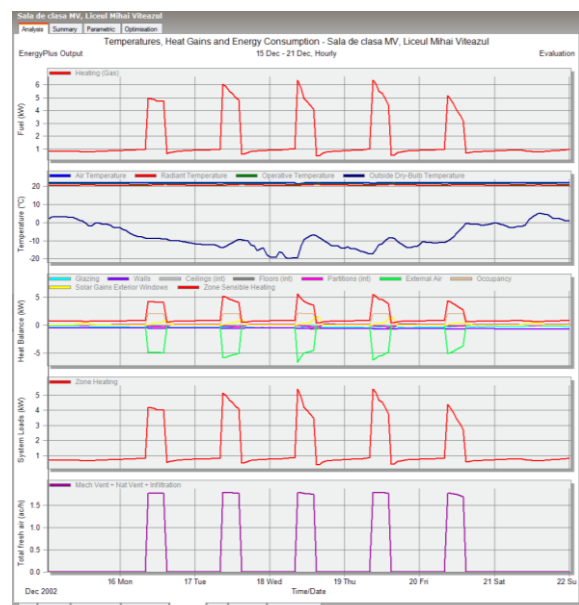


Fig. 26 Distribution results

3.3 QUANTITY SIMULATION OF THE IMPACT OF NATURAL VENTILATION ON THE IAQ AND THERMAL COMFORT OF A CLASSROOM -

3.3.1 Introduction

Since the energy crises of the 1970s, many of the leading industrial countries have been focusing on improving the energy efficiency strategies to reduce the overall energy consumption. While the countries that were rich in oil have benefited from this crisis period, others were shocked by the petroleum shortages and their governments have been forced to take drastic measures to reduce the consumption of the available resources [wikipedia]. For the civil engineering domain, these measures have represented the start of most of the indoor air quality related problems such as indoor air pollution or „sick building syndrome”, as the building owners were forced to reduce the energy costs by using highly insulated building envelopes and by reducing the functionality of the heating, ventilation and air conditioning (HVAC) systems [Ramos].

For several years, all of the attention was driven towards the energy efficiency of the buildings, mostly due to the general idea that the indoor environment was protected from the pollution outside. In the 1980s, after the release of several studies by different institutions all around the world, there was clear evidence of poor air quality in indoor environments and soon after it was recognized as a serious threat for the occupants well-being [Defining healthy housing - Wolfson]. Since then there has been a continuous struggle between the concept of energy efficient buildings and the concept of healthy indoor environment, mostly because the advantages of one meant a compromise for the other (for example, tightly constructed new buildings have lower energy requirements but usually present higher concentrations of indoor air pollution if a proper ventilation system is not installed).

During the last decades, the number of studies regarding indoor air quality (IAQ) has increased significantly and there are now national and international organizations that work together to implement worldwide regulations and standards with the goal to improve the overall indoor experience of the occupants by providing a healthy and comfortable environment [EFA Project] [WHO Guidelines] [Project SIMPHONIE]. Even though productivity in school is an important objective for any society, most of these studies have been performed for residential, industrial and office buildings, with only a small percentage being targeted at the educational buildings. [indoor air quality, ventilation and health symptoms].

In Europe, during the school days, there are on average 68 million occupants (both students and teachers) that are affected by the quality of the air inside the educational institutions.[brochure SIMPHONIE] Therefore, it is of most importance to ensure a healthy school environment in order to promote effective learning and to keep the occupants safe from any avoidable health risk factors that could cause asthma, allergic reactions, heart diseases, pulmonary diseases, headaches and other health issues. During the past 20 years there have been a few studies linking school absenteeism with poor air quality [Classroom Carbon dioxide concentration...][Do indoor air pollution and thermal conditions affect performance in schools ? (2005)], and many other studies that have shown the influence of higher concentration of air pollutants on the persons inside. Moreover, the children are more vulnerable to environmental pollutants because they tend to have higher respiratory rates that directly increase the dose of pollutants that get into the lungs. Considering that their young bodies may not be able to deal with some of the toxic chemicals found in the air, children are also more prone to develop health issues that may have long

term effects. [**The effects of air pollution on the health of children**] [**The effects of air pollution on lung development from 10 to 18 years**].

There are many variables that have to be taken into consideration when designing a ventilation scenario for a classroom full of students: the number of occupants, the age and the activity level of the occupants, the daily occupational schedule, the geometry of the building/classroom, the structure of the building, the age of the building, the outdoor climate, the level of maintenance, the current state of the HVAC system, etc. All these variables make it very difficult to propose a general guideline on how to achieve a healthy indoor environment without doing some in-situ measurements to verify the IAQ level. This is where numerical simulation software's could play an important role in the development of ventilation strategies for schools. All the variables mentioned earlier can be easily changed within a simulation program and, if the model is correctly set-up, the simulation results could help a professional HVAC engineer to determine if a certain ventilation strategy is viable or not. Of course, a computer program cannot offer an exact image of the real situation, therefore experimental validation is also necessary, but the time gained by using the software to predict the proper ventilation method is of significant importance.

The current paper focuses on developing a numerical simulation procedure that can be used to evaluate the efficiency of a natural ventilation system by monitoring the carbon dioxide (CO₂) evolution inside a high school classroom full of students. For each of the ventilation scenarios the thermal comfort, air humidity and energy consumption were taken into consideration by extracting the variation in time of the operative temperature, relative indoor air humidity, PMV, PPD, and heat load. The inclusion of these parameters allows to achieve a holistic view of the efficiency of the ventilation procedure which, correlated with the costs, can offer important information regarding the viability of the solution before putting into practice.

The software used for running the simulations is Design Builder Version 5 that relies on the Energy Plus code. The virtual model of the classroom has been realized with the same software using the architectural plans and the orientation of the real building. The results have been extracted using the "Design Builder Results Viewer" extension and the post processing of the data has been realized with Microsoft Excel.

3.3.2 Study case (Defining the virtual model)

A. Description of the real classroom

The classroom used for this study is located on the first floor of „Mihai Viteazul” high school, in Bucharest and it has a length (L) of 9 m, a width (W) of 6.8 m and a height (H) of 4.9 m resulting in a total usable ground surface area (S_t) of 61.2 m² and an interior volume (V_i) of 300 m³. During the school year when this study was done, there were maximum 25 students and 1 teacher present in the classroom, Monday to Friday from 8:00 AM to 14:00 PM. The student's desks are distributed in 3 columns and 6 rows, with a special teacher's desk in front of the classroom, as it can be seen in Fig.27. The total number of seats was higher than the number of occupants at the time the study was done, therefore we could expect differences in air quality and thermal comfort from one year to another depending on the variation of the number of occupants. This shows again an advantage for the numerical simulation approach, because the number of students can be easily changed to see how a higher or a lower number of occupants can affect the indoor parameters. The heating

system consists of 2 heating radiators with a specific power (P_{rad}) of approximately 2500 W/unit, this means that the total installed heating power (P_{tot}) is 5 kW.

The exterior walls of the building are made of a 90cm full brick layer with cement plaster finish on both sides, the interior or adjacent walls are made of a 35cm layer of the same full brick type with gypsum plaster on both sides, the adjacent floor/roof* is made of concrete slab with gypsum plaster finish on the roof side and a parquet wooden finish on the floor side. The classroom has 3 double glazed windows, with an arched top side, presenting the following dimensions:

Rectangle shaped zone: length (L) 1.5m, height (H) 2m;

Semi-circle shaped zone: length (L) 1.5m, radius (r) 0.75m.

The windows have only one opening area in the rectangle shaped zone and this area represents about one third of the full rectangle-shaped zone area as you can see in Fig. 2 a). The opening presents the following dimensions: length (L) 0.5m, height (H) 2m.

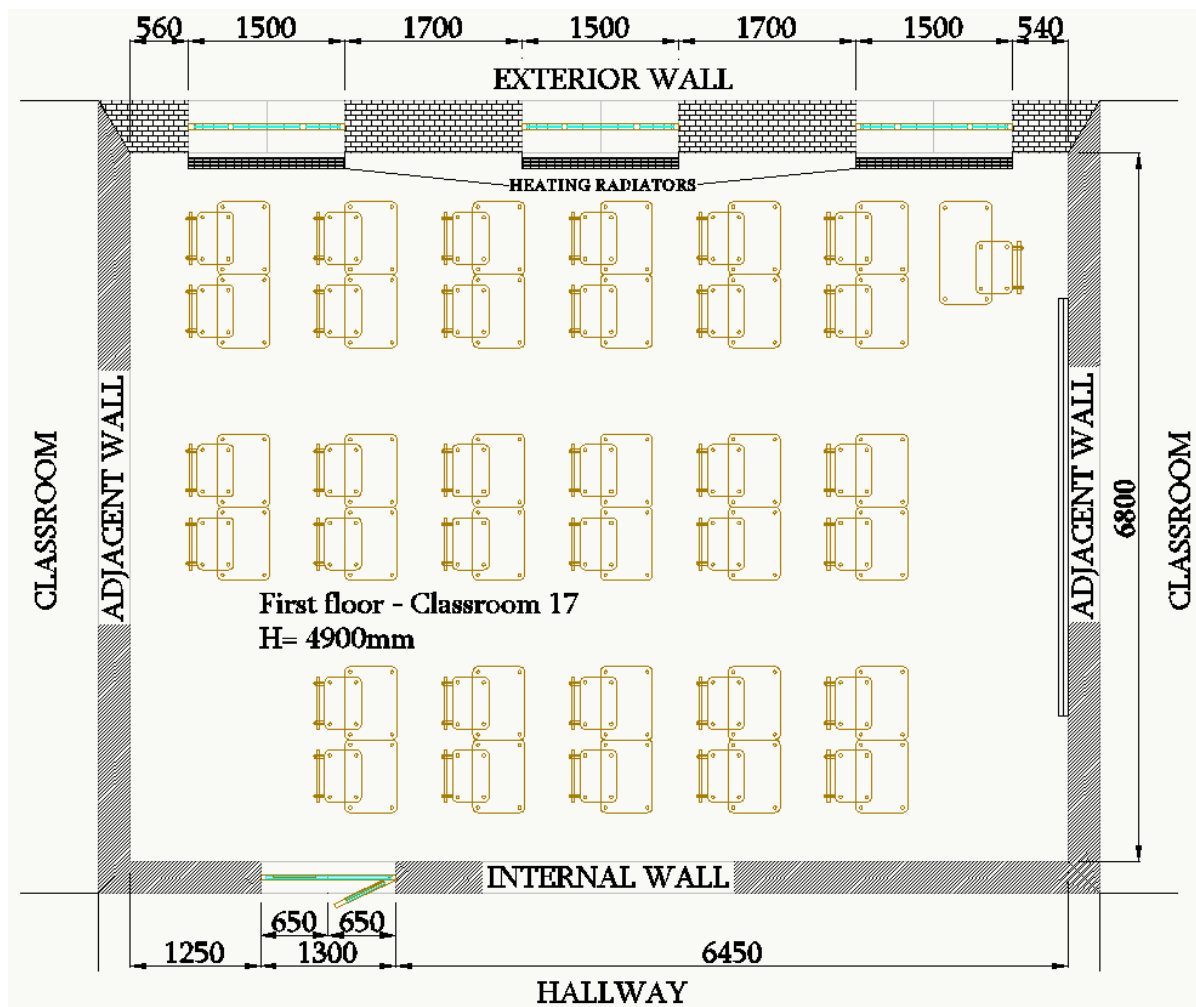


Fig. 27 – Top view of the classroom plan



Fig. 28 – a) Photo of the actual window, b) Photo of the actual door

The classroom also has two plywood doors, each one having a grille installed in the lower half, as you can see in Fig. 2 b), with the purpose of improving the ventilation rate when the windows are opened. The doors have a total length (L) of 1.3m and a height (H) of 2.5m with the grilles having a length of 0.45m and a height (H) of 0.3m. Above the doors there is also a fixed window area with a length (L) of 1.3m and a height (H) of 0.5m.

To ensure a good correspondence between reality and numerical simulation the virtual model has to be carefully set-up and thoroughly verified before assuming that the results are worth to take into consideration. In order to avoid human errors a specific flow of the process has been realized before starting the design of the virtual model.

B. Defining the virtual model

The software used to create the 3D virtual model of the classroom and to run the numerical simulations was „Design Builder V 5.0.2”. Design builder is a multi-zone simulation toolbox that offers CAD/BIM model importing, intuitive and easy to use 3D design tools, EnergyPlus algorithm for HVAC, airflow, daylight, energy efficiency and costs simulations, weather file import and advanced 3D visualization system for sun patterns and shadings and a CFD module for an in-depth analysis of certain areas of a building. For more information about the software and its capabilities please visit their website at <https://www.designbuilder.co.uk/software/product-overview>.

Firstly, to create the 3D model, the 2D CAD plan of the classroom has been imported into the program. Then the exterior perimeter was traced and the classroom block was created. Before inserting the windows and the doors, each of the 4 walls has been changed to the corresponding type (exterior, internal and adjacent) and their structure has been defined using materials with properties as close as possible to the real case. The adjacent floor, adjacent roof, and two of the adjacent walls have been changed to adiabatic elements because it is considered that the temperature in the neighboring classrooms is not much different from the test classroom. Even so, the program still takes into account the thermal mass of the structural elements, therefore it is still very important to define the construction correctly. To take into consideration the pressure difference and to correctly

predict the airflow through the door grilles, a portion of the hallway was also considered the 3rd adjacent wall. The physical properties of the layers used for each of the structural elements are presented in Table 1.

After the definition of the structural elements, the windows and doors have been added to the model. A double-glazed window model has been chosen from the software's own library, as the definition of a custom type of window implies a lot of work and it was considered unnecessary for the purpose of this study. The window presents the following characteristics: Low-E 3mm exterior glass layer, a 13mm Argon layer in the middle and a clear 3mm interior glass layer with a total solar transmittance (τ) of 0.595 and a conductivity (u) of 1.5 [W/m²*K].

The doors, however, have been modeled as a single layer of 4cm of Plywood which resulted in an average conductivity (u) of 2.3 [W/m²*K].

The hallway has been modeled as a closed zone with three exterior walls, an adiabatic floor and an adiabatic roof, and with an interior wall adjacent to the classroom. This was only a rough approximation of the real phenomena, but considering that there was no interest in analyzing the thermal comfort or the air quality on the hallway, a more accurate simulation was not necessary.

Properties of the structural elements

Exterior Wall	δ	λ	c_p	ρ	U
	[m]	[w/m*K]	[J/kg*K]	[kg/m ³]	[W/m ² *K]
Cement plaster	0.01	0.72	840	1760	0.682
Full Brick	0.9	0.72	840	1920	
Gypsum Plaster	0.013	0.4	1000	1000	
Interior/Adjacent Wall	δ	λ	c_p	ρ	U
	[m]	[w/m*K]	[J/kg*K]	[kg/m ³]	[W/m ² *K]
Gypsum Plaster	0.013	0.4	1000	1000	1.423
Full Brick	0.35	0.72	840	1920	
Gypsum Plaster	0.013	0.4	1000	1000	
Adjacent Floor/Roof	δ	λ	c_p	ρ	U
	[m]	[w/m*K]	[J/kg*K]	[kg/m ³]	[W/m ² *K]
Plywood floor	0.01	0.15	2500	560	2.27
Concrete	0.1	1.4	840	2100	
Gypsum Plaster	0.013	0.4	1000	1000	

After creating the enclosed environment, the next step was to define the different scenarios for: occupancy, HVAC components and ventilation.

C. Occupancy scenario

As it was specified in the description of the classroom at subchapter 2.1, the number of persons inside, for the school year when this article was written, was of maximum 25 students plus 1 teacher. Therefore, for the simulations, it was used a density of people (ρ_{pers}) of 0.42 people/m² which resulted in a nominal number of occupants (N_{occ}) of 26 people. Even though the classroom can accommodate up to 34 students, we decided to use only the maximum number of students present for that school year because some of the simulation results would then be compared to experimental data gathered during the same period.

The weekly occupancy schedule was set just as described, from Monday to Friday, with the start of the school day at 8:00AM and end of the school day at 14:00PM. The weekends were considered „no school” days, and winter and summer holidays were also taken into account, but since we were not interested in annual results the influence of the holidays were not of great importance. To also take into consideration the dynamic factor of the occupancy (children leaving classroom during breaks, teachers present only during class) a variable daily schedule was used which introduced a coefficient of 0.5 for the classroom occupancy during the breaks. The schedule used for the numerical simulation can be seen in table below.

Time	Monday -> Friday	Saturday -> Sunday	Holidays
7:50	Students entering classroom	No persons inside the classroom	No persons inside the classroom
8:00	1st class, 26 persons		
8:50	1st break, 13 persons		
9:00	2nd class, 26 persons		
9:50	2nd break, 13 persons		
10:00	3rd class, 26 persons		
10:50	3rd break, 13 persons		
11:00	4th class, 26 persons		
11:50	4th break, 13 persons		
12:00	5th class, 26 persons		
12:50	5th break, 13 persons		
13:00	6th class, 26 persons		
13:50	6th break, 13 persons		
14:00	Students leaving classroom		

For the hallway, the occupancy settings were left at the default values of the “Universities and Colleges – Circulation area, corridors and stairways” activity template [https://www.designbuilder.co.uk/helpv5.0/#Activity_Templates.htm]

An occupancy schedule has also been defined, with full occupancy factor ($N_{\text{occ}} = 2.41$ people) during the breaks and no occupancy during the classes.

After defining the occupancy schedule, the metabolic template was introduced. From the available templates the „Light office work/Standing/Walking” one was chosen, as it was considered the most suitable for a classroom full of students, which usually move more during the day compared to a typical adult at an office. The selected template introduces a nominal metabolic rate per person (Met) of 123 W/pers, but this value was multiplied by a metabolic factor (C_{met}) of 0.83 since it is considered that adolescents produce less heat than adults due to their improved health condition and due to the reduced body size. The factor was chosen as an average between the values recommended by Schofield and the ones recommended by the World Health Organization (WHO), for both genders. These values have been used in several studies and they have proven to properly predict the basal metabolic rate (BMR) in adolescents with ages between 10 and 18 years old **[Developing assumptions of metabolic rate estimation for primary school children... Table 2. BMR Prediction equations for children]**.

For the CO₂ generation rate, the software suggests a recommended value depending on the activity template that was chosen. This value can also be set manually, but in our case there was not sufficient experimental data to calculate it and, besides that, one of the objectives of the study is to see how well a numerical simulation program can estimate the indoor CO₂ production. Therefore, the CO₂ generation rate (q_{CO_2}) was left at the default value of 0.0000000382 [m³/s*W], which has been verified with data from other sources **[Carbon dioxide generation rates for building occupants - Table 4. CO₂ generation rates at 273 K and 101 kPa for ranges of ages and level of physical activity]** and it was found to be in the recommended range with a total CO₂ emission of $E_{CO_2} = q_{CO_2} * Met * 1000 = 0.0039$ [L/s*pers] (recommended range is $E_{CO_2} = 0.0036$ L/s*pers for adolescent females and $E_{CO_2} = 0.0045$ L/s*pers for adolescent males). It is worth noting that the input value for the CO₂ generation rate (q_{CO_2}) depends on the metabolic level of the people, therefore the program will properly calculate the CO₂ concentration even when the no. of occupants or the activity within a zone is changing.

