A NEW VENTILATED WINDOW DESIGN

Study of the impact on the indoor environment in a Danish school from a changed ventilated window design

Aalborg University – Department of Civil Engineering
Building Energy Design Master Thesis – Group 1.307-1

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Title: A NEW VENTILATED WINDOW DESIGN
Study of the impact on the indoor environment in a Danish school from a changed ventilated window design.

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Synopsis: The ventilation of a building has a huge influence on the indoor environment. The indoor environment consequently has a large influence on people's health, their learning and cognitive capacity. Therefore, high ventilation rates are needed in schools to maintain a good indoor environment. This also has to be done according to the high energy demands in the newest regulations. Therefore, this report will investigate the effect of an improved version of a ventilated window installed at the Ødis school in Kolding and compare it to the ventilated window design that it replaced. The volatile organic compound sensors are also investigated for the capability to describe the indoor environment. This is paramount for the control of the indoor environment. This solution utilized the natural forces to create ventilation while preheating the air to maintain good thermal comfort. Combined with a well-designed control of the ventilated window, a preferable solution can be made that can ventilate according to the demands. Horn Group, which is the producer of the ventilated window, assisted in the makings of this report.

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Abstract

Not enough ventilation is an issue in existing buildings, causing an unacceptable indoor environment with too high CO_2 levels, too cold or hot temperatures and too high relative humidity. Especially in Denmark, where there is a lot of wind, rain and cold air temperatures stopping people from venting the necessary amount (*Living Better giver verdens bedste indeklima i nybyggeri og renovering*, 2019). For this reason, the VentilationsVinduet company created a solution comprising a window that can preheat air from the outside and supply it preheated to the indoor environment. This could also be done by installing a centralized ventilation system with heat recovery, but this would need a larger installation, since it would need many air ducts and ventilation units. The ventilated window would only need to be installed to replace the normal windows in the buildings. Furthermore, the ventilated window uses natural forces for supplying and preheating the air as well as recovering the thermal losses from the room before they exit.

This type of window has been built by the Horn group and has been tested to improve both energy consumption and indoor climate (*Living Better giver verdens bedste indeklima i nybyggeri og renovering*, 2019). The newest version of the ventilated window has been installed at the Ødis school in Kolding, replacing a previous design from Horn Group, and will be compared to the previous design.

The investigation shows an improved indoor environment after the new window type has been installed. More frequently, levels of CO_2, temperature and relative humidity falls into the acceptable limits according to requirements. According to the investigation done in this report, there are indications that the new design of the ventilated window has a lower pressure resistance, causing higher airflow into the rooms. This is based on the result that the extraction flow rates in the rooms has increased. The improved temperatures and relative humidity in the rooms could be explained by the higher outside temperatures during the investigation. The new ventilated window shows lower heat recovery during the same temperatures. The VOC sensor investigation shows that sensors could be improved be applying compensation curves to improve its monitoring of the indoor environment.

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1 Introduction

The indoor environment of buildings has a great influence on the human health and efficiency. This combined with the fact that people spend 90% of their lives inside buildings, calls for ensuring good indoor environments. In order to do this, it is important to consider the resources needed, since they are not infinite. Therefore, finding a way to insure good indoor environments while doing it energy efficient is the logical step. This gives rise to renovating older buildings as to not waste resources tearing them down and not to lose the culture and connection to history that the buildings pose.

The renovation is a difficult and costly process that can also completely change the appearance of the buildings. Furthermore, not all buildings are designed to be able to be changed, causing difficulty finding the space for the changes. This gives rise to finding renovations that can improve the indoor environment, without changing the essence of the building as well as being practical to install.

When people are in the growing stages of life, and learning, the indoor environment has a larger influence. Studies show that people themselves are a great pollution source which causes the indoor environment to be harmful to people. This is caused by bio effluents emitted by the human body. These bio effluents cause reduction in the cognitive -and learning abilities. By supplying fresh air through ventilation, the concentration can be maintained at levels where they do not pose a problem. Therefore, proper ventilation is incredibly important when it comes to maintaining a good indoor environment.

The ventilated window was installed at the Ødis school in Kolding, where the windows are being testing to see if they are adequate to maintain an acceptable indoor environment in a school setting. An earlier version of the ventilated window was installed, which was investigated in the master thesis of Marta Bonet Arbos, Leire Chavarri Remiro and Aleksandra Maria Tutaj called 'Intelligent ventilated window performance and further improvements: A case study in a Danish primary school.'. In the report, two rooms were investigated where the windows were installed. Room 1 had only natural ventilation with an extract grate where only the window supplied fresh air to the room. Room 2 had mechanical extraction, with a constant extract flowrate and fresh air supply from the ventilated windows.

The investigation performed in the above-mentioned report showed that there were too high CO_2 levels in the rooms where the ventilated windows were installed, and higher ventilation was necessary. No serious issues were found with the relative humidity or the operative temperature in the rooms. It was found that more fresh air was needed to be supplied to the rooms and this gave rise to a new ventilated window design that could give higher flow rates for the air supplied by the window.