For the calculation of the thermal comfort indices (PMV, PPD) a clothing level of 1 Clo was chosen for winter and a clothing level of 0.5 Clo was chosen for summer.

The indoor comfort outputs are influenced by both temperature and humidity, therefore the internal algorithm, based on a polynomial function, was used to calculate the latent and sensible heat gains from the occupants.

D. HVAC scenario

As presented before, the HVAC system consists of only fixed heating radiators that can offer a total heating power (P_{heat}) of around 5000 W. This did not pose any problems for the heat distribution or temperature gradients because the air temperature distribution type that was used for the model was the mixed mode which considers the air temperature as being uniform through the zone. **[DB Help v5]** For a more detailed analysis of the comfort inside the classroom a CFD simulation is more adequate.

A particular schedule has also been used for the heating system, since this is one important factor that influences the indoor thermal comfort. The system was considered to run at full capacity from early in the morning (4:00 AM), so that the walls would heat up until the students arrive, until the end of the school program (14:00 PM). During the rest of the day, from 14:00PM to 04:00AM, the system was considered running at partial capacity, as well as during the weekends and the holidays as presented in table below. The system is controlled by two temperature values for each zone: a comfort temperature (t_c) and a set back temperature (t_{sbk}). The comfort temperature was set individually for each zone, with 24

°C for the classroom while the set back temperature was defined globally at 15 °C. The set back temperature is used to reduce the energy consumption while avoiding indoor condensation and keeping the HVAC system at a safe temperature (to avoid freezing of water).

One thing to consider is that the software allows the selection of the type of temperature control between mean air temperature and operative temperature. Since most thermostats use the mean air temperature we decided to also use this type as the control temperature. This means that the actual thermal sensation will not be of 24 °C but of a lower value corresponding to the operative temperature, as it will be shown later in the PMV results.

Even though outside temperatures can get really high in summer, there is no cooling system present in the classroom. Therefore, one objective is to see if the temperature in the classroom can be kept at a reasonable level just by using natural ventilation through open windows.

Time	Monday -> Friday	Weekend	Holidays
0:00 - 4:00	Set back temperature 15°C	Set back temperature 15°C	Set back temperature 15°C
4:00 - 14:00	Comfort temperature (24°C / 20°C)		
14:00 – 24:00	Set back temperature 15°C		

E. Ventilation scenario

During the 1900s there was an increasing interest in indoor air quality and societies like ASHRAE (American Society for Heating, Refrigerating and Air-Conditioning Engineers) were already developing standards to improve the ventilation rate per person and the quality of the outdoor air that was introduced in the buildings (ASHRAE 53.1 – 1946 – Light and Ventilation; ASHRAE 62-1973 – Standards for Natural and Mechanical Ventilation). After 1973, due to the oil embargo, ASHRAE and other societies from Canada and Europe were forced to focus on reducing the energy consumption of the buildings rather than on the quality of the air inside, therefore the ventilation rates were lowered and the building envelopes were better sealed. At the same time the number of indoor pollutant sources has started to increase due to the apparition of more household appliances, interior decorations, changes in building materials, increased number of household products and the lately increase in electronic devices.

Since then, there have been several studies that linked different aspects of IAQ to the ventilation rate and to the CO₂ concentration inside a building. Most of the studies are using the CO₂ level as an indicator of the indoor air quality and how well an indoor space is ventilated [Ventilation rates and CO₂ level for US Army Buildings] [Association of Vent rates and CO₂ concentrations with health and other responses] [Standard Guide for Using CO₂ Concentration to evaluate IAQ and Ventilation]. Even though it is not a precise method to describe the overall quality of the air, it was a necessary implementation to improve the energy efficiency of the HVAC systems by correlating the ventilation rates with the CO₂ levels so that overventilation was avoided. Besides that, the measurement of CO₂ concentration is rather cost efficient and easy to implement, compared to solutions that

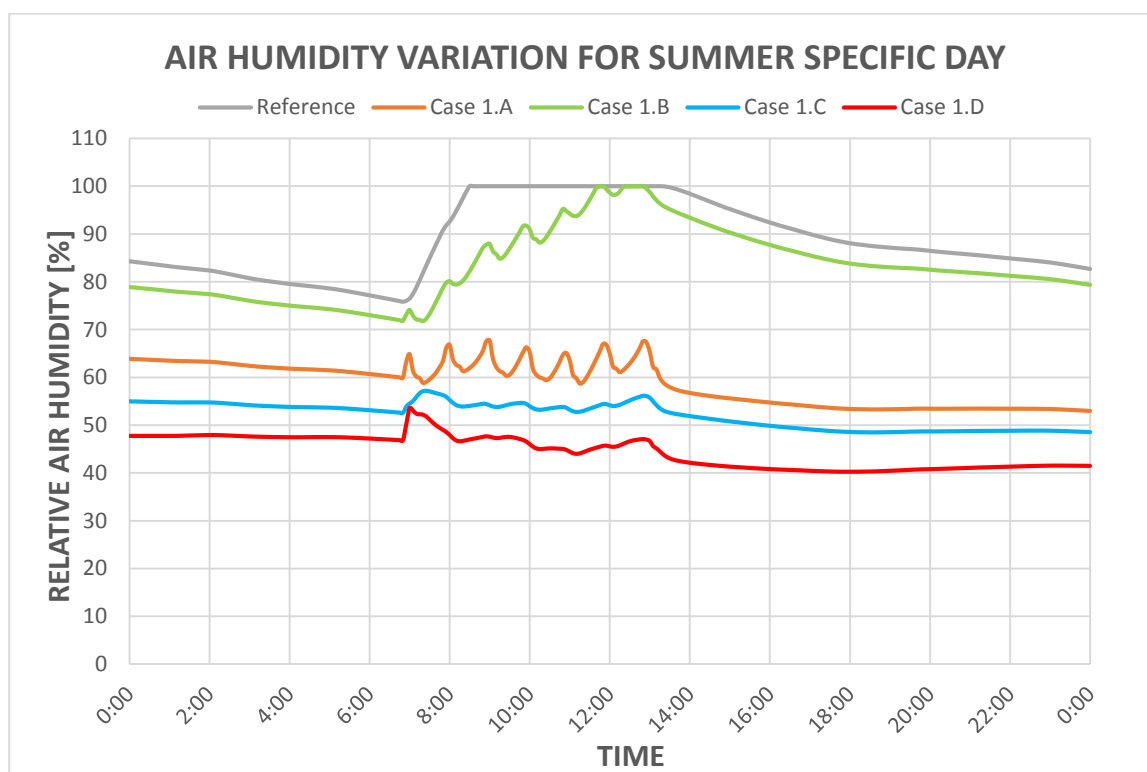
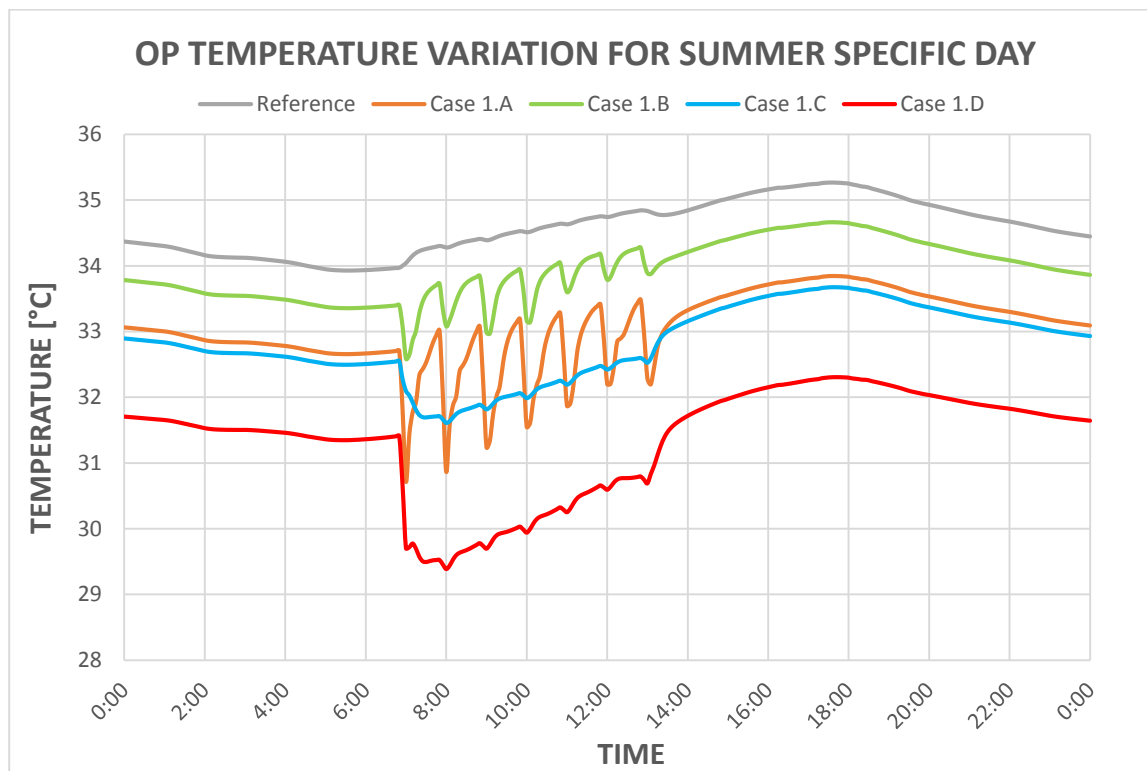
involve a more thorough analysis of various other indoor pollutants (VOCs, PM, CO, NO₂, Ozone etc.).

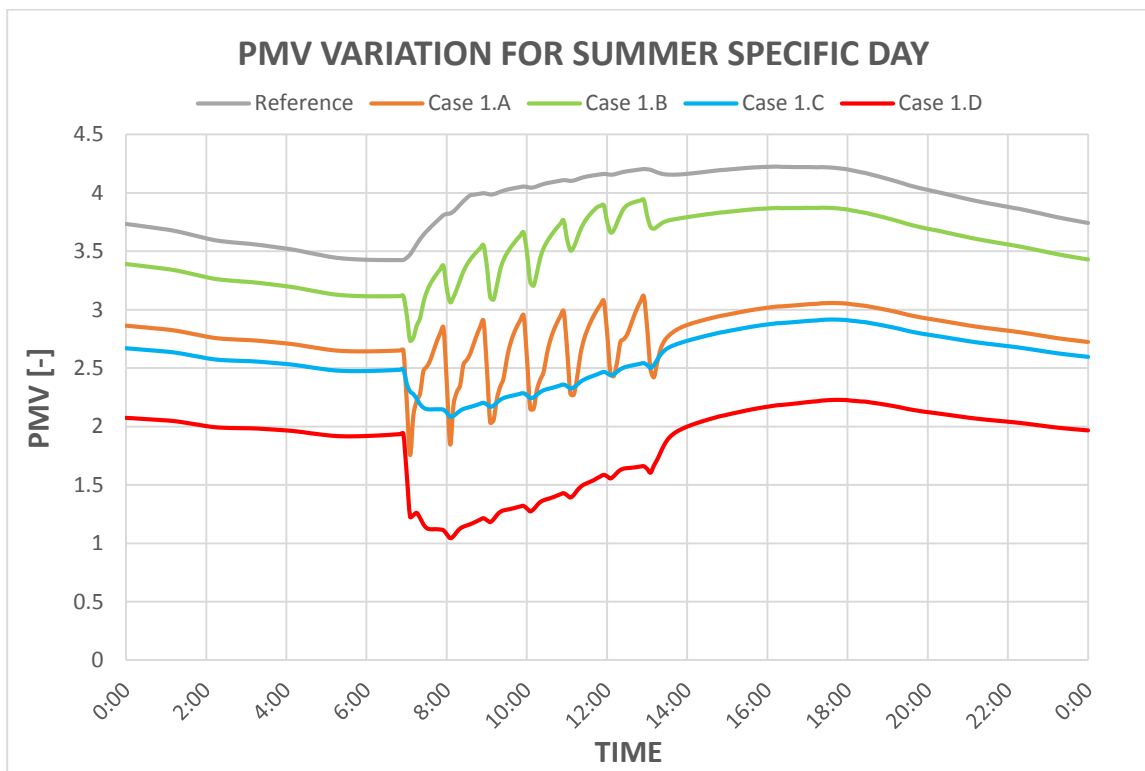
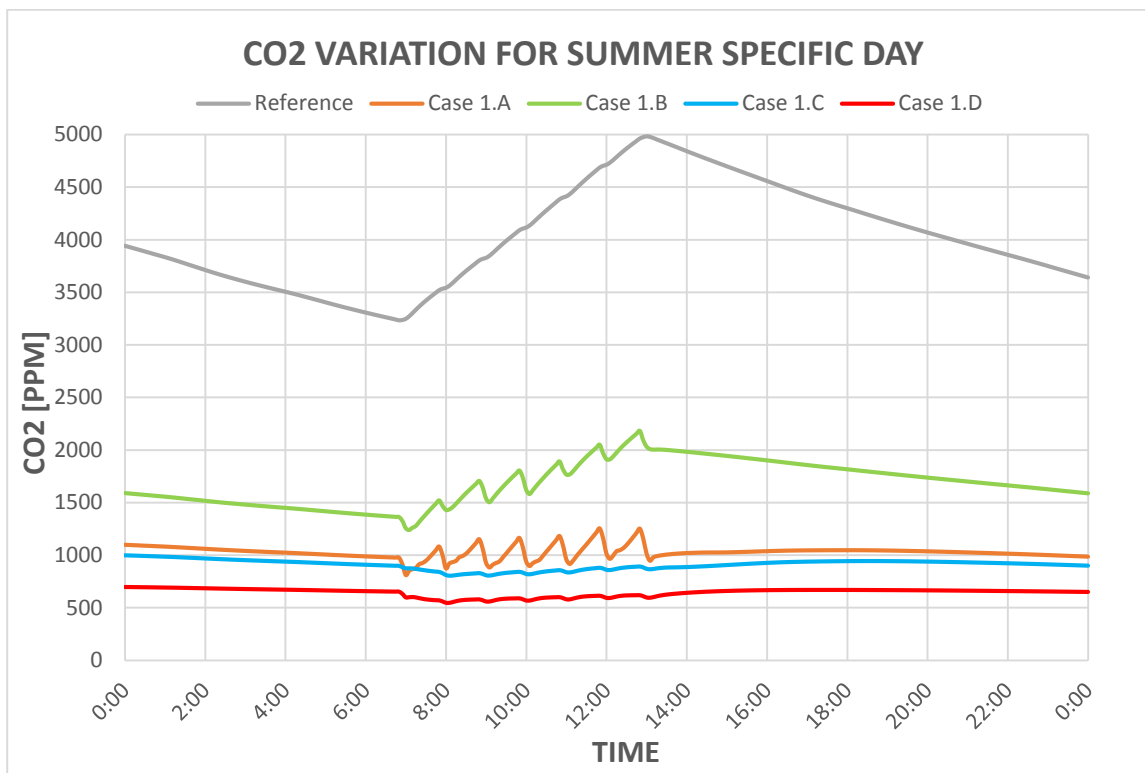
These being considered, for the present study the CO₂ concentration has been used to characterize the general state of the IAQ. This approach is rather suitable for the case of a classroom where the main source of indoor pollution is represented by the persons inside and where the concentration of other pollutants is most probably lower due to the age of the building and the lack of interior decorations or excessive use of cleaning products (low VOC and formaldehyde emission). The problem of particulate matter (PM) carried and/or generated by the high no. of students each day, and the apparition of mold due to inadequate humidity levels could still have an important impact on the IAQ, but both of these pollutants are directly linked to the occupancy level, just like the CO₂ emission. Therefore, any increase in CO₂ levels means an increase in the ventilation rate demand, and a decrease in PM concentration and mold apparition chance (considering that the outdoor air does not present higher concentrations of PM, like the zones near the parks). The objective of the study is to test different ventilation methods and then compare and analyze the results to see how each method performs during the two extreme seasons, winter and summer. To accomplish this, a set of four case scenarios has been considered for each season. For these scenarios two ventilation schedules have been used, one that considers the windows opened only during breaks and another that keeps the windows opened during the whole school day (8:00AM to 14:00PM). Along with the schedules, two different percentages for the open window area have been used, one that considers only a single window opened to 50% of the glazed area and another that considers all three windows opened to 50% of the glazed area. A list of the four cases is presented in table below.

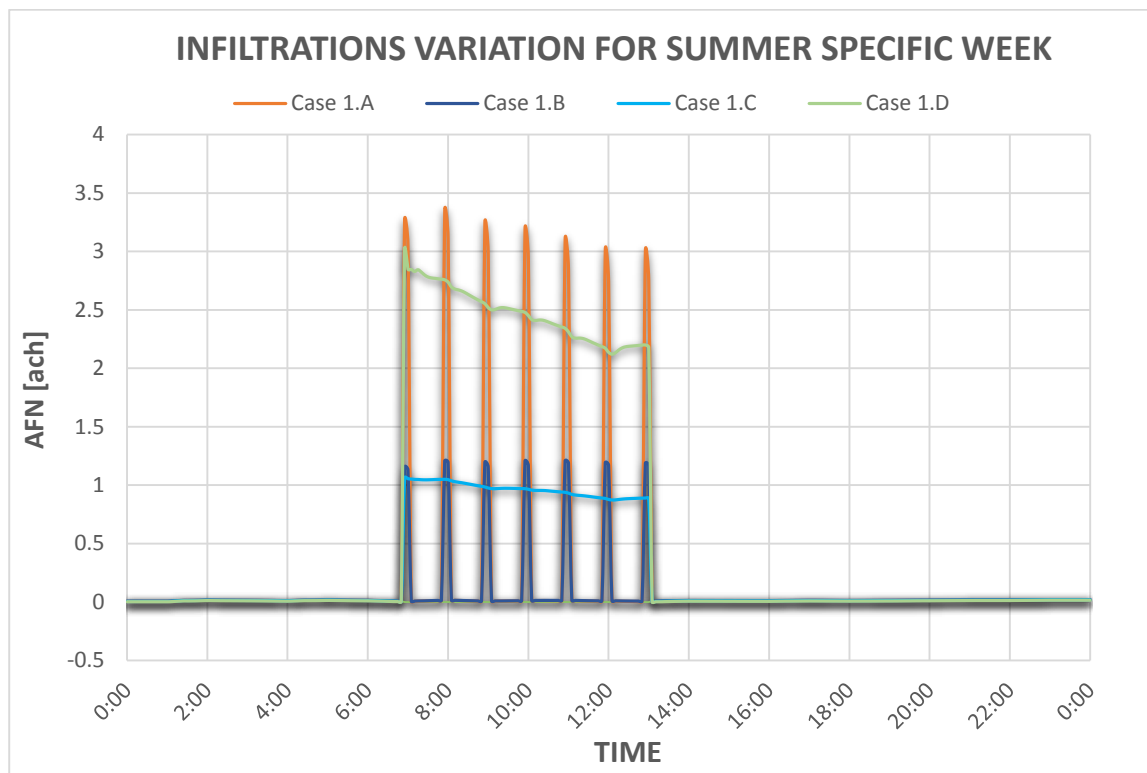
Even though there are numerous possibilities when using a simulation program like this, the decision to use only the four presented cases has been made on the basis of most probable situations and worst/best case scenarios. This way there was less, but sufficient, post processing data to verify the accuracy of the software in estimating a real-life situation.