The sensors used in the control of the ventilated windows were also investigated in the previous master thesis where it was found that the VOC sensors could not accurately describe the indoor environment in the rooms.

Since then, the new ventilated window design has been installed, therefore this report will focus on the investigation of the changes in the indoor environment conditions, i.e. CO_2 levels, relative humidity and indoor operative temperature. Also the sensors for monitoring the rooms conditions as well as window performance.

1.1 Purpose of the investigation

The purpose of this report was to investigate the changes in the indoor environment and window performance since the installation of the new ventilated window type and to investigate the functionality of the sensors used to control the ventilated windows. The exhaust air flow was also measured. The project was guided by three research questions:

1. How has the indoor environment changed since the installation of the new ventilated window design at the Ødis school?
2. What differences are the on the window performance of the previously installed ventilated window and the newly installed window at the Ødis school?
3. How well do the sensors used to describe the indoor environment used in the control of the ventilated window perform?

1.2 Limitations

Because of the different conditions of this report such as the time available, manpower, and experience there are certain limitations that will be stated in this part of the report.

- The focus of the of this report will be on long term measurements on room level of the indoor environment, i.e. relative humidity, CO_2 and room temperature which will be compared to the previous master thesis. The energy consumption or savings will not be investigated in this report.
- The energy performance of the building will not be investigated in this report.
- Most of the terminology from names of the window types and their cavities will be reused from the previous master thesis made in the school. This is to make the comparison easier when reading both theses.

1.3 Reading guide

Since this report is mainly a comparison report between the measurements made during this investigation and the investigation performed by previous master thesis, there will be many references made to that thesis in the form of previous investigation, previous measurements etc.

2 Study Case

2.1 What is a ventilated window?

The ventilated window consists of a normal energy window, with two glass panes with a gas between them, facing outside but with and additional glass pane facing the inside forming a cavity. In this cavity the fresh air from outside can enter the bottom of the window, rise and enter the room in the top of the window. In the following paragraphs typical modes of operations depending on typical season conditions will be described.

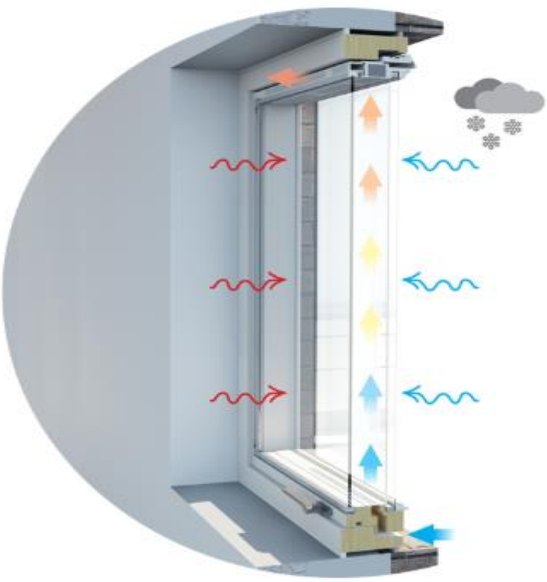


Figure 1 - Ventilated window operation – Winter (*Living Better giver verdens bedste indeklima i nybyggeri og renovering*, 2019)

The fresh air enters the window cavity from the outside at the bottom, where it rises to the top and becomes heated mainly by the heat losses from the room. The preheated air is then pass into the room. This is called the preheating mode of the ventilated window.

Figure 2 - Ventilated window operation - Spring and Autumn (Living Better giver verdens bedste indeklima i nybyggeri og renovering, 2019)

In spring and autumn, the air passes in through the bottom vent in the window and rise up through the cavity in the window. But here there is not only the heat losses that heats up the air but also the solar radiation from outside helps by heating the air further. Then the preheated air is supplied to the indoors. Here it is also the preheating mode.

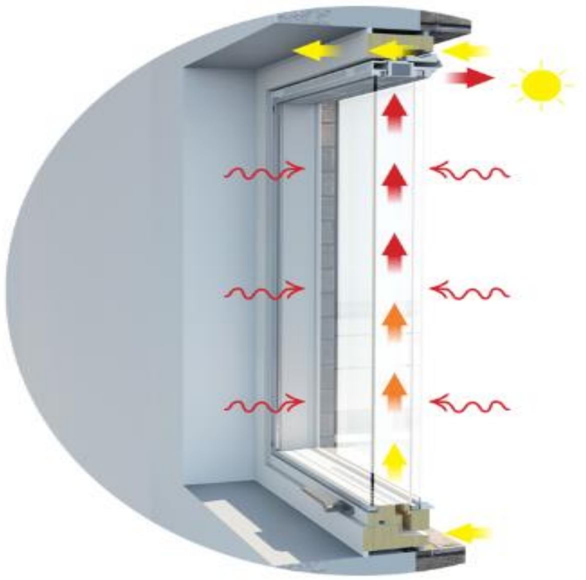


Figure 3 - Ventilated window operation – Summer (Living Better giver verdens bedste indeklima i nybyggeri og renovering, 2019

In the summer, the air enters the window cavity at the bottom and rises up through the window, but the combination of solar radiation and high outdoor temperature causes too high temperatures in the cavity to be supplied to the inside, leading to the air being exhausted back outside. Instead, a bypass valve is opened in the top of the window, causing fresh air to be supplied straight into the indoors. This is the cooling and bypass mode of the ventilated window.

2.2 Changes in the window design

After the previous master thesis investigation, the window design was changed in order to increase the airflow through the window. The window type 1 (WT1) had two equally sized glazing area positions, one at the top and one at the bottom. Window type 2 (WT2) had three cavities where the top one was short and wide and the two identical at the bottom were thin and tall. The different design results in different glazing area and cavity sizes.

The windows can be seen in Figure 4 with WT1 on the left and the WT2 on the right. All cavities work with the general theory described by chapter 2.1.

Figure 4 - Previous ventilated window design (WT1) to the left and current ventilated window design (WT2) to the right (Bonet Arbos et al., *2019)*

The main difference between the two ventilated window types in Figure 4 is the way that the valves are controlled. The window type in the WT1 (left) has thermal expansion valves that are controlled by the temperature causing them to open or close. The WT2 (right) has electrically controlled valves that are operated by a control unit placed in the room. The data investigated during the rest of the report will be distinguishable by the type of window it refers to, meaning window type 1 (WT1) refers to the previous investigation and window type 2 (WT2) refers to the current investigation.

The windows WT2 can also be opened manually to supply fresh air by venting as seen on Figure 5.

Figure 5 - Manually opening WT2 with handle

The window type that is currently installed and that will be investigated in this report is the WT2, therefore a description of the window will be made here.

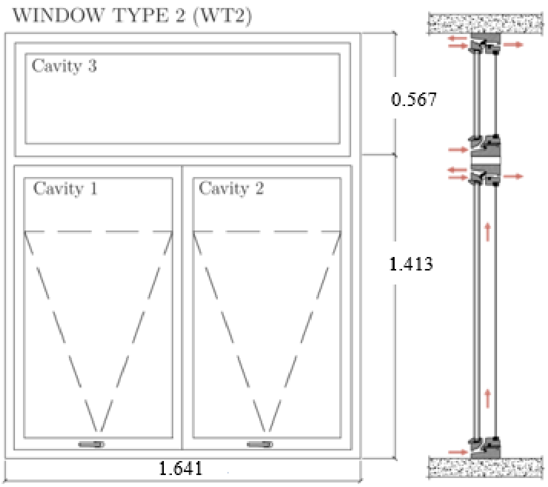


Figure 6 - Details about the design of window type 2 (WT2).Dimensions in m. (Bonet Arbos et al., 2019)

In Figure 6, the details of the window type 2 can be seen, with the cavities named depending on their placement, starting with the lower left cavity being cavity 1, the next cavity to the right will be called cavity 2, and the top cavity will be mentioned as cavity 3. This will be the same through the whole report. To the right in Figure 6 it can be seen how the fresh air enters the window at the bottom, rise through the cavity and either exit the window again or enter the room, depending on if the operation mode is preheating or cooling. The window has a double layer of glazing facing outside with argon gas in between, then the cavity for the air flow and lastly a glazing separating the cavity from the inside.

2.3 Description of the building and rooms

The building where the windows were installed at the Ødis school in Kolding can be seen in Figure 7.

Figure 7 - Ødis School in Kolding

The building is a brick-based building with an outer wall thickness of 33 cm. The building is from the 1960's and according to the building regulations of 1961, the U-value of the walls at that time was maximum 0.99 W/m^2*K. The inner wall is 18 cm meters wide and the typical space for insulation at that time was around 6 cm *(Bonet Arbos et al., 2019).* There are no indications of other renovations of the school other than the ventilated window.

The rooms that are the focus of the investigation in this report are two neighboring rooms placed in the south facing side, as shown in Figure 8 where room 1 (R1) has natural ventilation and room 2 (R2) has mechanical ventilation. R1 is the end room and has two external walls whereas R2 only has one external wall. Both rooms have only brick walls and a wooden ceiling.

Figure 8 - Room 1 and 2 seen from outside at Ødis School

In Figure 8 the two rooms can be seen from the outside with the new window design WT2 installed and their placement according to the main entrance.