Case	Schedule	Opened windows	Open Area
Reference	No ventilation.	0	0
Case 1.A	Ventilation only during breaks (10 mins between classes)	3 Windows	50% per window (0.5 m ² /window)
Case 1.B		1 Window	
Case 1.C	Continuous ventilation from 8:00 to 14:00	1 Window	
Case 1.D		3 Windows	

3.3.3 Results: totals graph summer case for a specific day – 04th of June



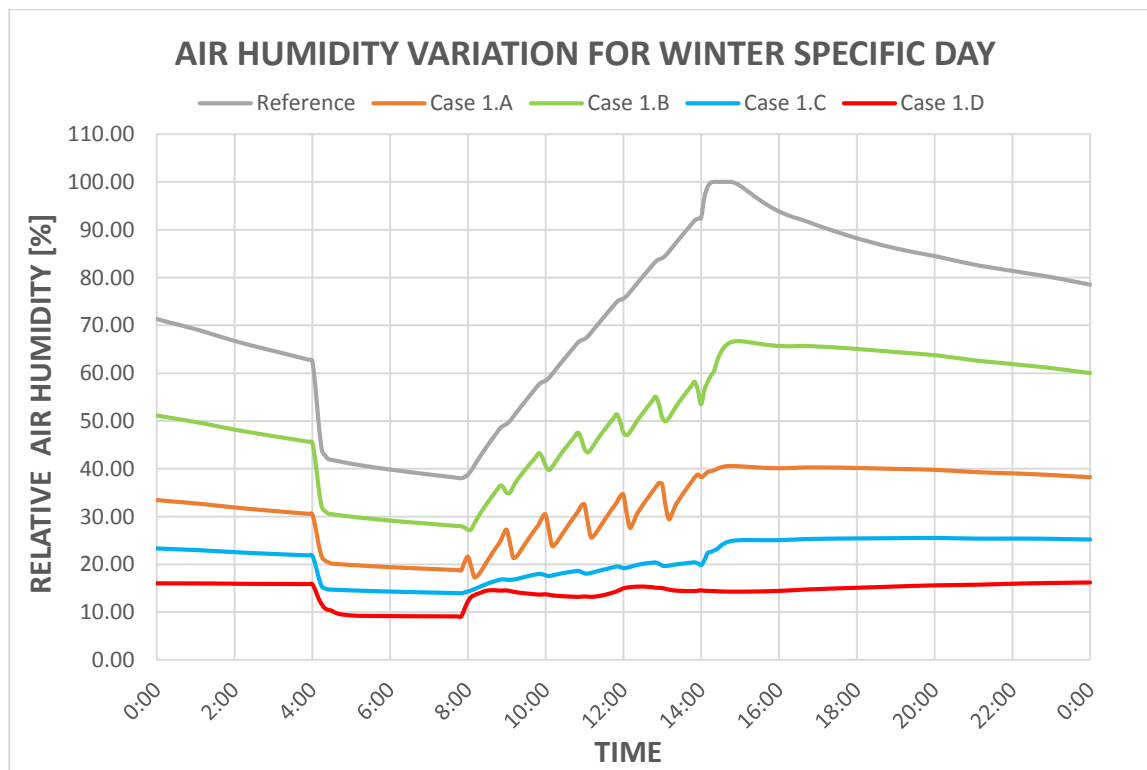
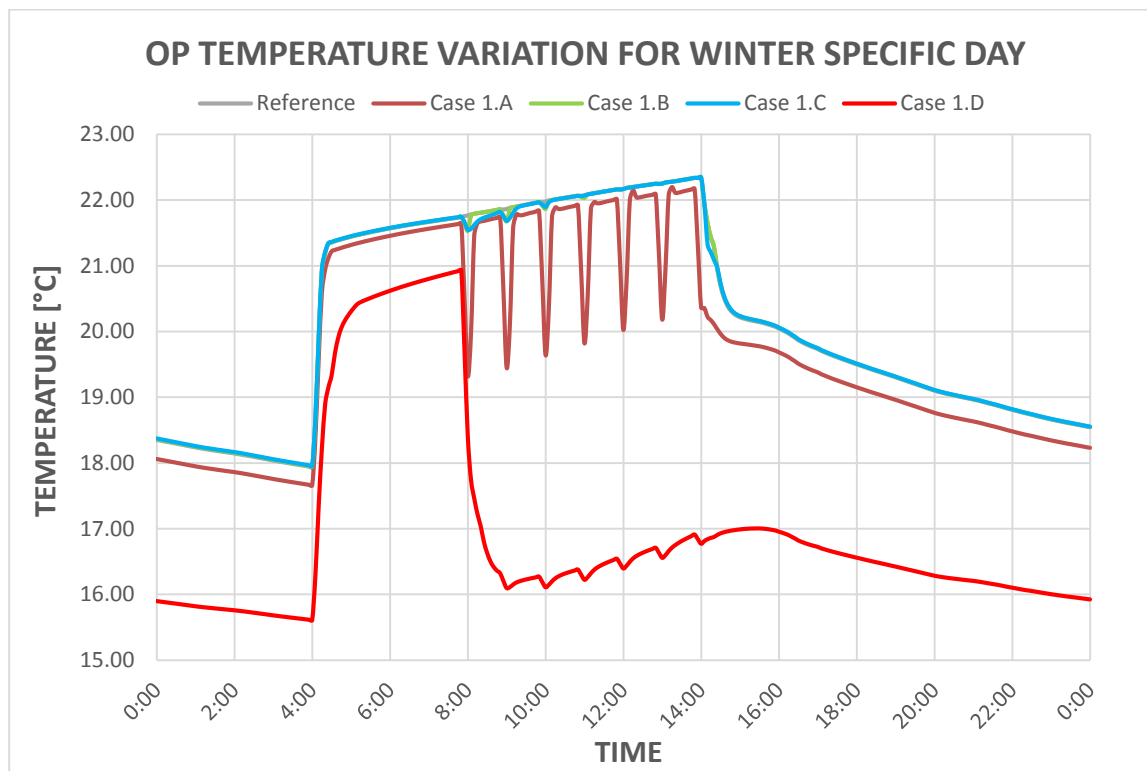


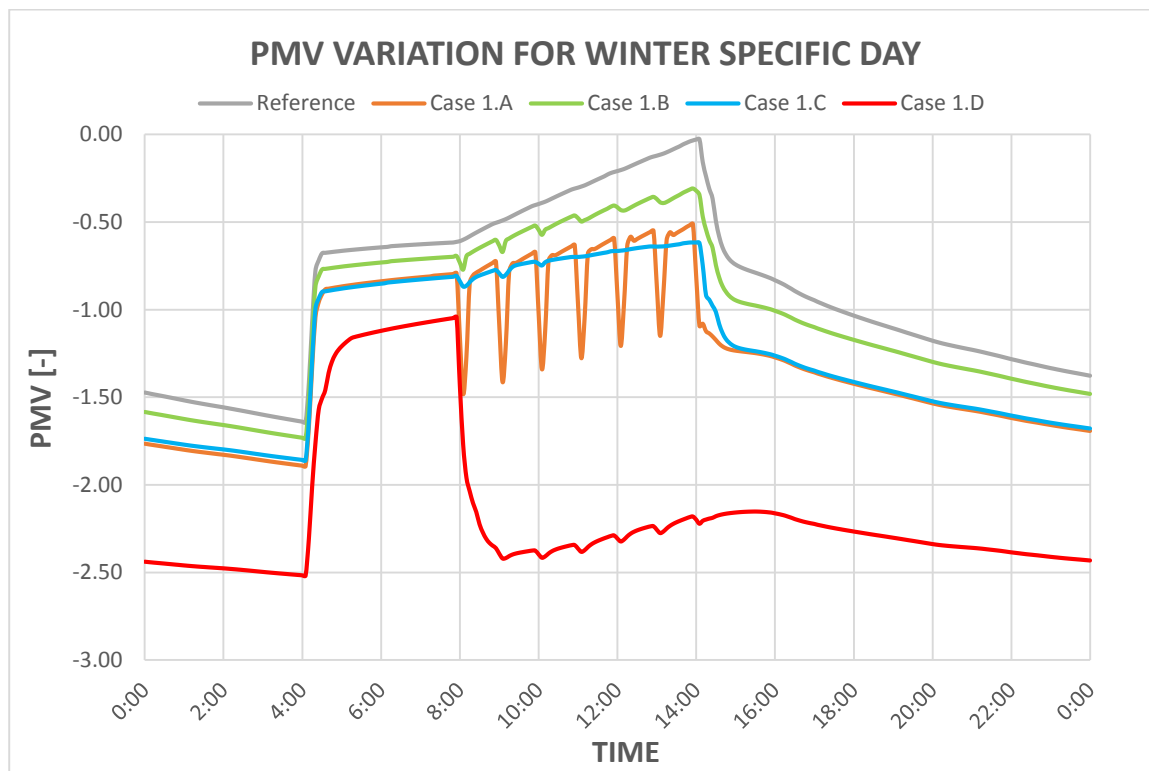
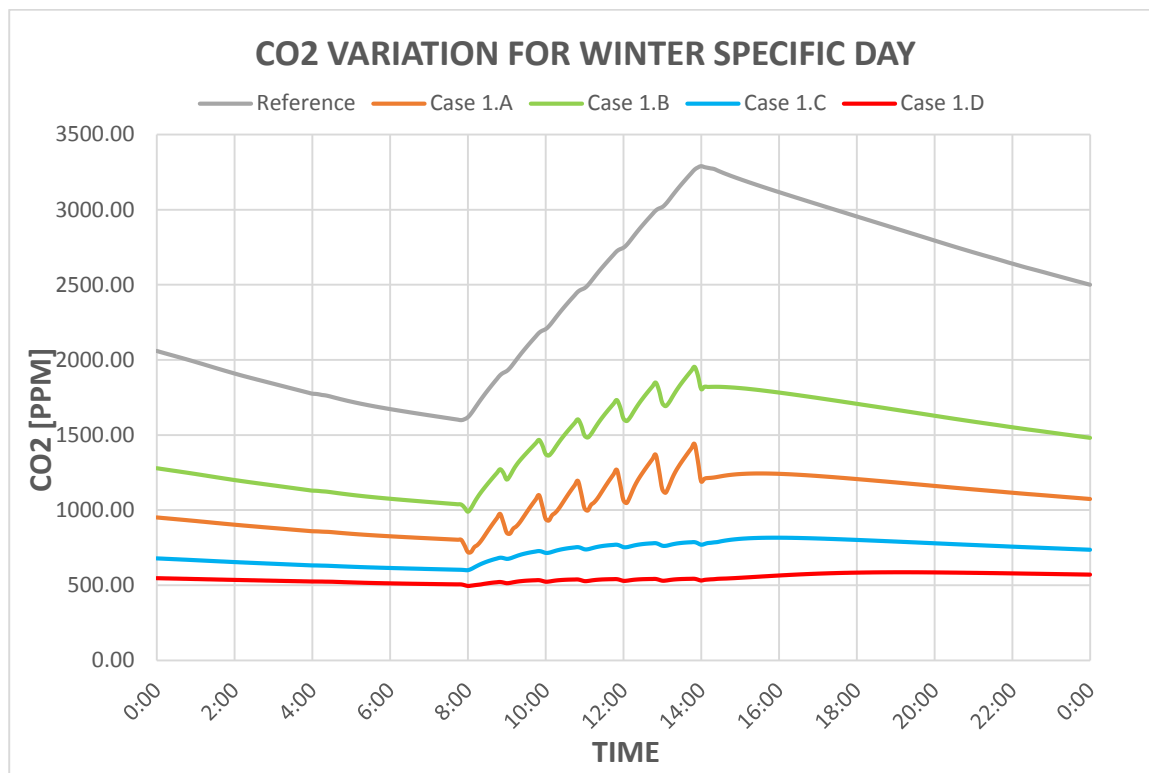


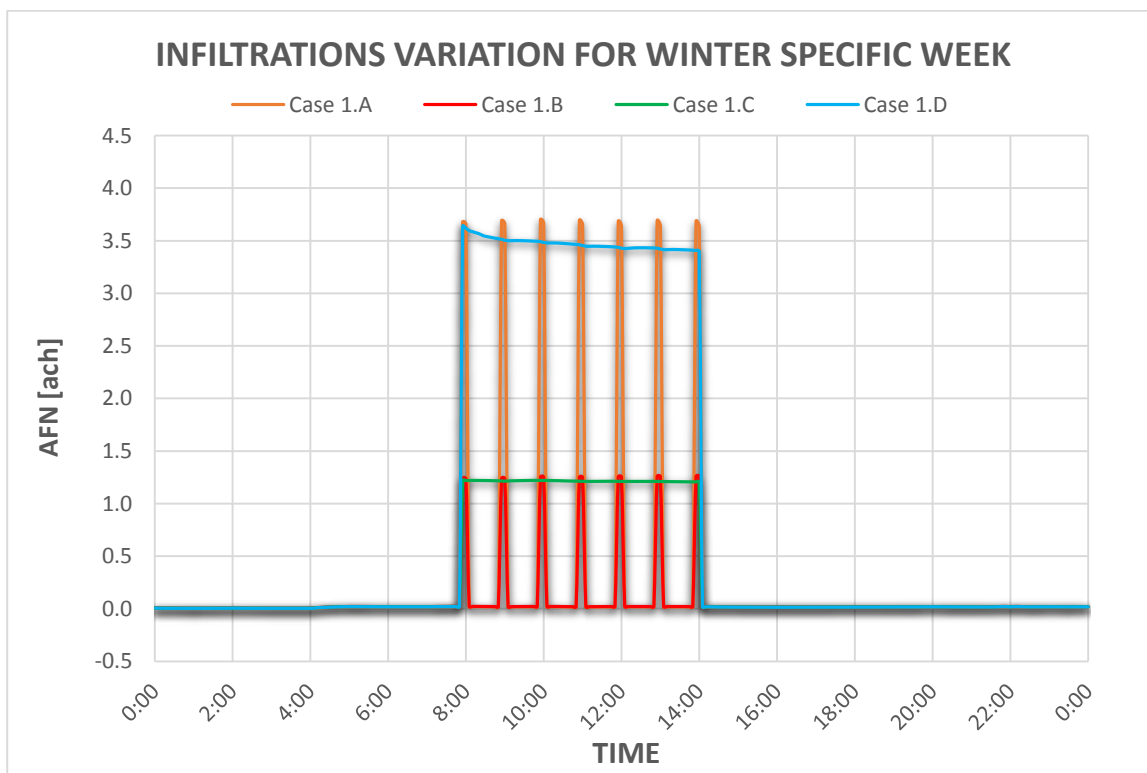
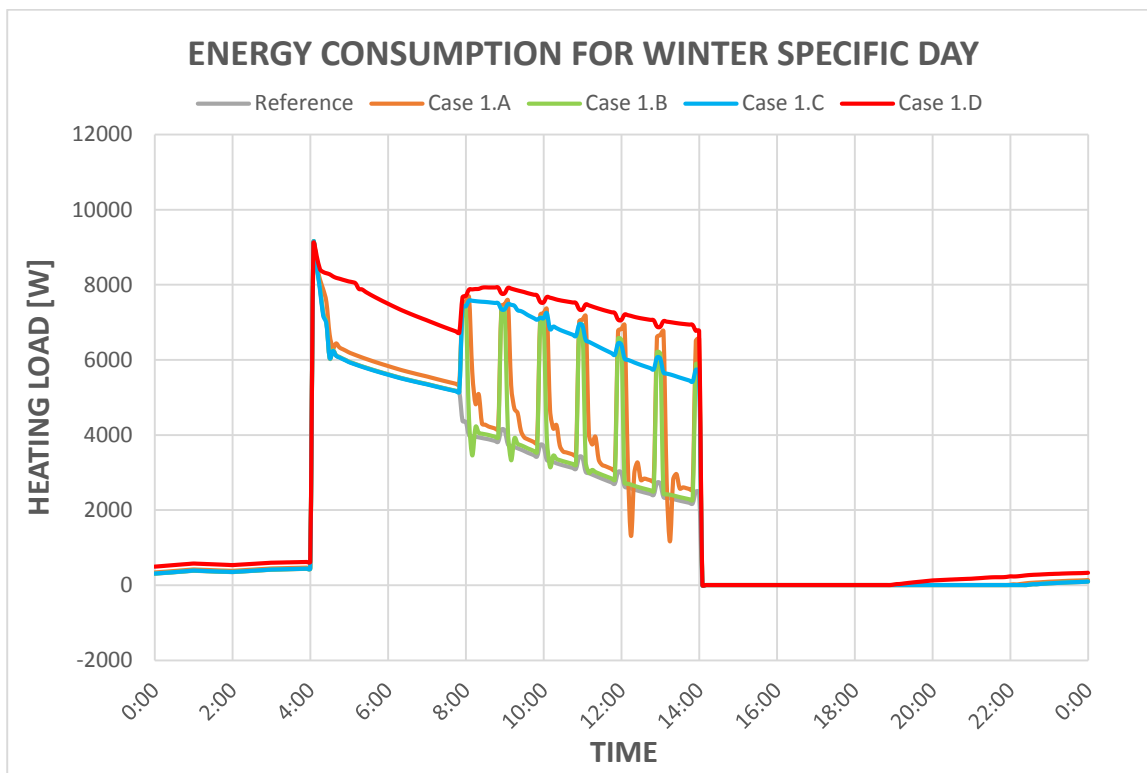
CO2 COMPARISON TABLE (weekly)					
	MAX	MIN	AVERAGE	ERROR [-]	ERROR[%]
REFERENCE	5231.71	1212.63	3513.20	0.00	0.00
CASE 1.A	1405.32	590.42	987.71	-2525.49	71.89
CASE 1.B	2180.47	701.51	1499.12	-2014.09	57.33
CASE 1.C	1035.56	564.27	867.04	-2646.16	75.32
CASE 1.D	711.52	484.27	624.18	-2889.02	82.23

CO2 COMPARISON TABLE (daily - only occ hours)					
	MAX	MIN	AVERAGE	ERROR [-]	ERROR[%]
REFERENCE	4982.69	3520.86	4358.78	0.00	0.00
CASE 1.A	1254.59	873.08	1035.34	-3323.44	76.25
CASE 1.B	2180.47	1429.33	1810.96	-2547.83	58.45
CASE 1.C	892.14	805.62	850.60	-3508.18	80.49
CASE 1.D	641.15	546.63	593.75	-3765.03	86.38

3.3.4 Results: totals graph winter case for a specific day – 22nd of Jan







CO2 COMPARISON TABLE (weekly)					
	MAX	MIN	AVERAGE	ERROR [-]	ERROR[%]
REFERENCE	4130.39	1105.44	2502.36	0.00	0.00
CASE 1.A	1524.82	588.01	1000.86	-1501.50	60.00
CASE 1.B	2090.98	706.07	1395.49	-1106.86	44.23
CASE 1.C	828.12	492.87	692.57	-1809.79	72.32
CASE 1.D	594.96	455.83	539.77	-1962.59	78.43

CO2 COMPARISON TABLE (daily - only occ hours)					
	MAX	MIN	AVERAGE	ERROR [-]	ERROR[%]
REFERENCE	3289.09	1597.89	2458.08	0.00	0.00
CASE 1.A	1440.44	720.82	1073.53	-1428.82	57.10
CASE 1.B	1953.07	989.56	1512.65	-989.71	39.55
CASE 1.C	786.25	600.52	729.14	-1773.22	70.86
CASE 1.D	542.33	495.29	529.03	-1973.33	78.86

3.4 QUALITY SIMULATION OF THE IMPACT OF NATURAL AND MECHANICAL VENTILATION ON THE IAQ AND THERMAL COMFORT OF A CLASSROOM

3.4.1 Introduction

In the present simulation, the same classroom was used, but the ventilation type was changed from natural ventilation to mechanical ventilation. In this case, the air flow was simulated two different situation. One, when the air is introduced with outside temperatures, mean -10°C and second when is used a recovery unit and the introduced air is 20°C.