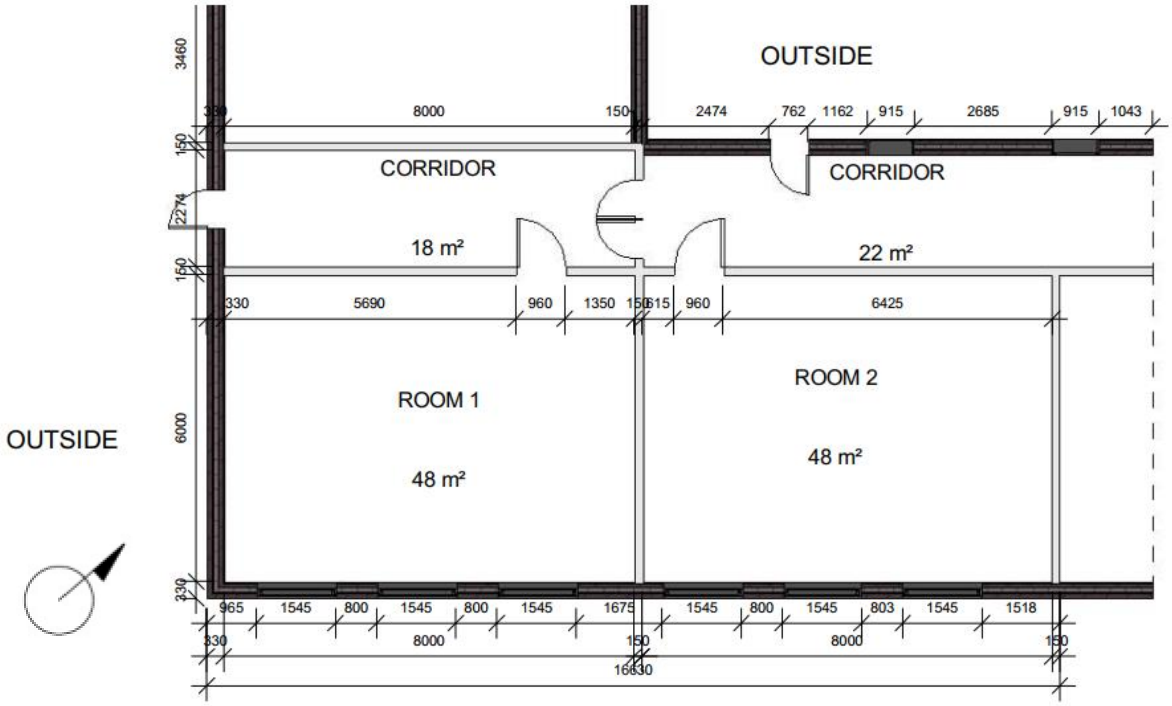


Figure 9 - Floor plan of the two rooms with ventilated windows installed and their orientation (Bonet Arbos et al., 2019)

Figure 9 shows the floor plan of the rooms with the windows facing south-east.

Both rooms have three of the WT2 installed, each with radiators beneath them. The extracts are placed near to the entrance of each room. The mechanical ventilation is operating 24 hours a day, every day of the year, and does not have a time or season schedule. The radiators have thermostats placed by the valves that can be turned between the 3 and 4 setting, as seen in

Figure 10. It cannot be set to a higher or a lower setting. It is not known if there is a time or season schedule for the heating system.

Figure 10 - Radiator thermostat minimum and maximum setting

Each room has automatic light control based on occupants entering the room but can also be controlled manually by a switch on the wall.

The windows installed in the room have venetian blinds in the cavities that are electrically manually controlled by a switch on the wall. When the down switched is pressed, the venetian blinds go down until they reach the bottom where they will turn the blinds from closed to open. This means that the blinds cannot go halfway down and then open, they need to be rolled all the way to the bottom until they open. It is not possible to manipulate one cavity at a time, only all cavities in the room at once.

2.4 Control strategy of the ventilated windows

This chapter will explain how the current control strategy is supposed to act for the purpose of comparing how the ventilated window is acting with how it should act. This is to investigate flaws in the operation and control in the windows control strategy, since what the system is planned to do in certain situations is not necessarily what happens. These flaws can then cause unwanted situations to happen in the indoor environment e.g. too high temperature, CO_2 concentration and/or relative humidity. These flaws should be rectified in order to achieve an acceptable indoor environment.

2.4.1 The control parameters

As described in chapter 2.1 there are three operation modes of the window, i.e. heating, cooling and bypass mode. But when the windows should act in which mode is determined by different parameters of the window and room conditions.

The windows all have three cavities and each cavity is independent from each other in their control. This means that each cavity is measuring its own parameters and is acting according to them and to the indoor measurements. The windows are also controlled according to indoor parameters of temperature, volatile organic compounds (VOC) and relative humidity.

There is no seasonal or time control for the windows.

First, the control checks if it should act by observing if certain conditions in the room are present. There are several parameters that decides when the window should act or not. The parameters are put in the following order of importance:

1. Indoor air quality (CO_2 concentration): Max 1000 ppm.
2. Indoor relative humidity level in the room: Max 75%.
3. Indoor operative temperature: Setpoint 22±0,5°C.

Then the control needs to decide how to react to the conditions measured in the room. This means that the window should be in the different operation modes according to the following conditions:

- Heating mode: When the indoor operative temperature is below 21,5°C.
- Cooling mode: When the indoor operative temperature is above 22,5°C.
- Bypass mode: When cooling mode is on then bypass mode is on.

General facts about the window control:

- Neither the mechanical extraction nor the blinds in the window are included in this control strategy.
- Due to issues with the sensor used to measure the indoor air quality, which was discovered in the previous master thesis, this parameter is currently not included in the existing control.
- All cavities act independently of each other, depending on their own sensors in the top of their cavity, measuring temperature, relative humidity and air pressure.
- All cavities act according to the same measurement of temperature/CO_2/moisture in the room.

Indoor air quality

In this control strategy the indoor air quality had the highest priority, which was based on the high priority of comfort that the company VentilationsVinduet had. Generally, a window's function is to ventilate to improve the atmospheric comfort in the room, and this is still the main function of the ventilated window. The sensor is not measuring CO_2, but it was intended that the VOC would have a correlation with the CO_2.

Relative humidity

The second most important parameter in this strategy was the relative humidity, which was because of the possible damages to the building that too high humidity can cause and the discomfort of stale air for the occupants.

Operative temperature in the room

The last parameter was the operative temperature in the room, which was measured by the sensor in the room.

The previously described parameters decided 'when' or 'if' the ventilated window should ventilate. Which operation mode the window should use was decided depending on the temperature in the top of the cavity. It is not known what temperatures are chosen for which operation mode.

2.4.2 The room sensor for ventilated window control

In order to measure the parameters of the rooms a sensor was chosen by the Horn Group to control the ventilated window. This sensor was a 4-in-1 sensor that measured the following:

- Volatile organic compounds (VOC)
- Temperature
- Relative humidity
- Air pressure

These values were chosen either to create the control now or for improving the control in the future with additional control conditions.

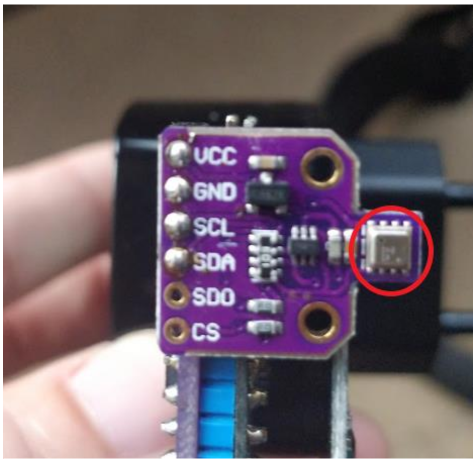


Figure 11 - BME680 BOSCH 4 in 1 sensor

In Figure 11 the BME680 sensor can be seen on the control chip. The sensor has been produced by BOSCH in order to measure indoor climate in buildings. The sensor was chosen for its compact size with multiple functions and low power consumption.

Figure 12 - Setup at the school with the BME680 sensor and power supply

In Figure 12 the setup of the BME680 and power supply at the school can be seen. The sensor is placed right below the teacher's smart board approximately at the center width of the room at 0.9 m.

2.4.3 The control equipment

The electrical controlled valves were controlled by a processor called a Raspberry Pi, which sends the commands to the window valves and logs the measurements of the window sensors and the rooms sensors. One processor was placed in each room, so each room acted independently according to the dedicated Raspberry Pi's command.

The valves of the window

Figure 13 - Overview of the window valves and operation mode

Overview of the window valves position

Figure 13 show the overview of each of the window cavities, their temperature and their valve position in degrees. WINDOW #1 and WINDOW #2 are the top cavity of the window furthest to the left in room 1. While WINDOW #3 is the lower left cavity and WINDOW #4 is the lower right cavity of the window. This pattern continues for all the window cavities in the two rooms. The operation mode can also be seen in the dark blue squares stating e.g. closed, bypassing, heating or cooling.

The number, e.g. T:23.35, shown in WINDOW #1 is the temperature measured in the top of the cavity. But generally, it seems to be fully open or fully closed.

The number, e.g. 180(180), shown in WINDOW #1 indicates that the valve is fully open, 0(180) means fully closed.

It was not possible to get the data showing the valve position caused by issues with the Raspberry Pi in the rooms during the measurements.

3 Measurement methodology and data treatment

During the investigation, measurements of the indoor environment, window performance and sensor performance needed to be performed. To do this, the equipment and methodology used will be described in this part of the report to understand how the measurements were performed, as the influence of this on the results.

3.1 Equipment used in measuring the indoor environment

In order to measure the indoor environment Indoor Climate meters or IC meters were used. These are instruments that can measure precisely relative humidity, operative temperature and CO_2 concentration (*Hvad er IC-Meter? | IC-Meter*, 2019). It can measure these values, send them to an online server where it visualizes the data and stores it for later download for treatment. This is an all-around sturdy and reliable measuring device that is used by Aalborg University. An IC meter can be seen on Figure 14.

Figure 14 - IC meter instrument

To measure the windows performance, temperature sensors called PT100 were used. These are small sensors, approximately 3x3mm, and their electrical resistance is influenced by temperature. An example of the PT100 can be seen on Figure 15.