3.4.2 Results

A. CFD results of natural ventilation: winter case for a specific day – 22nd of January, 12 o'clock

a) Case 1.C, continuous ventilation from 8:00 to 14:00, 1 window opened 50% (near blackboard)

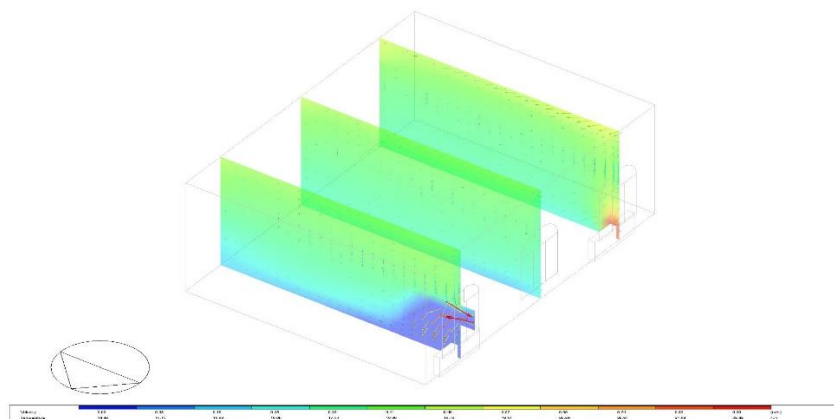


Fig.29: Isometric view of temperature and velocity distribution, middle of windows

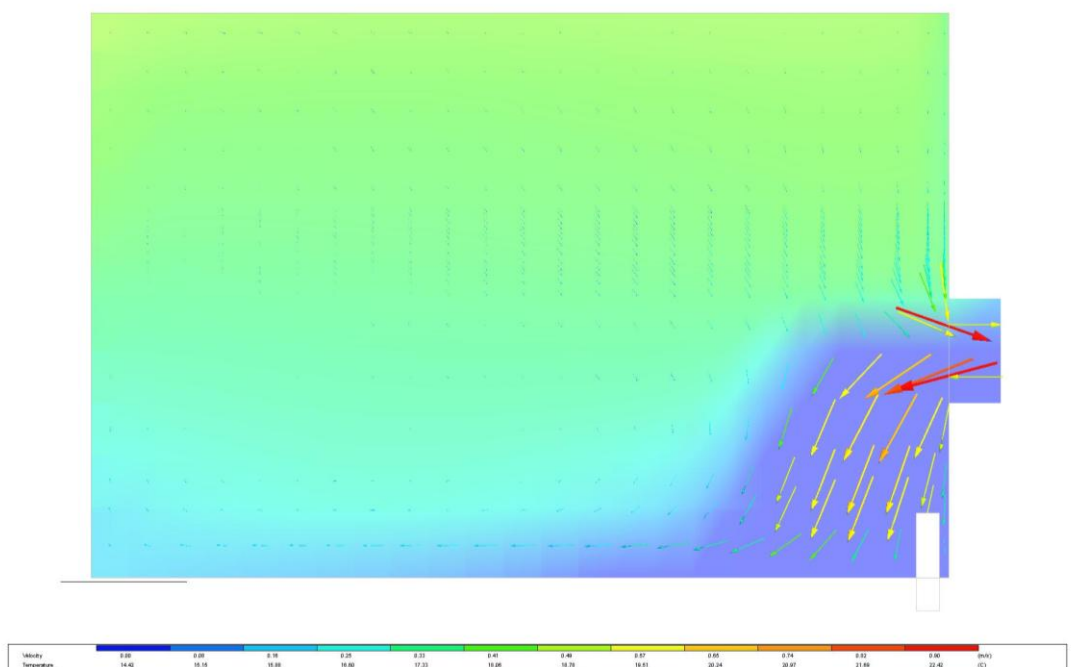


Fig.30: Right view of temperature and velocity distribution, middle of window

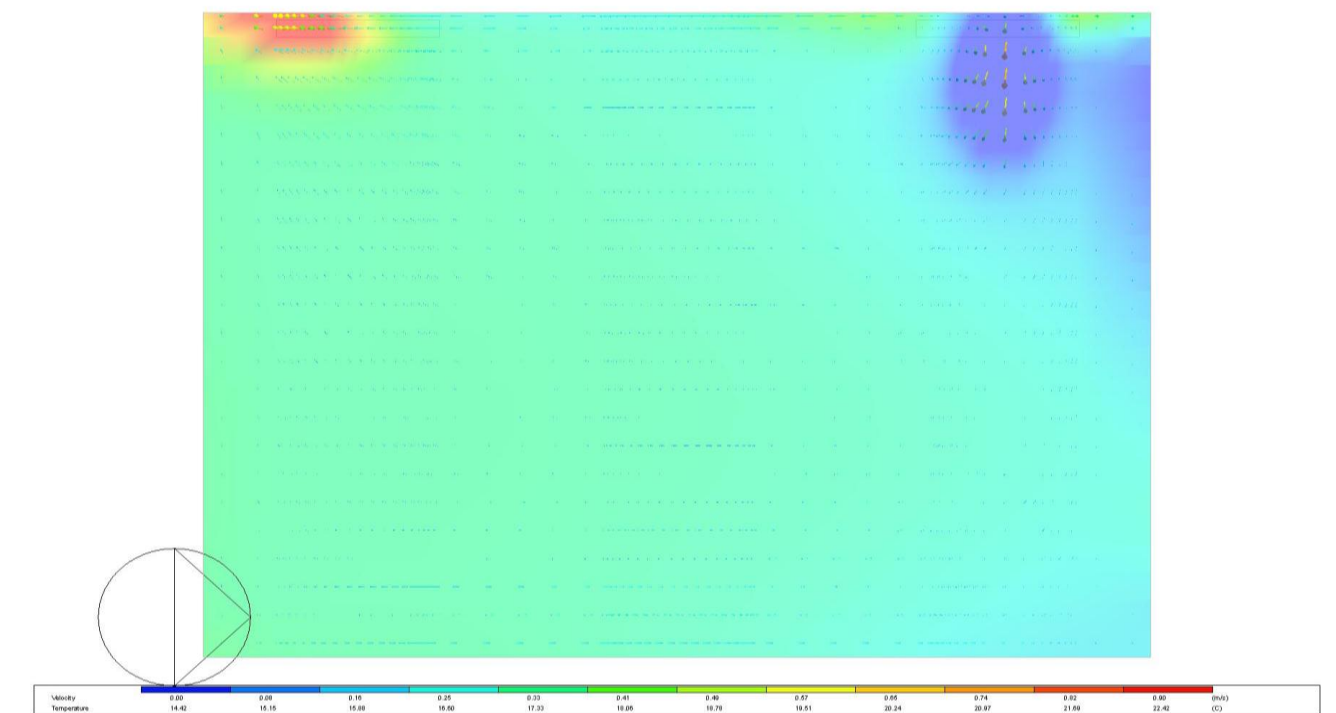


Fig.31: Plan view of temperature and velocity distribution at height of 1m

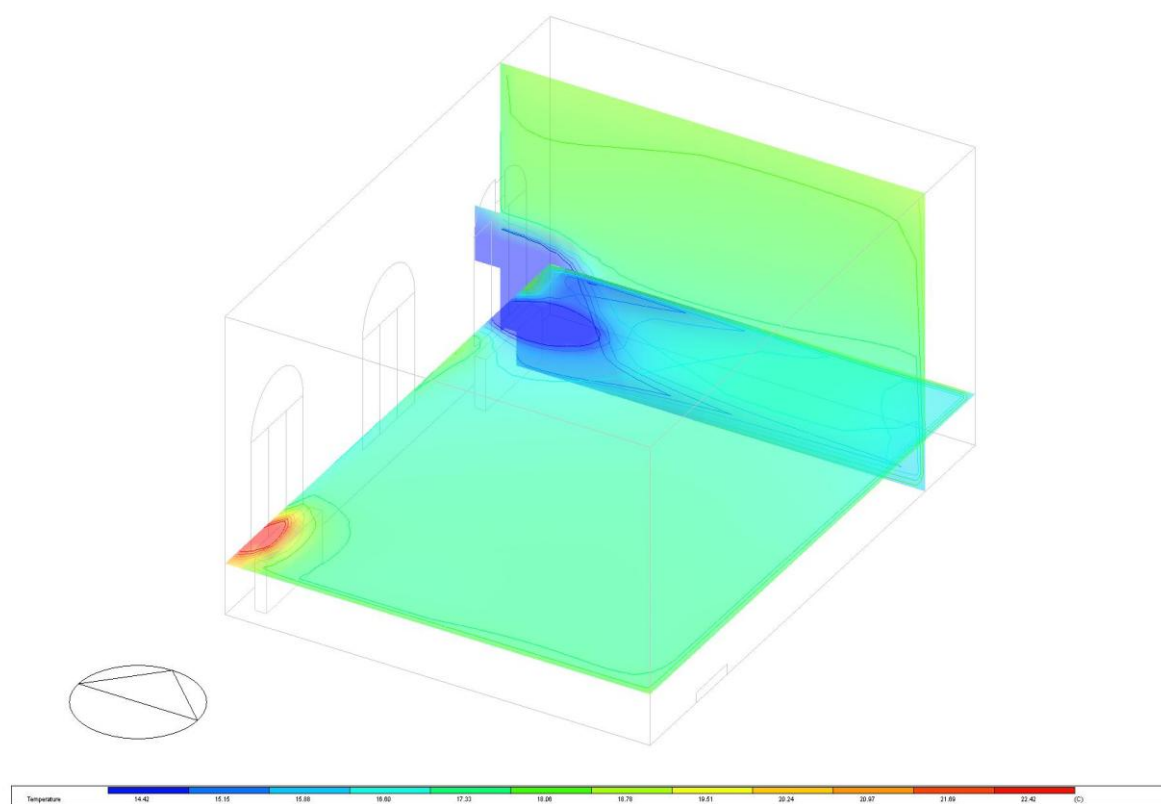


Fig.32: Isometric view of temperature and velocity distribution, middle of window + height 1m