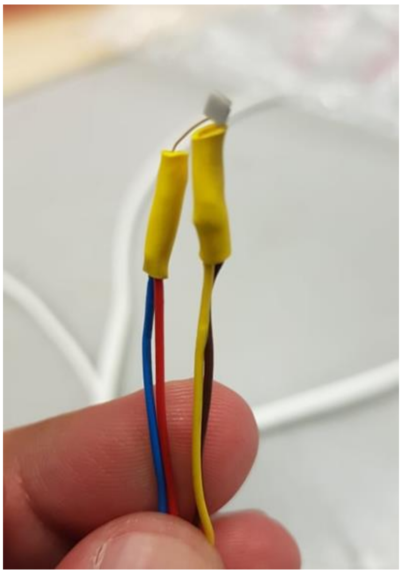


Figure 15 - One PT100 RTD

To measure the airflow from the extraction, Lindab FTMU pressure differential sensors were used. This instrument uses ultrasound sensor to measure the airflow. The instrument can be seen installed on the mechanical extraction duct in Room 2 of the Ødis school in Figure 16.

Figure 16 - Lindab flowmeter

All sensors have been calibrated at the Aalborg university lab, and calibration curves were applied to the data when treated (See Appendix 8.2).

3.1.1 Sample rate and averaging

To do the measurements it was necessary to choose the sampling rate, considering how much data would be the result and how accurate data was needed.

If the sampling rate is too often over a long period, it will result in a very precise but large set of data that will be difficult and time-consuming to treat. Too low sample rate and the data will not be very precise in its depiction of what it is trying to measure.

The way that the data is averaged according to a time will also affect the data, by 'flattening' the highs and lows in the data. Therefore, it is also important to consider the averaging of data.

Also, averaging between several sensors in the same room needs to be considered, because it can cause a distorted view of the room's conditions.

In the case of this comparison, the sampling rate and averaging was considered in order to also make a more accurate comparison with the previous master thesis about the ventilated window.

These results in the sampling and averaging are shown in Table 1.

Instrument	**Sample rate**	**Averaging**
IC meters	Every 5 min	Every 10 min
PT100s	Every 1 min	Every 10 min
Lindab flowmeters	Every 1 min	Every 10 min

Table 1 – Sampling rate and averaging of data

The number of sensors used is shown in Table 2.

Instrument	**Number and placement**	**Total**
IC meters	4 in each room, 1 outside, 1 in hallway	10 pcs
PT100s	4 in cavity 3, 3 in cavity 1, 1 at the window room inlet	16 pcs
Lindab flowmeters	1 at each extract of the rooms	2 pcs

Table 2 - Instruments used in the investigation

In order to record the data, a small computer called NUC was placed at the school and connected to the PT100s and the Lindab flowmeters. A LabVIEW program provided by Hicham Johra was used to record the data from the Lindab flowmeters and PT100s.

In order to have remote access to the NUC computers at the school, for surveilling the measurements and extracting data, a router provided by Aalborg University was installed at the school. The software used for the remote access was called TeamViewer.

3.1.2 Measurements specifics

The measurements at the Ødis school were made in the period between the 21-Oct-2019 to the 24-Nov-2019, i.e. week 43 to 47 of 2019. This included all days and hours of the day, but was filtered only to contain the weekdays between 08.00 to 17.00, where it was assumed that the occupancy would occur. It was compared to the previous investigation (Bonet Arbos *et al.*, 2019), where the measurements however occurred during the period between the 18-Dec 2018 to the 1-March 2019.

3.2 Assumptions, standards and regulations

In this part of the report the indoor environment of school and the window performance was investigated and compared to the findings in the previous investigation.

In order to compare what differences, there were in the indoor environment, it was important to have a general overview of what parameters influenced the indoor environment.

Parameter	Previous investigation	Current investigation
Window design	Two cavity windows – WT1	Three cavity windows – WT2
Valve control	Thermal expansion valves	Electrically controlled valves
Occupants	Max 15 people in the rooms	Max 15 people in the rooms
Schedule	Approx. 24 lessons of 45 min a week	24-26 lessons of 45 min a week
Outside conditions	18-Dec 2018 to 1-March 2019	21-Oct 2019 to 24-Nov-2019

Table 3 - Parameters affecting the indoor environment

Assumptions

Occupants have influence on the indoor environment. In the previous investigation, it was found that there was a correlation between the CO_2 levels in the rooms and the occupancy. There the same number of max occupants and the students were close to the same age.

The schedule, the number of hours and maximum occupancy was similar to the previous investigation. The same basic structure of the schedule was also still the same, i.e. that Wednesdays are always from 8:15 to 14:55. The periods on Wednesdays can be anything from physical education to math, which means that it is not certain that the students will be in the classroom.

Except the change in the ventilated window, the building envelope and systems had not been changed since the previous investigation. It was assumed that the parameters affecting the indoor environment, such as infiltration and the setting of the heating system control was the same.

The door and the windows may have been opened during the measurements, which would have influenced the measurements, but this is not considered in this investigation. The curtains were assumed to be up at all time during the measurements.

The students were assumed to have standard winter clothing insulation of 1 clo, and a sedentary activity met of 1,2.

Standards and regulations for the indoor environmental investigation
For this investigation of the indoor environmental parameters was assessed according to standards and regulations for the indoor environment in buildings. The used standards, regulations, range and maximum allowed values are shown in Table 4.

Air Quality – CO_2 level indication			
Document	**Description**	**Range**	**Value**
BR18 § 447	Maximum CO_2 level allowed	Acceptable	1000ppm
Added for better indication of CO_2 level	CO_2 levels between 1000-1500	Unacceptable	<=1500ppm
Added for better indication of CO_2 level	CO_2 levels above 1500ppm	Unacceptable	>1500ppm
Thermal comfort - Operative temperature			
Document	**Description**	**Range**	**Value**
DS CR 1752, Table 1	Temperature range allowed	Category I	22 +-1°C
DS CR 1752, Table 1	Temperature range allowed	Category II	22 +-2°C
DS CR 1752, Table 1	Temperature range allowed	Category III	22 +-3°C
Air Quality – Relative humidity			
Document	**Description**	**Range**	**Value**
DS 15251 Table B.6	Relative humidity range allowed	Category I	30-50%
DS 15251 Table B.6	Relative humidity range allowed	Category II	25-60%
DS 15251 Table B.6	Relative humidity range allowed	Category III	20-70%
DS 15251 Table B.6	Relative humidity range allowed	Category IV	<20-70<%

Table 4 - Categories of standards and regulations

3.3 Setup of the measurements at the school

3.3.1 IC meters setup

The two investigations were performed with different methods, caused by the difference in time for the project and manpower. These differences should be clear in order to asses if these differences affect the comparison of the results of the two projects.

Figure 17 - IC meter numbers and placement in Room 1 with natural ventilation

The IC meters in room 1 were placed as seen in Figure 17 where the IC 11 (at the exhaust) & 15 (in the center of the room above the occupied zone) were placed at the same positions as in the previous investigation. This was done to reduce the differences in the measurements caused by different placements of the IC meters. Two IC meters (16 & 17) were added to each room to investigate if the room had a uniform indoor environment or if it had temperature and CO_2 stratification. Furthermore, one of the additional IC meters (IC 16) was placed right next to the sensor that controls the windows to investigate if the placement was adequate for controlling the ventilated windows.

Figure 18 - IC meter number and placement in Room 2 with mechanical extraction

In Figure 18 the placements of the IC meters in room 2 can be seen. In the back: IC 23, in the center of the room: IC 19, at the exhaust: IC 18 and at the teachers board: IC 20. These had the same functions as described in Figure 17. IC meter 18 and 19 were placed in the same place as in the previous investigation, to have a more accurate comparison of measurements.

Figure 19 - IC number 12 & 26 and their placement, outside (left) & hallway (right)

Figure 19 shows two additional IC meters placed outside at room 1 (IC 12) and in the hallway (IC 26) at the entrance of room 2. IC 12 was placed outside in order to see the influence on the window performance and indoor environment. IC 26 was used in order to assess if the door was open, causing the indoor environment in the rooms to not ventilate using clean air from outside but the polluted air from the hallway. More details about the placement of the IC meters is shown in Table 5.

Name of IC meter	**Height placed**	**Distance from entrance wall**	**Distance from wall closets to the entrance**	**Location**
IC 12	1,8 m	6 m	1,2 m	Outside, Under windowsill at room 1
IC 26	2,5 m	0 m	1 m	In the hallway above entrance to room 2
IC 11	2,4 m	0,3 m	0,5 m	R1 Located in front of the extract ventilation duct
IC 15	2,4 m	2,5 m	4,5 m	R1 Center of the classroom
IC 16	0,9 m	2,5 m	8 m	R1 At teacher's smartboard close BME680 sensor.
IC 17	1,1 m	2,5 m	0 m	R1 Opposite wall than the teacher's smartboard in the back
IC 18	2,4 m	1 m	0,5 m	R2 Located in front of the extract ventilation duct
IC 19	2,34 m	2,5 m	4 m	R2 Center of the classroom
IC 20	0,9 m	2,5 m	0,2 m	R2 At teacher's smartboard close BME680 sensor.
IC 23	1,1 m	2,5 m	8 m	R2 In the back wall, opposite the teacher's smartboard

Table 5 - Location of sensors in the investigated rooms at Ødis school

3.3.2 PT100 sensors setup

The investigation of the window performance focused mainly on the analyzes of the data collected by the PT100 sensors installed at the WT2 cavities in each room during the investigated period. This was done to check if the WT2 was supplying air to the rooms and to see the temperature gradient at the window cavities.