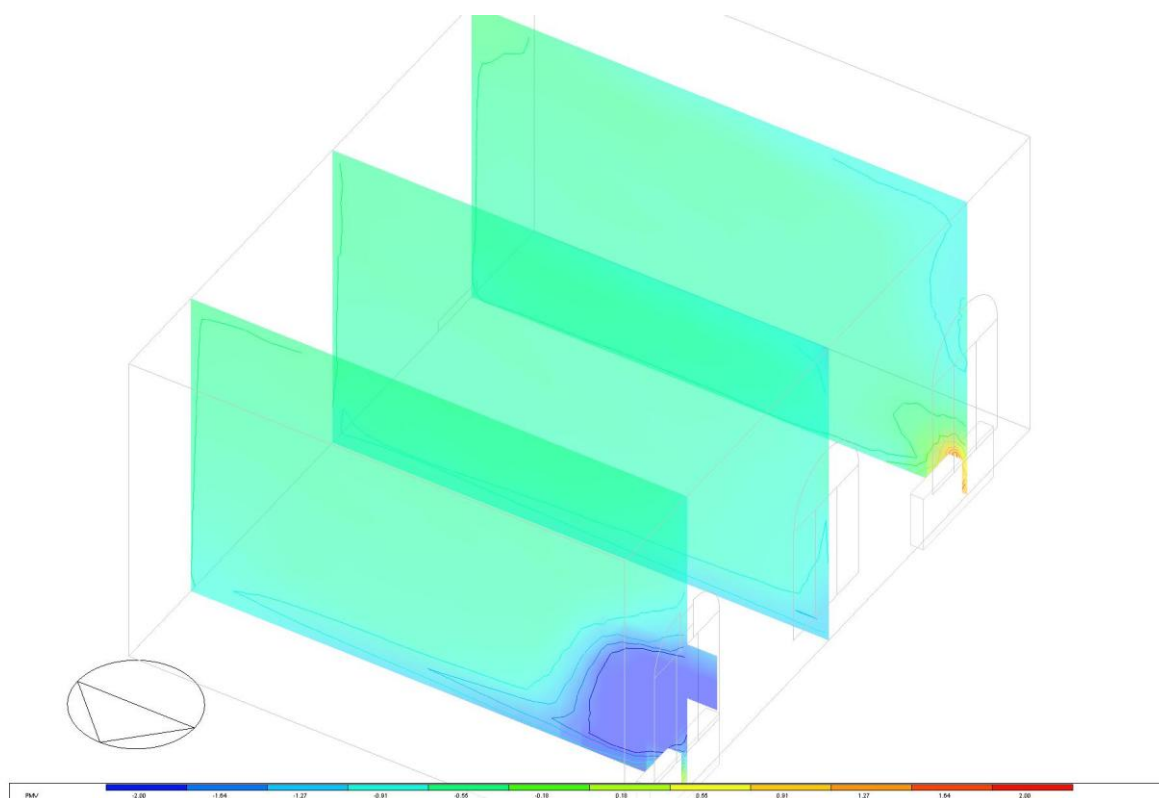


Fig.33: Isometric view of PMV distribution, middle of windows

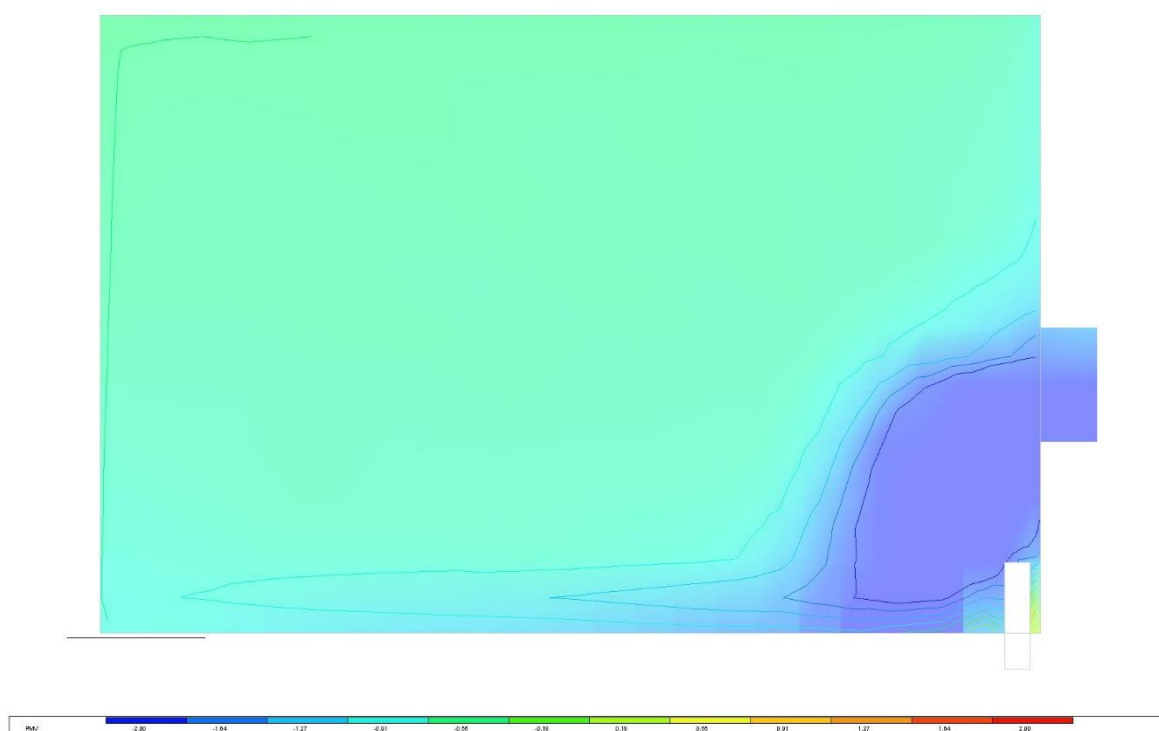


Fig.34: Right view of PMV distribution, middle of window

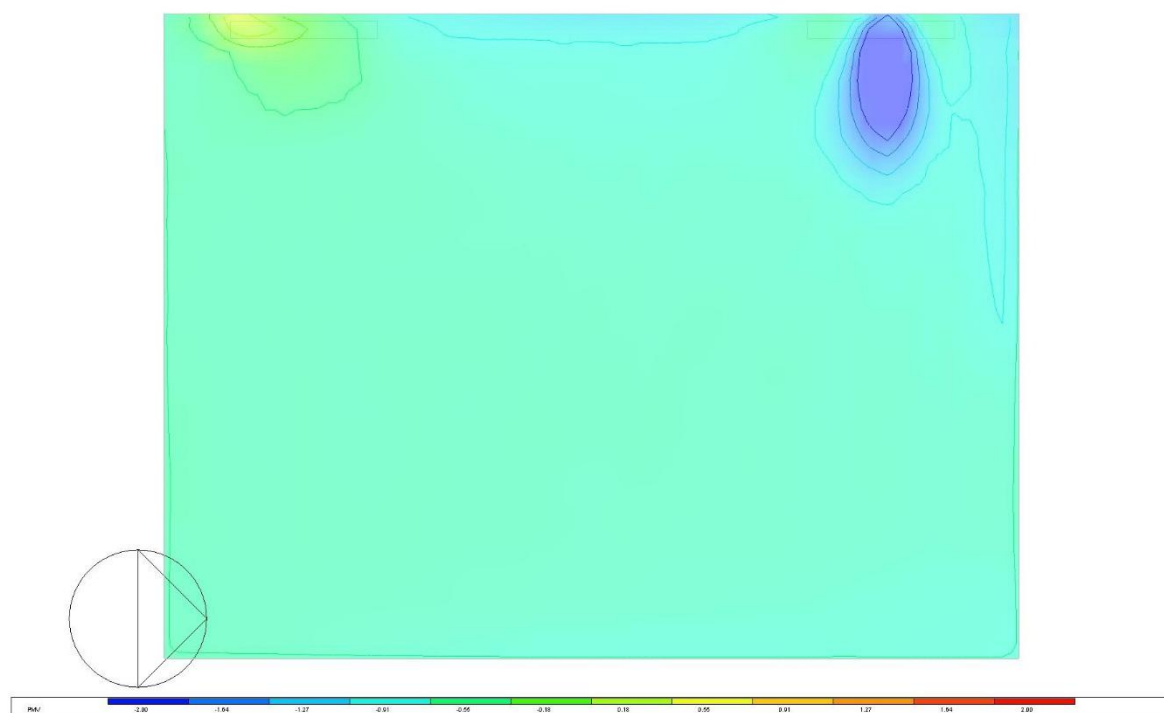


Fig.35: Plan view of PMV distribution at height of 1m

b) Case 1.D, continuous ventilation from 8:00 to 14:00, 3 windows opened 50%

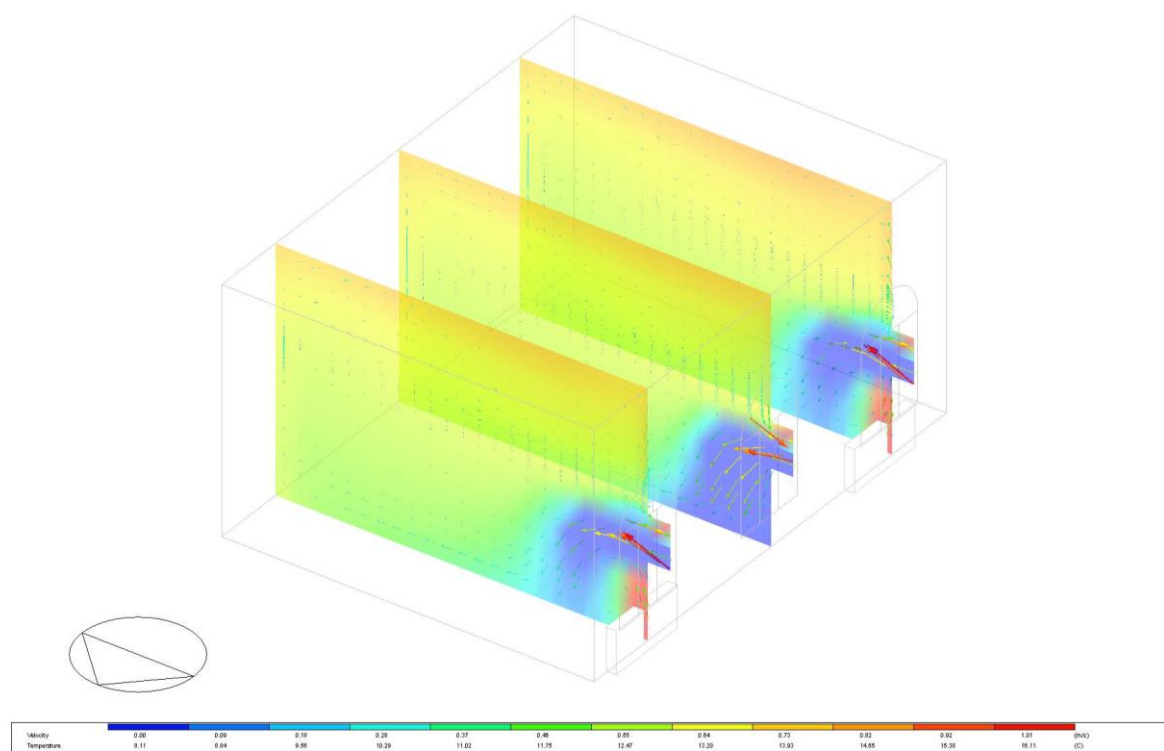


Fig.36: Isometric view of temperature and velocity distribution, middle of windows

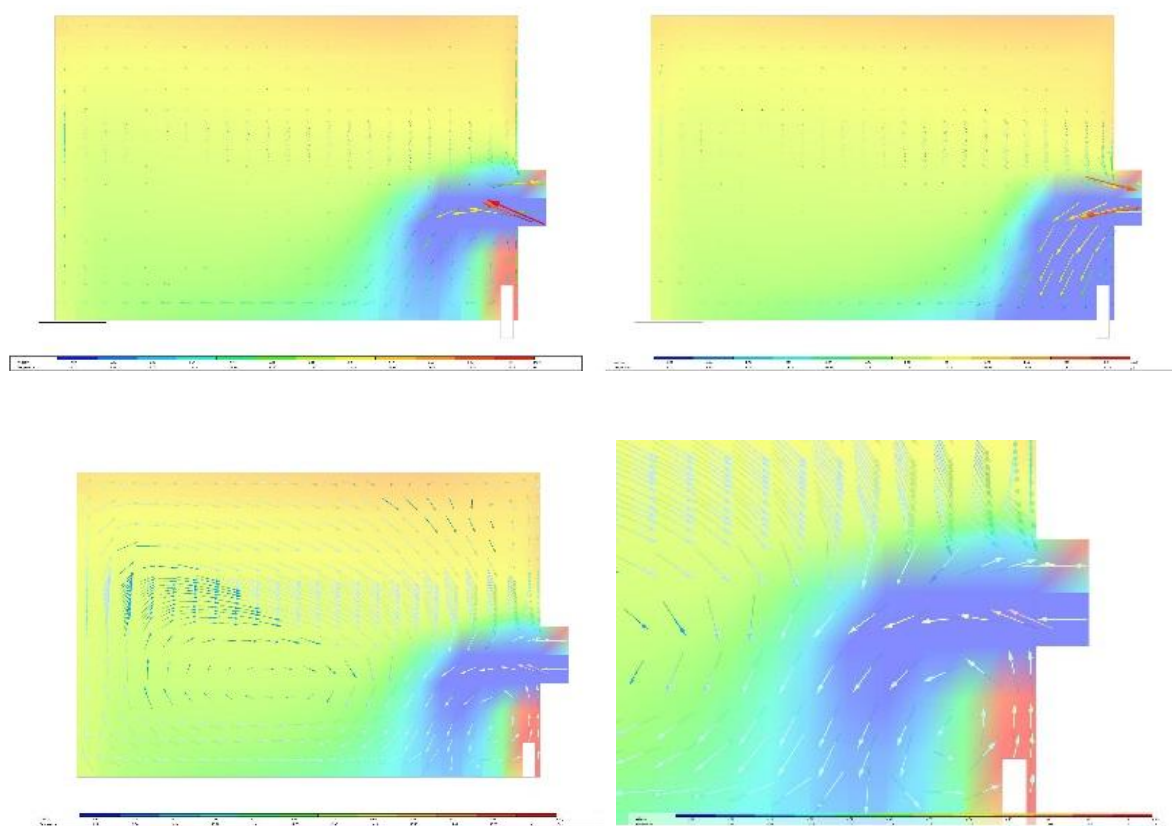


Fig.37: Right view of temperature and velocity distribution, middle of window

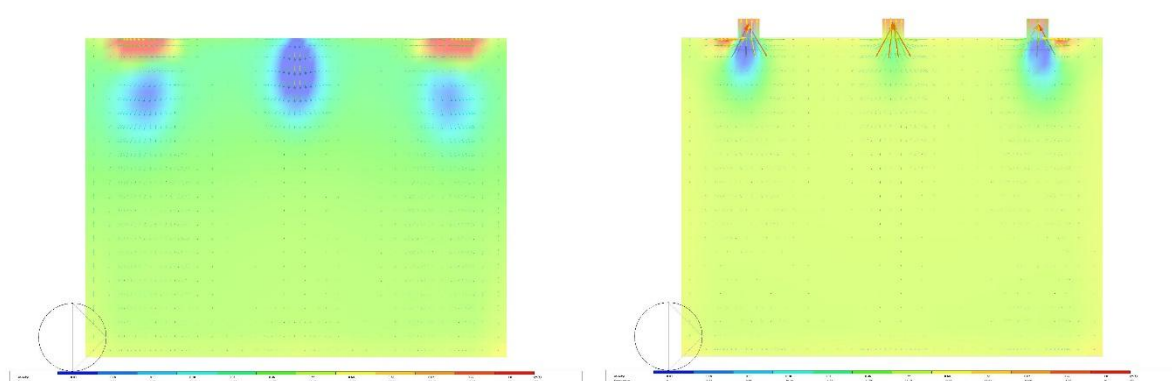


Fig.38: Plan view of temperature and velocity distribution at height of 1m

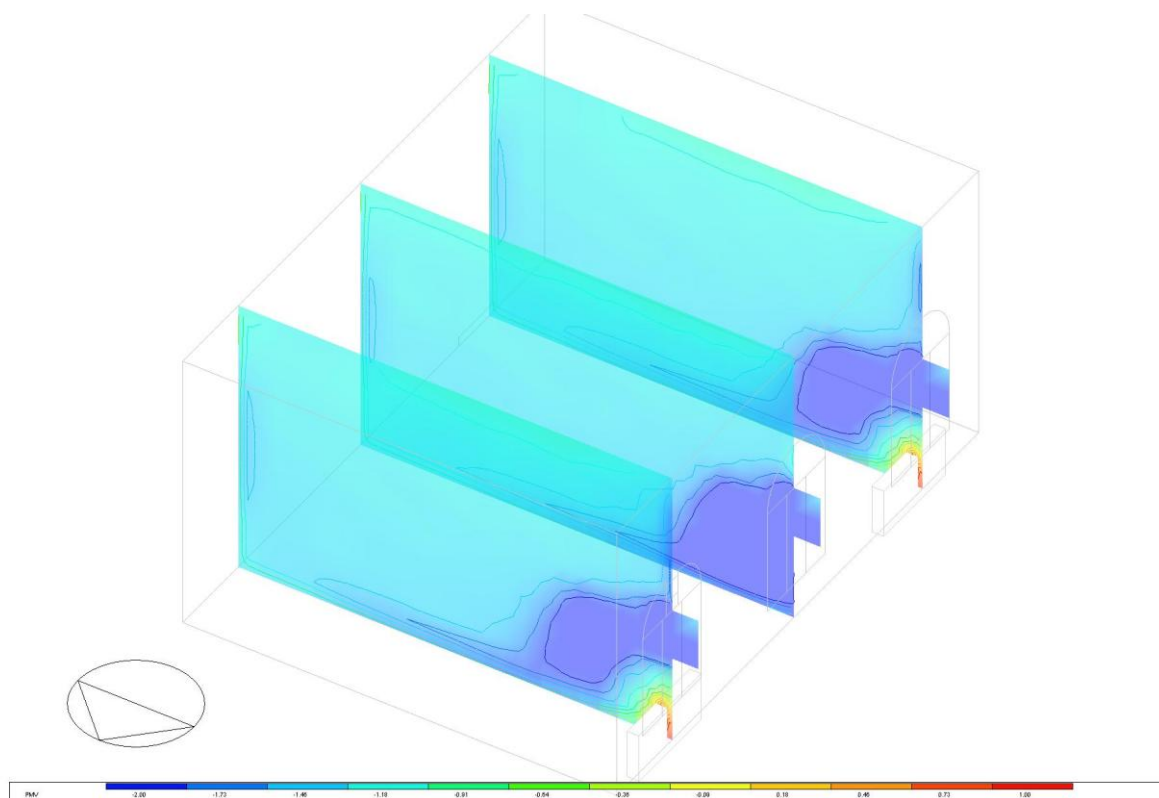


Fig.39: Isometric view of PMV distribution, middle of windows

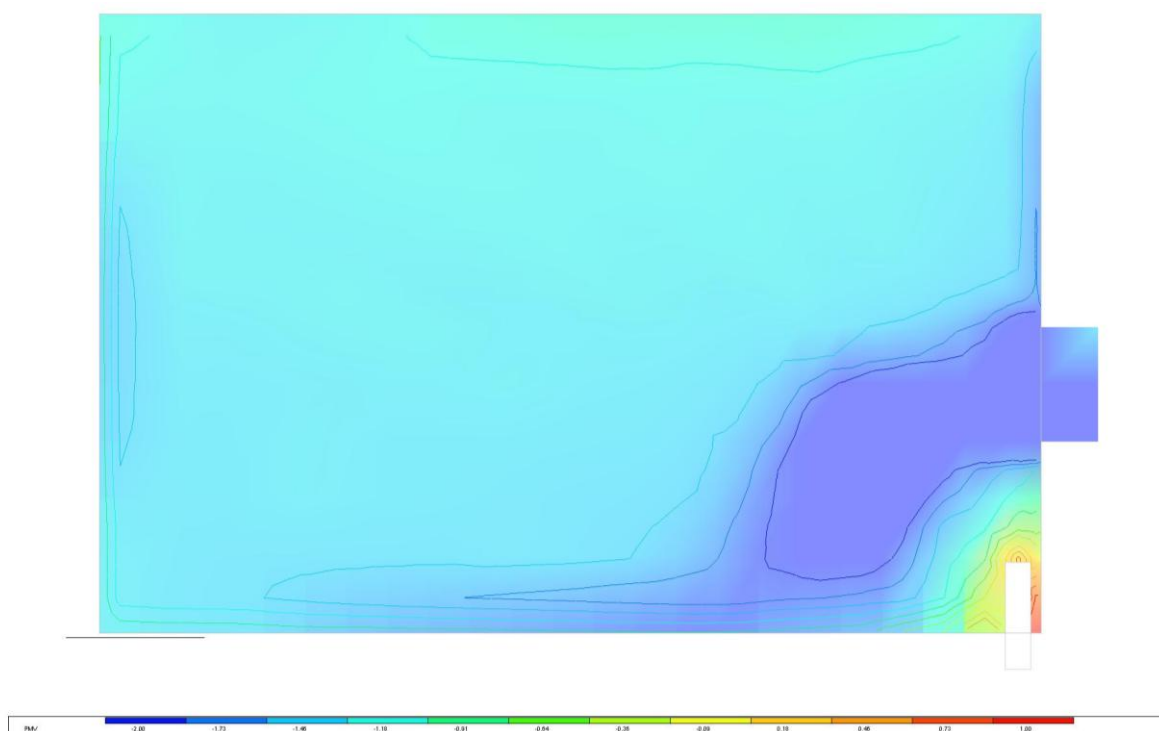


Fig.40: Right view of PMV distribution, middle of window

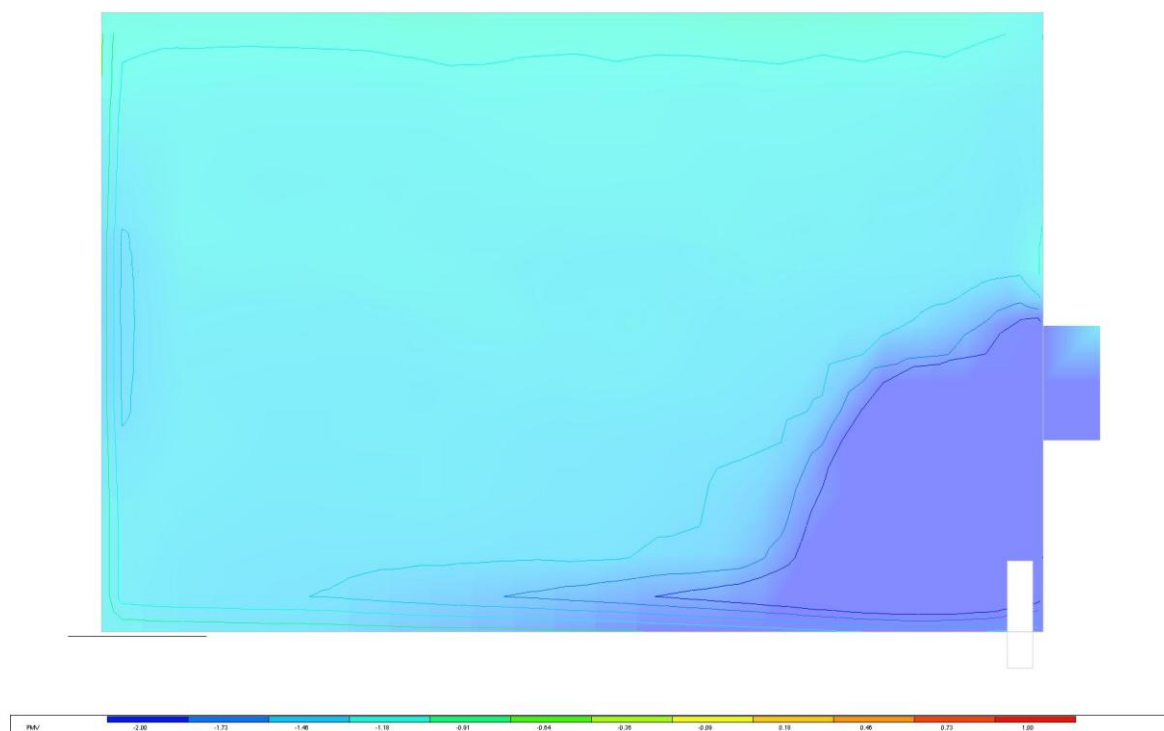


Fig.41: Right view of PMV distribution, middle of window

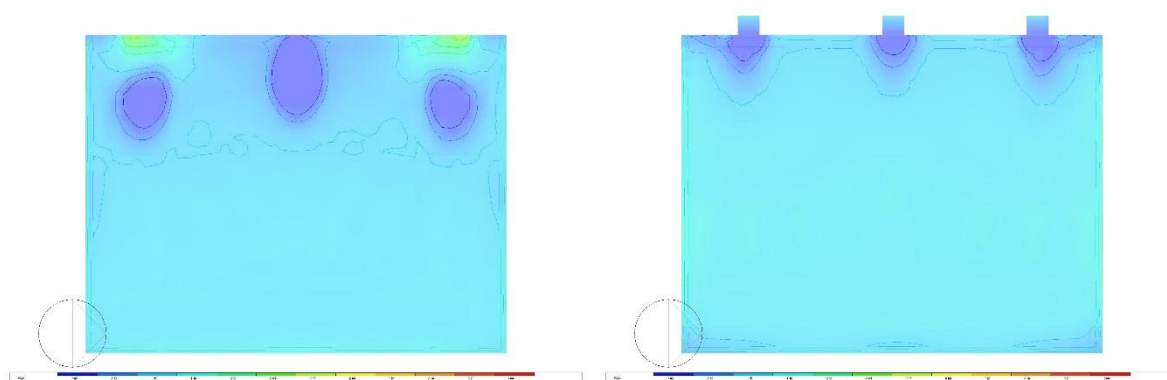


Fig.42: Plan view of PMV distribution at height of 1m

B. CFD results of mechanical ventilation: winter case for a specific day – 22nd of January, 12 o'clock

a) Case 1, supply fresh air with external temperature $t_{out} = -10^{\circ}\text{C}$ and flow $Q_{fresh\ air} = 600\text{ m}^3/\text{h}$

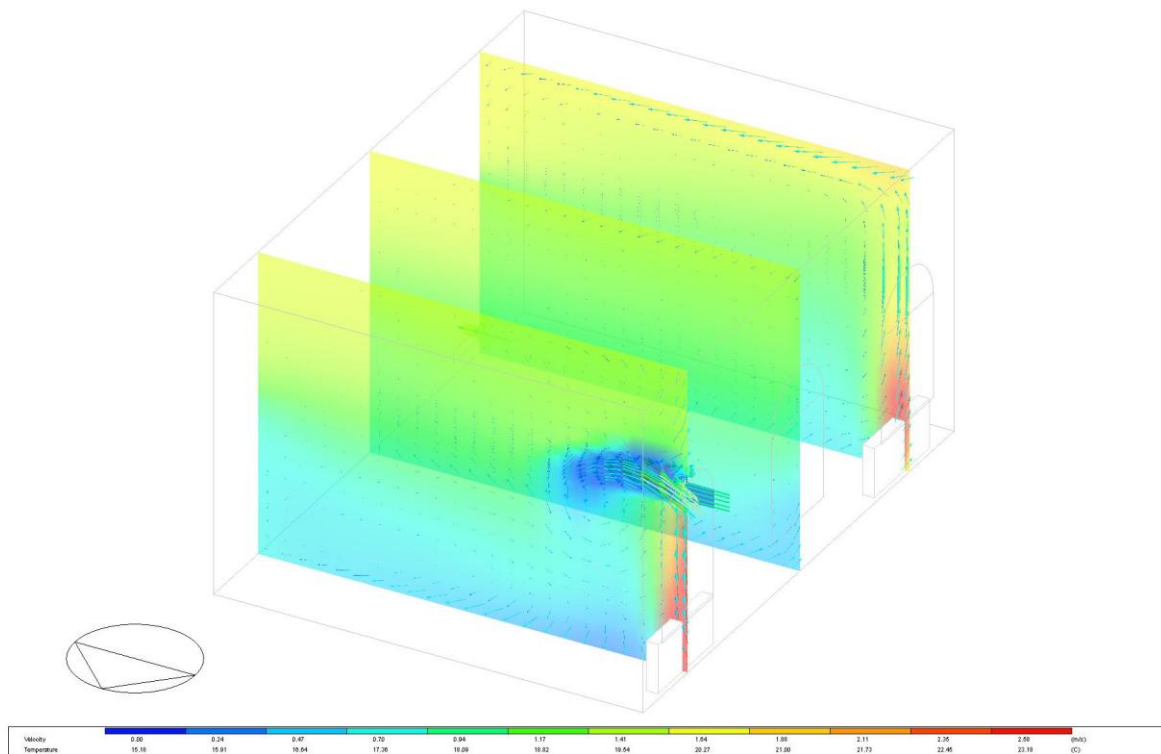


Fig.43: Isometric view of temperature and velocity distribution, middle of windows

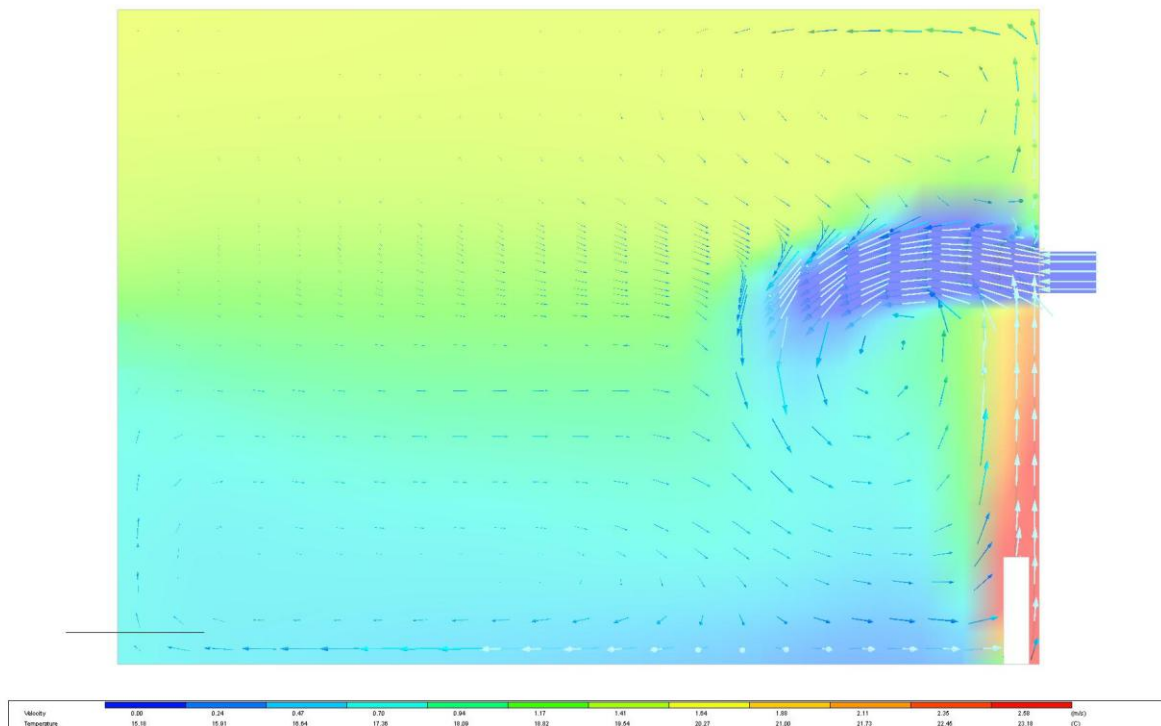


Fig.44: Right view of temperature and velocity distribution, middle of window

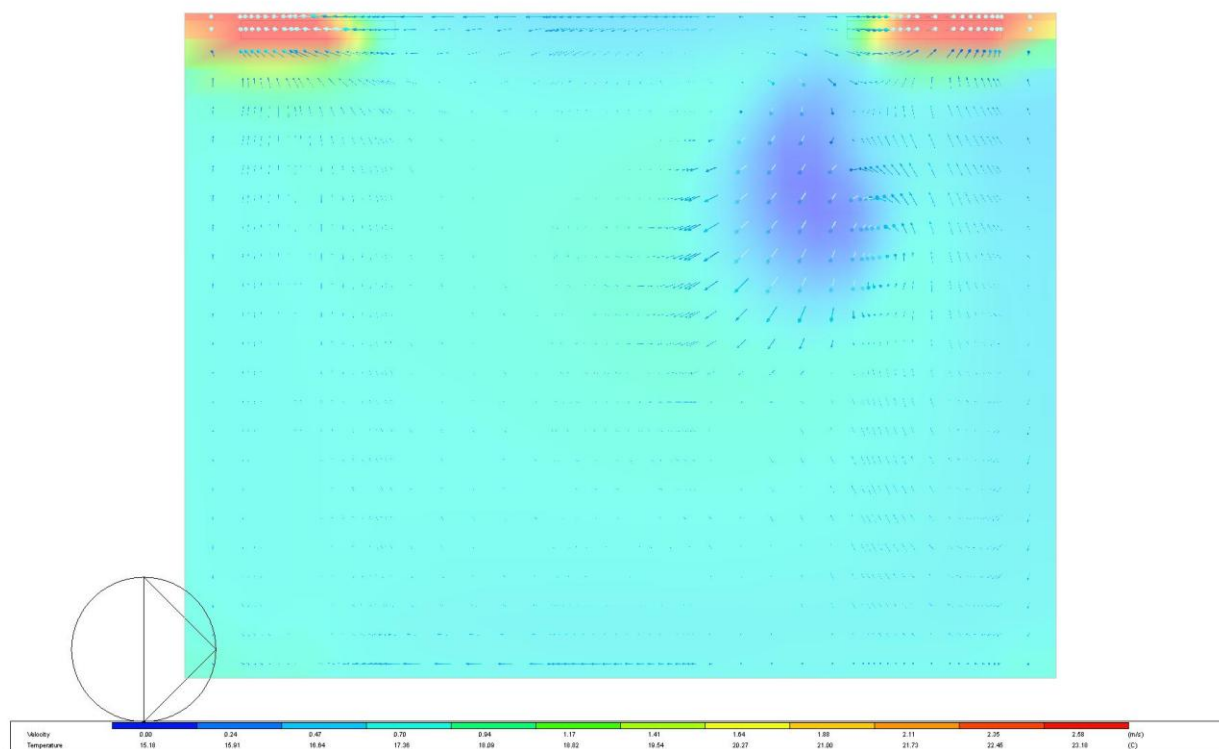


Fig.45: Plan view of temperature and velocity distribution at height of 1m

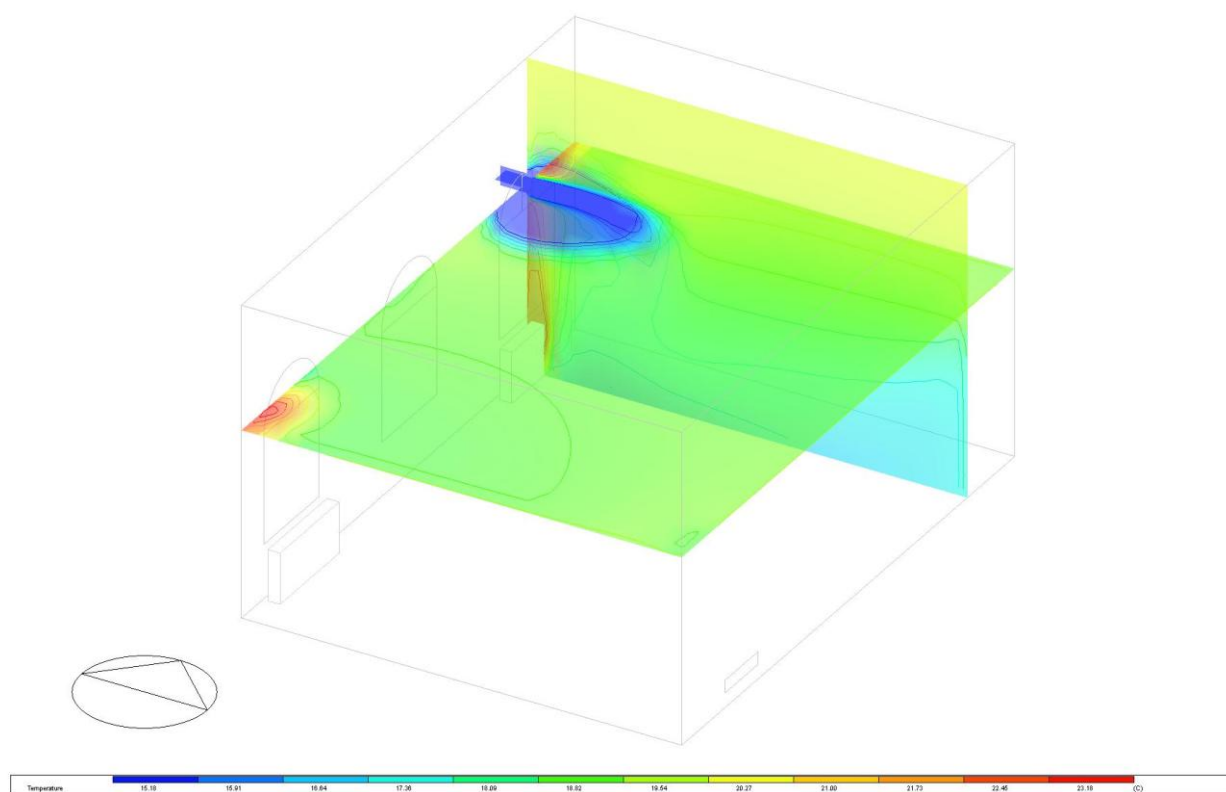


Fig.46: Isometric view of temperature and velocity distribution, middle of window + height 2.5m

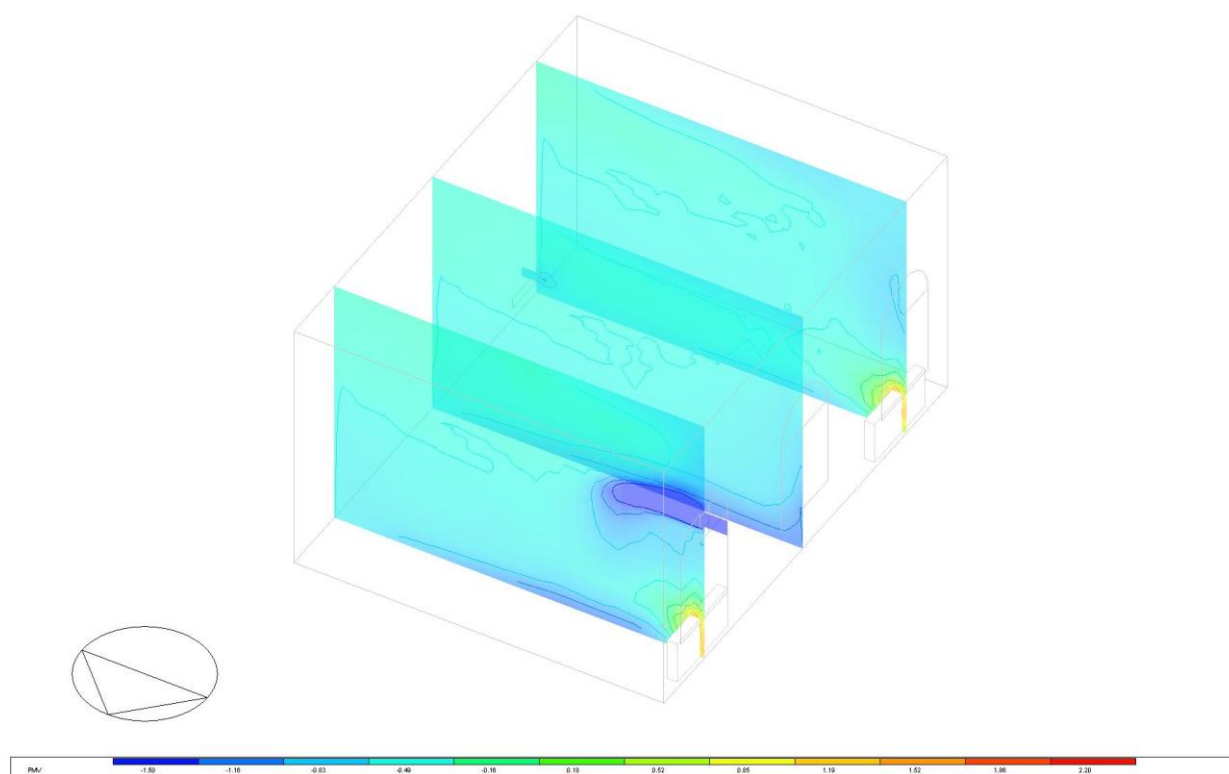


Fig.47: Isometric view of PMV distribution, middle of windows

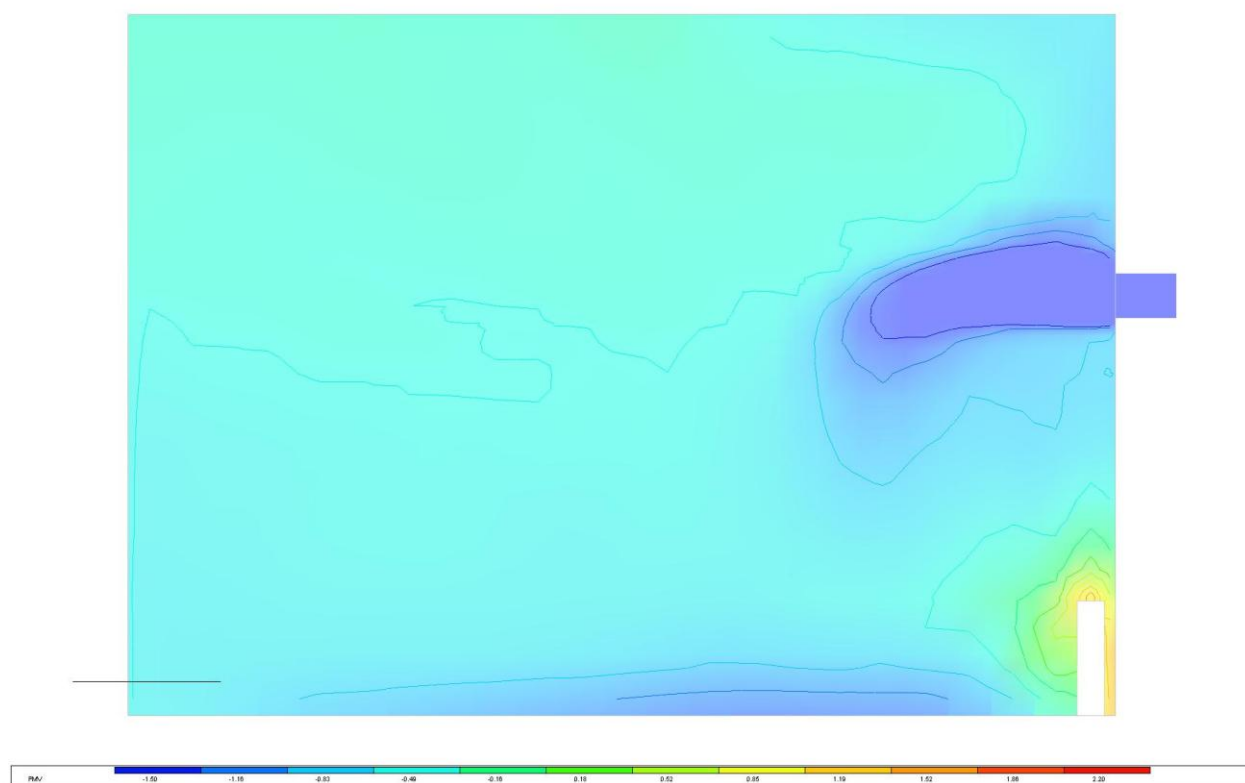


Fig.48: Right view of PMV distribution, middle of window

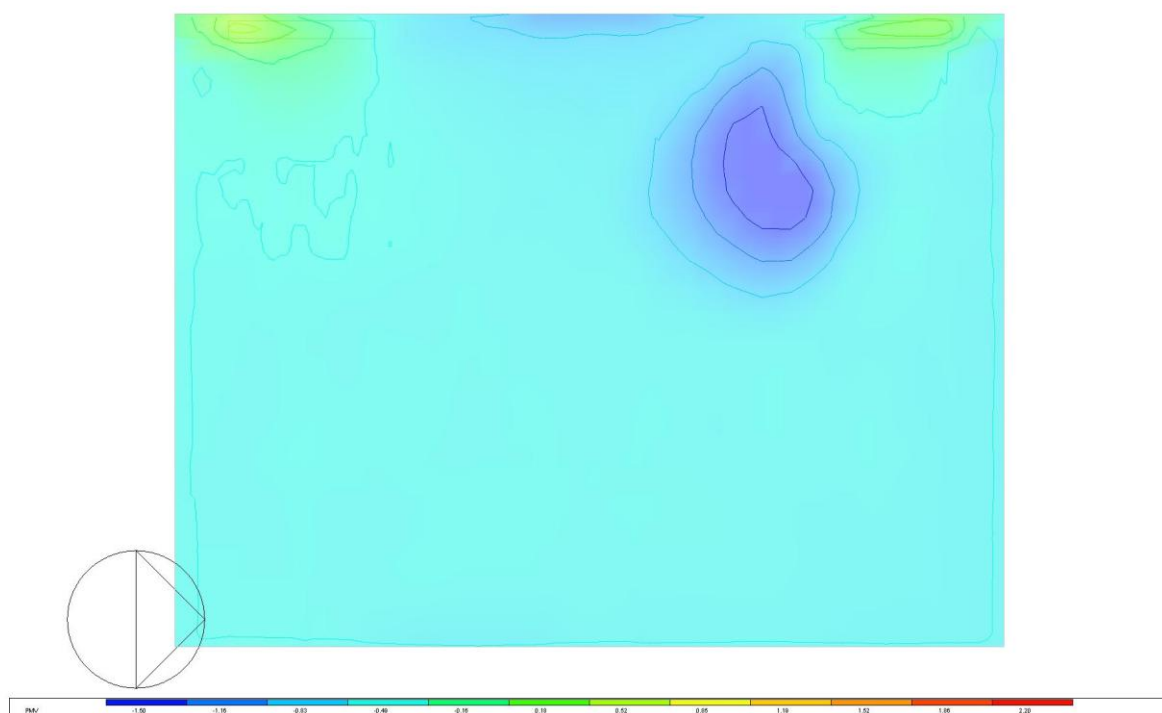


Fig.49: Plan view of PMV distribution at height of 1m

b) Case 2, supply fresh air with recovery unit ($t_{out} = -10^{\circ}\text{C}$) and flow $Q_{fresh\ air} = 600\text{ m}^3/\text{h}$, $t_{supply} = 20^{\circ}\text{C}$

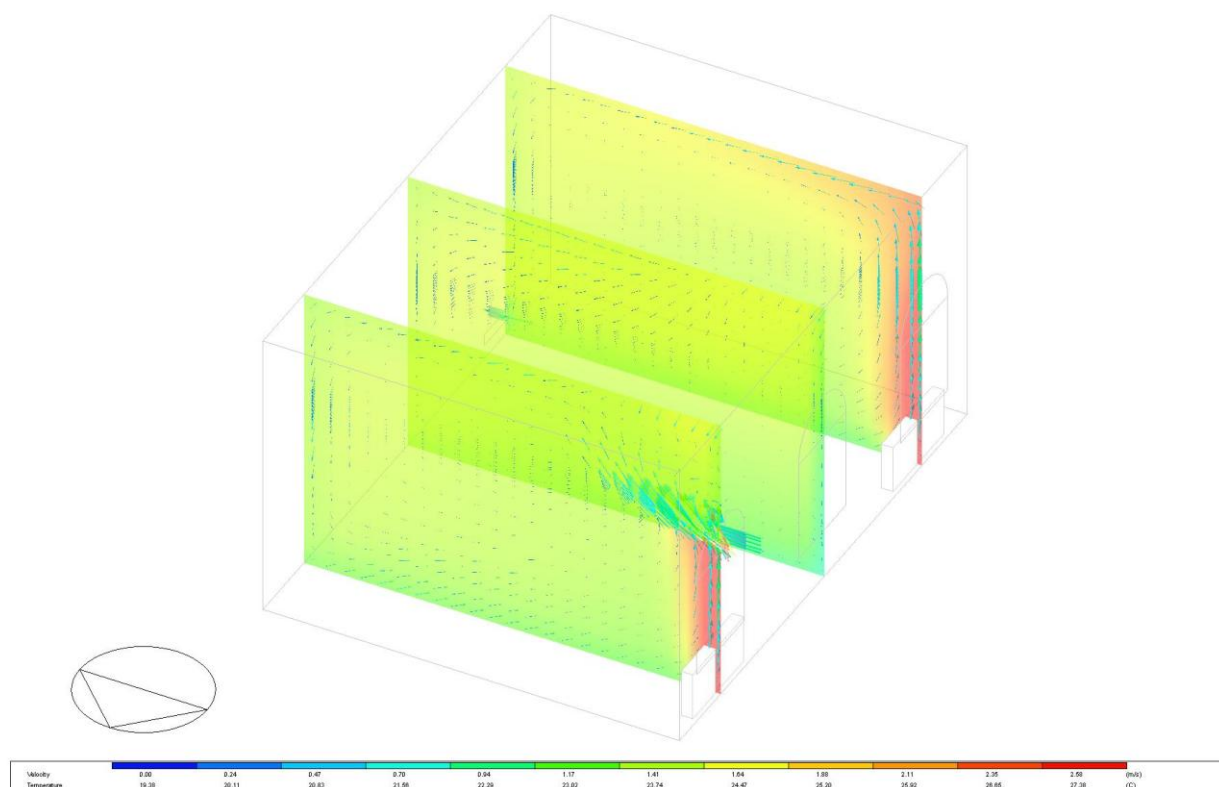


Fig.50: Isometric view of temperature and velocity distribution, middle of windows

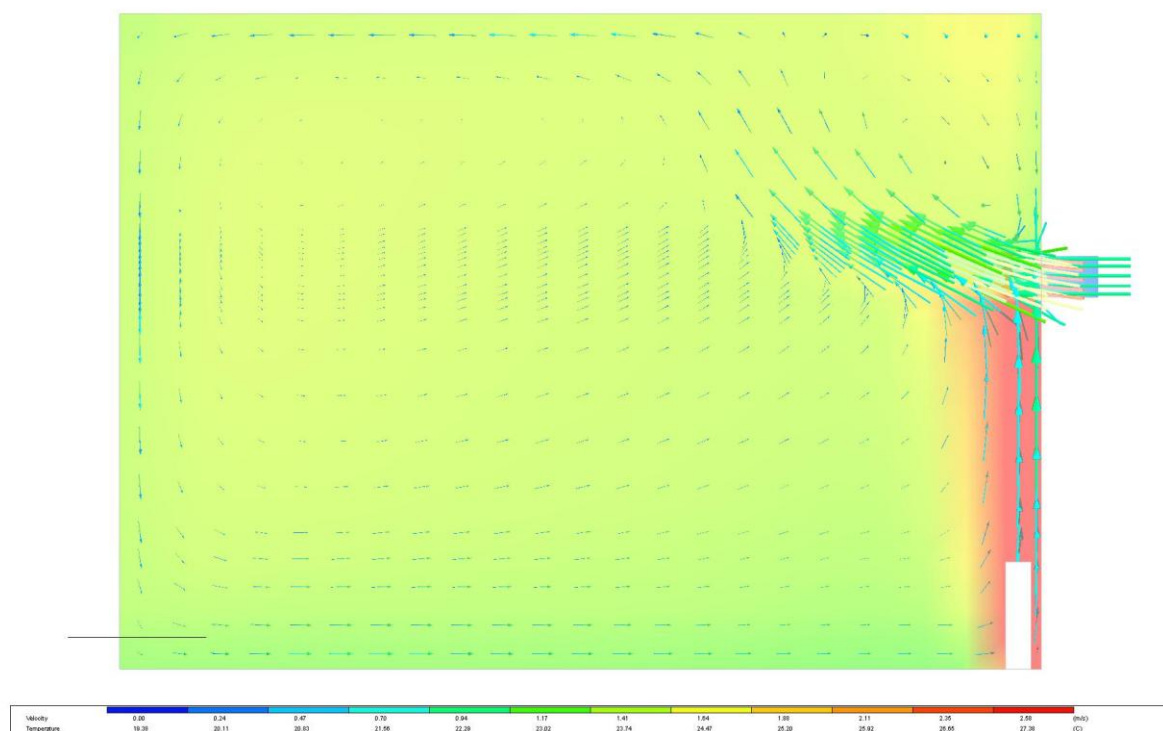


Fig.51: Right view of temperature and velocity distribution, middle of window

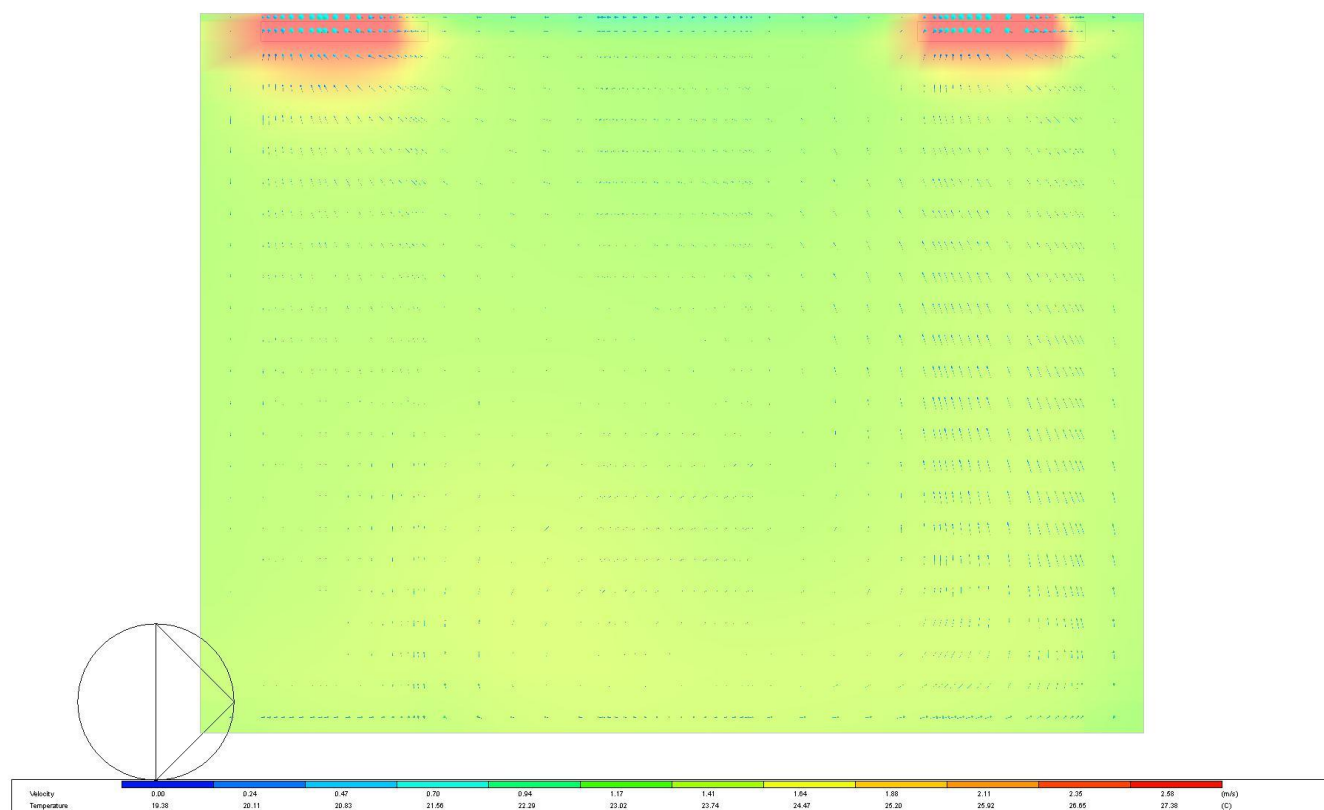


Fig.52: Plan view of temperature and velocity distribution at height of 1m

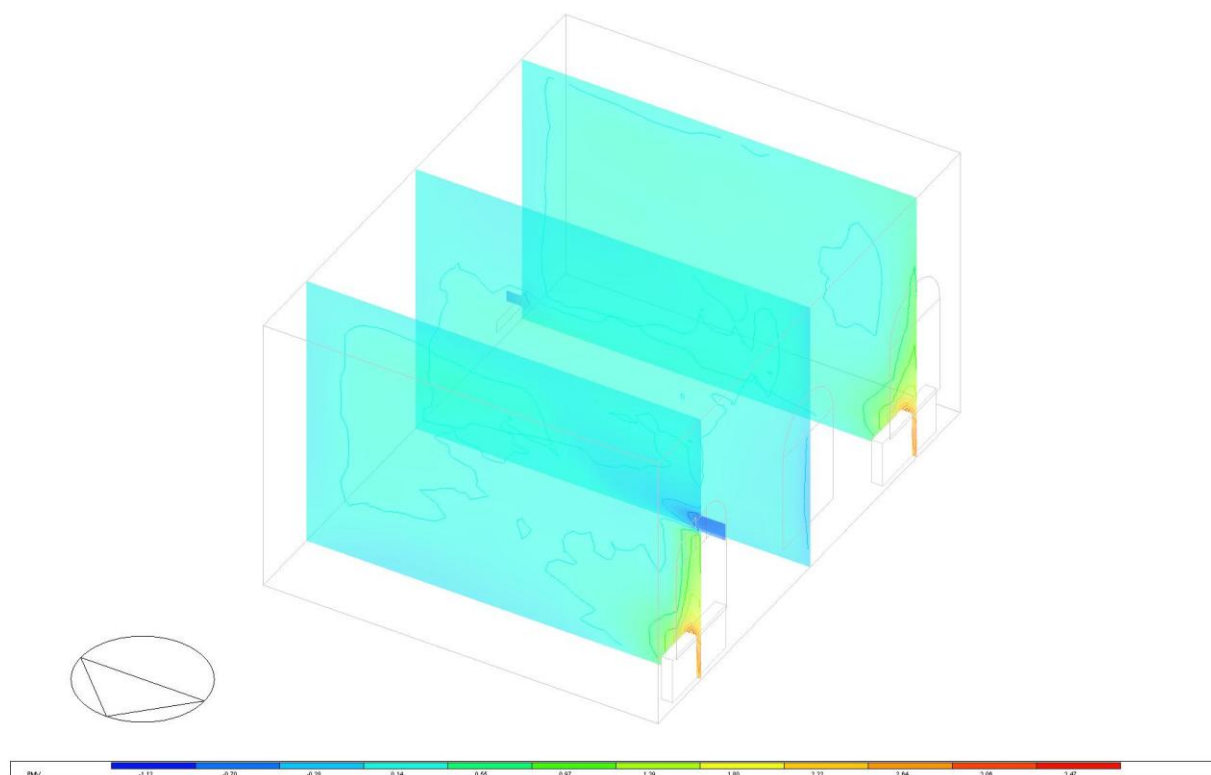


Fig.53: Isometric view of PMV distribution, middle of windows

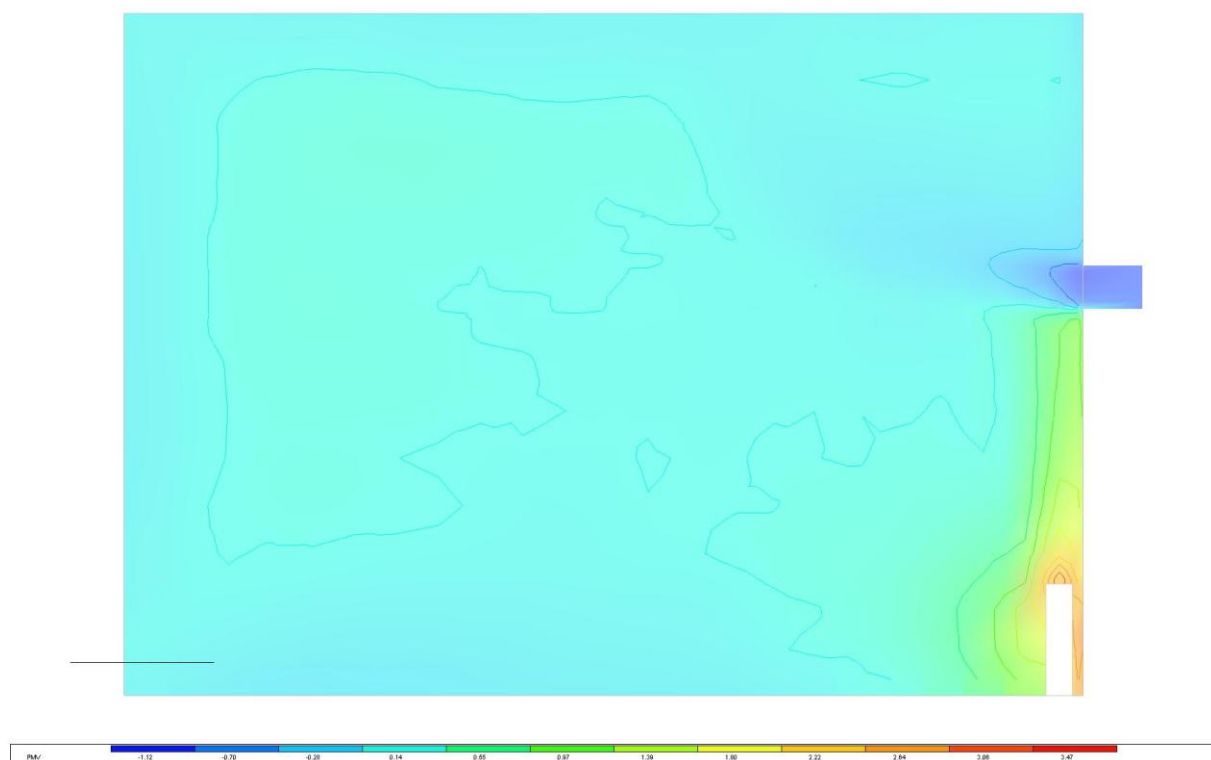


Fig.54: Right view of PMV distribution, middle of window

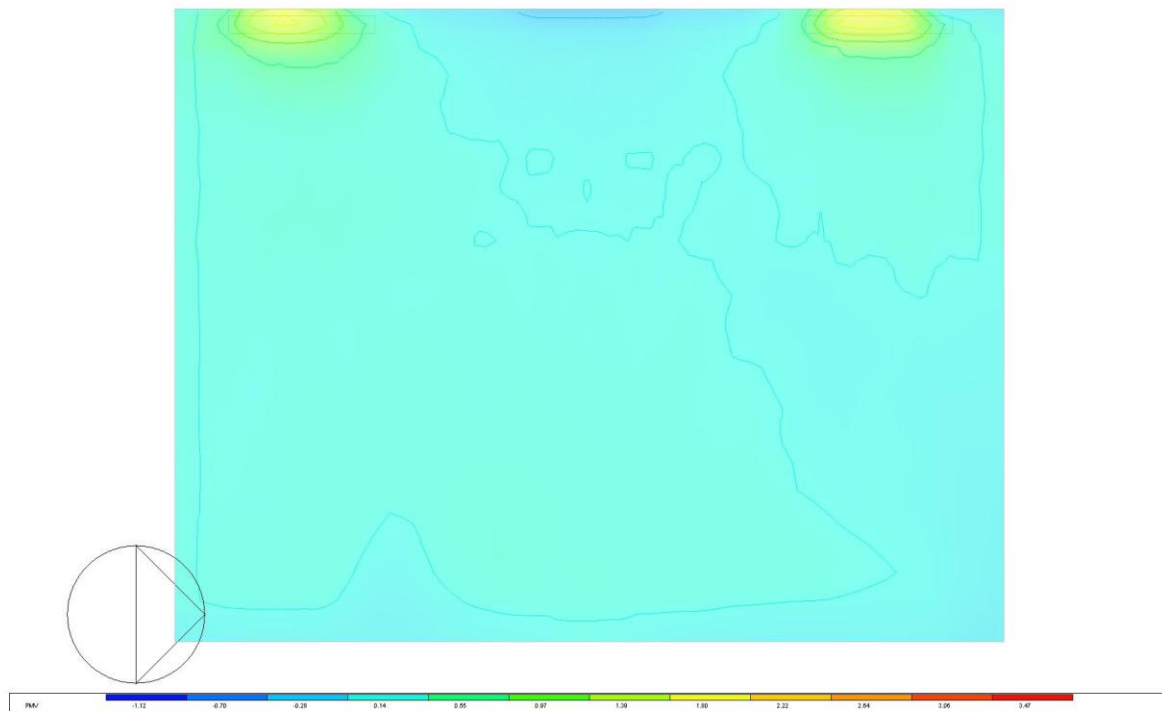


Fig.55: Plan view of PMV distribution at height of 1m

- c) Case 3, supply fresh air with humidity sensitive air vents ($t_{out} = -10^{\circ}\text{C}$) and flow $Q_{fresh\ air} = 210\text{ m}^3/\text{h}$

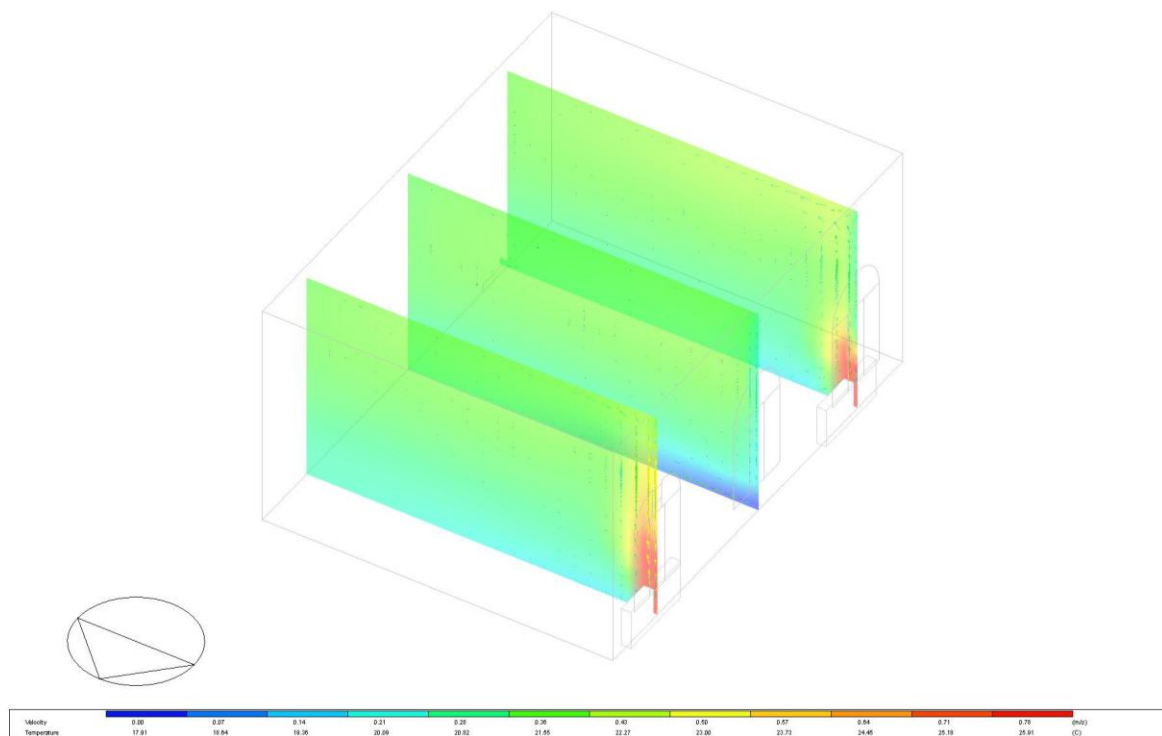


Fig.56: Isometric view of temperature and velocity distribution, middle of windows

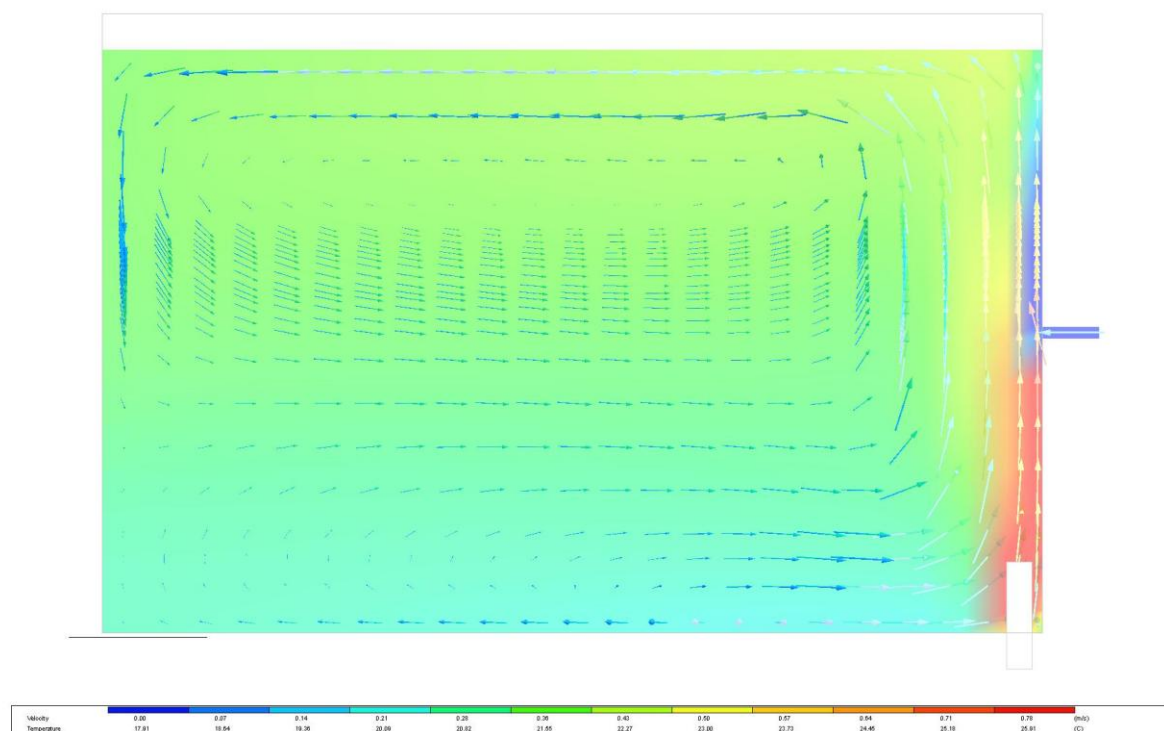


Fig.57: Right view of temperature and velocity distribution, middle of window

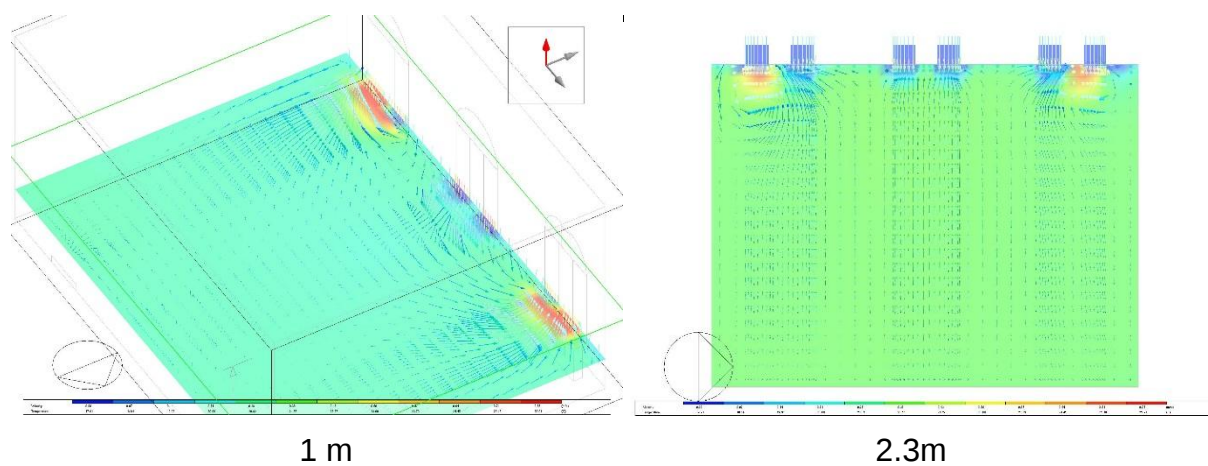


Fig.58: Plan view of temperature and velocity distribution

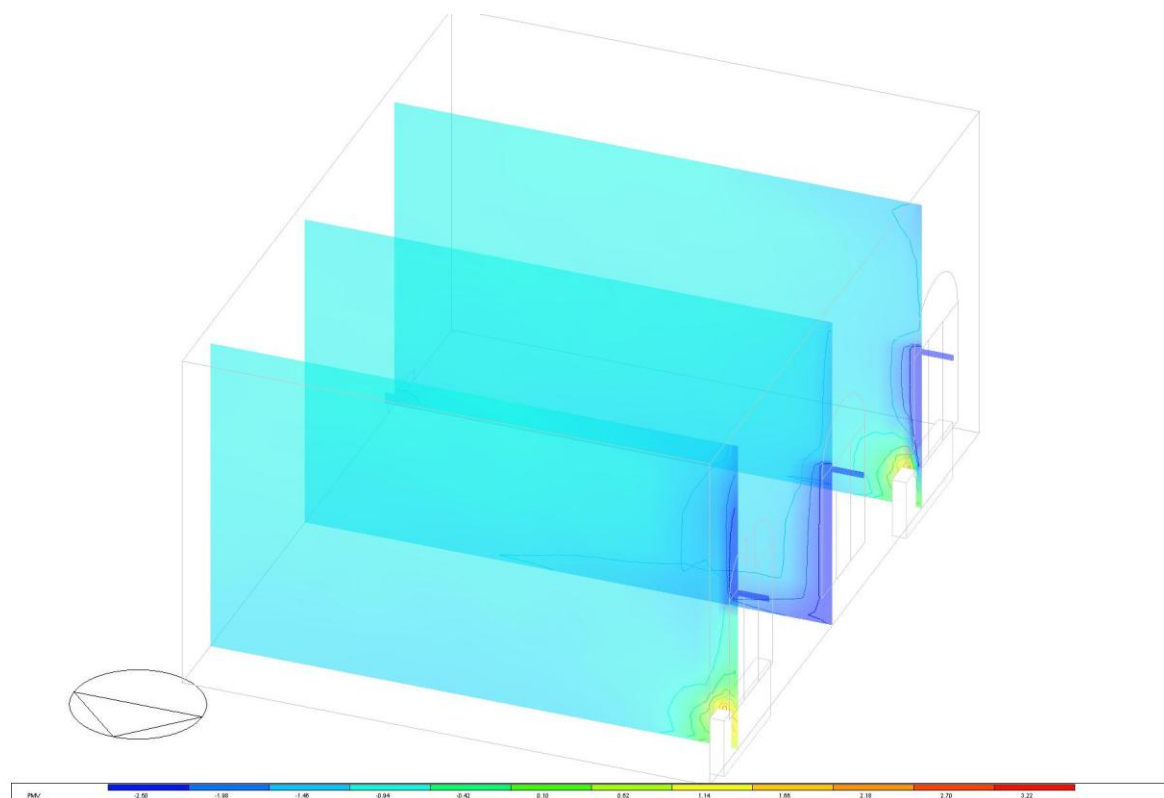


Fig.59: Isometric view of PMV distribution, middle of windows

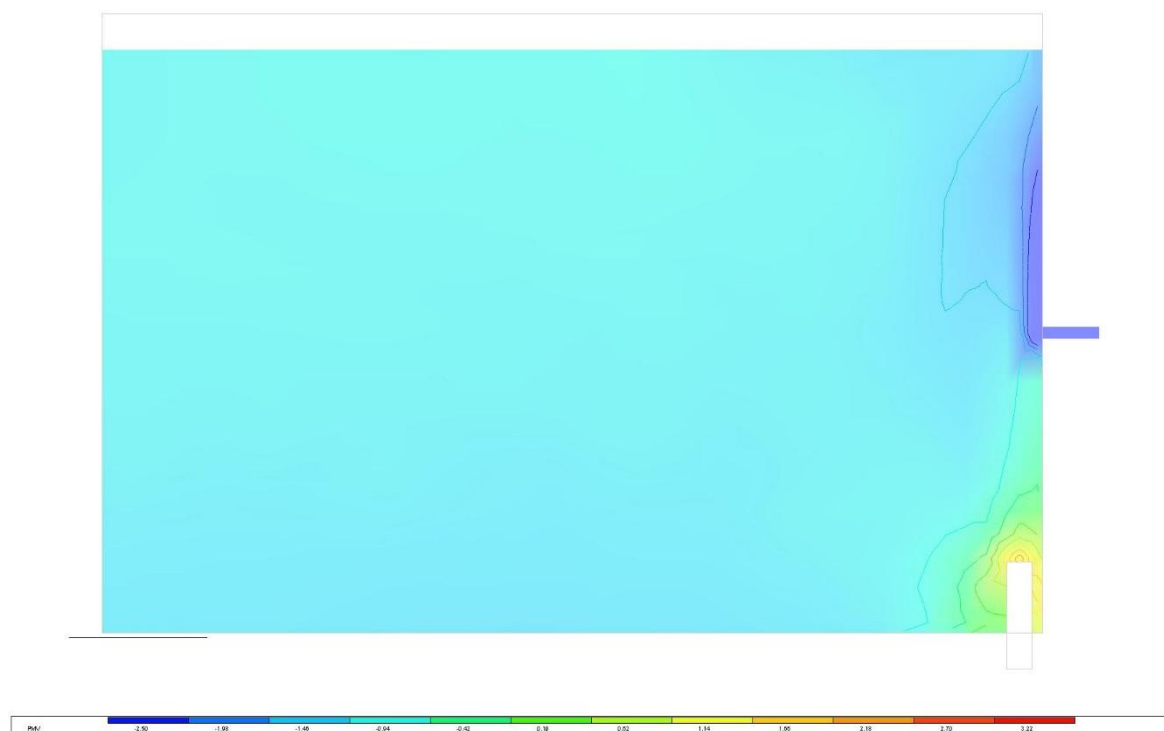


Fig.60: Right view of PMV distribution, middle of window

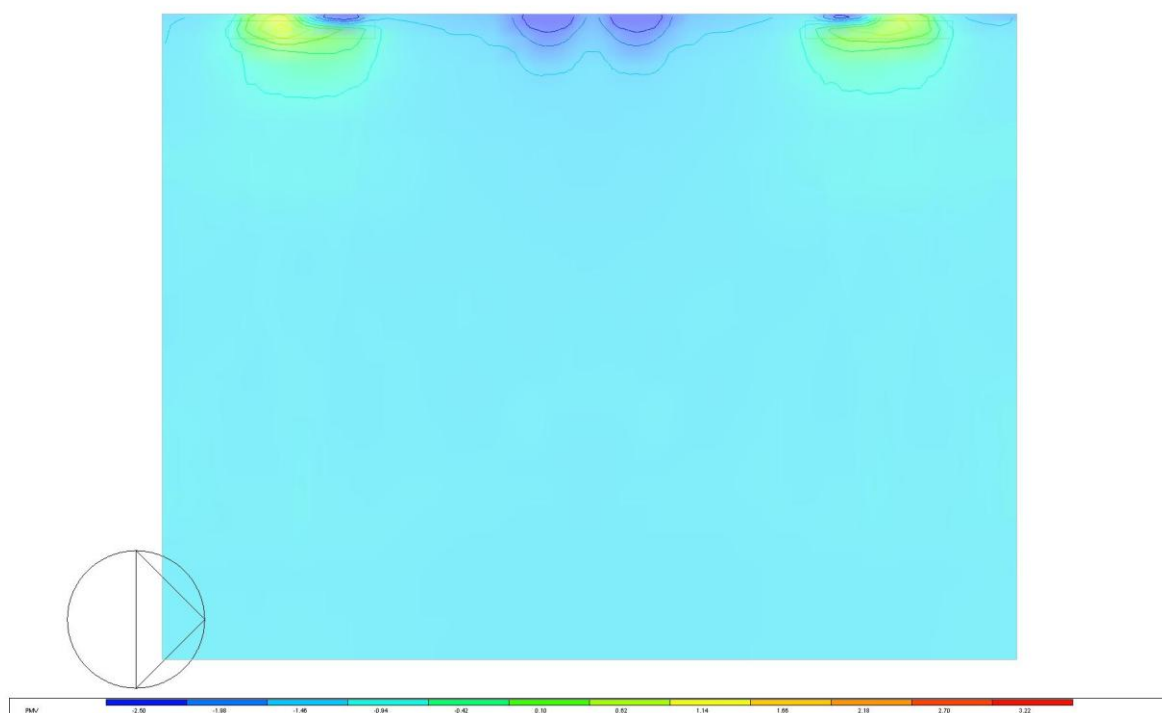


Fig.61: Plan view of PMV distribution at height of 1m

4 CONCLUSIONS

4.1 Quality simulation of the impact of natural and mechanical ventilation on the iaq and thermal comfort of a classroom

4.1.1 Results

A. CFD results of natural ventilation: winter case for a specific day – 22nd of January, 12 o'clock

a) **Case 1.C, continuous ventilation from 8:00 to 14:00, 1 window opened 50% (near blackboard)**

It can be seen in the images obtained from the simulations that the temperature inside the room drops quite a lot reaching values up to 14 ° C in the vicinity of the open windows. In the case of the middle window where the radiator is not fitted, the cooling is even more pronounced. It can be seen in the images obtained from the simulations that the PMV index inside the camera decreases quite a lot by reaching values less than 2 in the vicinity of the open windows. This indicates a thermal discomfort to over 70% of occupants

c) **Case 1.D, continuous ventilation from 8:00 to 14:00, 3 windows opened 50%**

It can be seen in the images obtained from simulations that the temperature inside the camera decreases quite a lot by reaching values up to 8 ° C in the vicinity of the open windows. In the case of the middle window where the radiator is not fitted, the cooling is even more pronounced. It can be seen in the images obtained from the simulations that the PMV index inside the camera decreases quite a lot by reaching values less than 2 in the vicinity of the open windows. This indicates a thermal discomfort to over 70% of occupants.

B. CFD results of mechanical ventilation: winter case for a specific day – 22nd of January, 12 o'clock

a) **Case 1, supply fresh air with external temperature $t_{out} = -10^{\circ}\text{C}$ and flow $Q_{fresh\ air} = 600\text{ m}^3/\text{h}$**

It can be seen in the images obtained from the simulations that the temperature inside the camera decreases quite far reaching values up to 16 ° C in the vicinity of the input fan. Since the jet is concentrated and low temperature, it falls fairly quickly and does not have the time to equalize with room temperature, this can easily be seen in the figure above. In this situation, it is recommended that the air be evacuated from the room not introduced. It can be seen in the images obtained from the simulations that the PMV index inside the camera reaches values of up to -0.83, indicating a thermal discomfort of up to 60% of the occupants, near the radiators the PMV index increases to 1.5. From the results it appears that this solution is not recommended due to high air currents and low occupant temperatures

b) **Case 2, supply fresh air with recovery unit ($t_{out} = -10^{\circ}\text{C}$) and flow $Q_{fresh\ air} = 600\text{ m}^3/\text{h}$, $t_{supply} = 20^{\circ}\text{C}$**

It can be seen in the images obtained from the simulations that the temperature inside the room is constant and uniform with values of 22 ... 23 ° C in the entire room volume. The main drawback of this solution is that large amounts of energy are needed to heat the air from -10 ° C to 20 ° C for a flow of 600 m³ / h and schools do not have such power (electrical / thermal) installed. It can be seen in the images obtained from the simulations that the PMV index inside the room reaches 0.14, indicating a high thermal comfort for 95% of the occupants. From the convenience point of view, this solution is recommended

c) Case 3, supply fresh air with humidity sensitive air vents ($t_{out} = -10^{\circ}\text{C}$) and flow $Q_{fresh\ air} = 210\text{ m}^3/\text{h}$

It can be seen in the images obtained from the simulations that the temperature inside the room is relatively constant, cold air currents are driven by the convective air jet coming from the radiator at the top. In the case of the middle window where the radiator is not mounted, the temperature is lower. It can be seen in the images obtained from the simulations that the PMV index inside the camera reaches values of up to -0.94. This indicates a thermal discomfort to up to 25% of the occupants, near the radiators the PMV index increases to 0.42, indicating a thermal discomfort of up to 10% of the occupants.

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