The sampling rate of the data was collected for every minute and then averaged for 10 minutes periods. The following equipment was used:

- 4 IC meters were placed in each room to evaluate the indoor climate for comparison with the readings from the local Bosch BME680 sensor. Averaged values were used in order to calculate the heat recovery of the window.
- 1 IC meter was installed on the outside of the WT2, measuring the outside conditions. Averaged values were used in order to calculate the heat recovery of the window.
- In each room, 8 PT100 sensors were installed in the WT2 at cavities 1, 3 and window frame (in front of the window frame inlet to the room located on top of cavity 1).

In Figure 20, Table 6 and Table 7 the placement of the PT100 sensors used in the calculation of the window performance is shown. The same setup was made for room 1 & 2.

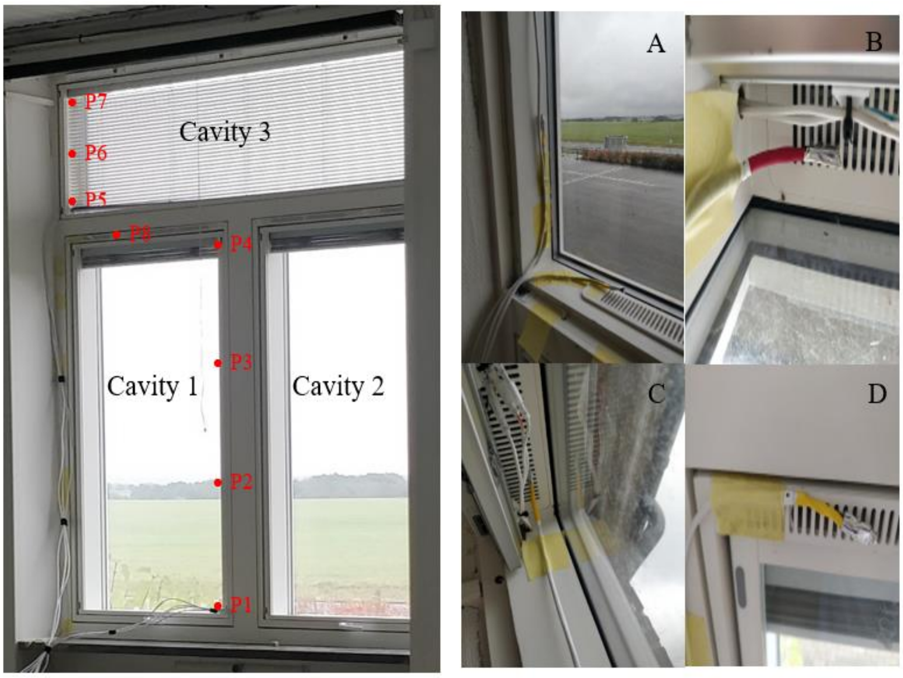


Figure 20 - Inside view of the WT2, located in the room 1 at the Ødis school showing the placement of the PT100 sensors in the cavities 1(P1,P2,P3,P4), 3 (P5,P6,P7) and window frame(P8). A – Cavity 3; B – Top cavity 1; C – Top cavity 3; D: Window frame)

Cavity 1 (CV1)	
P1	Bottom of the cavity 1 near to the valve/actuator
P2	0.42 cm from the bottom of the cavity 1
P3	0.84 cm from the bottom of the cavity 1
P4	Top of the cavity 1 near to the valve/actuator
Cavity 3 (CV3)	
P5	Bottom of the cavity 3 near to the valve/actuator
P6	0.22 cm from the bottom of the cavity 3
P7	Top of the cavity 3 near to the valve/actuator

Table 6 - Placement of PT100s in the cavities

Window frame (WF)	
P8	In front of the window frame inlet to the room located on top of cavity 1

Table 7 – Placement of the PT100 sensors at the WT2 window frame at the Ødis school in rooms 1 and 2

The PT100s were connected to the NUC computer where the data was collected and stored using LabVIEW.

The heat recovery was calculated for the WT2 top cavities 1 and 3 and compared to the analysis of WT1 for top cavity 1 performed by the previous study.

4 Results of the measurements at the school

In this part of the report the results from the data treatment and investigation will be presented and analyzed.

4.1 Results from averaging the IC meters in the rooms

In order to evaluate the indoor environment properly it can be necessary to see if all IC meters used in a room are close to the same value. If not, this suggest that the indoor environment is not very uniform and has occurrences of non-uniformity of both temperature and CO_2 concentration. But averaging groups of data can change the image quite a lot and therefore the data must be investigated individually first, before it can be averaged.

Reasons for averaging the data from the four IC meters into one set of data are the following:

- Reduces the individual error caused by uncertainty from each sensor.
- Fills out gaps in groups data resulting in a more complete set of data.
- Gives a more global description of the room's environment compared to a single sensor's, more local description.

The data had to be averaged first, in order to compare the IC meters to the each other, since they measured every 5 minutes, but did not start at the same point. It was necessary to average them to the same sample rate, which was chosen to be every 10 minutes. This was also done in order to make the process as close to the previous investigation as possible, to reduce the influence of the difference in the measured result cause by the difference in process.

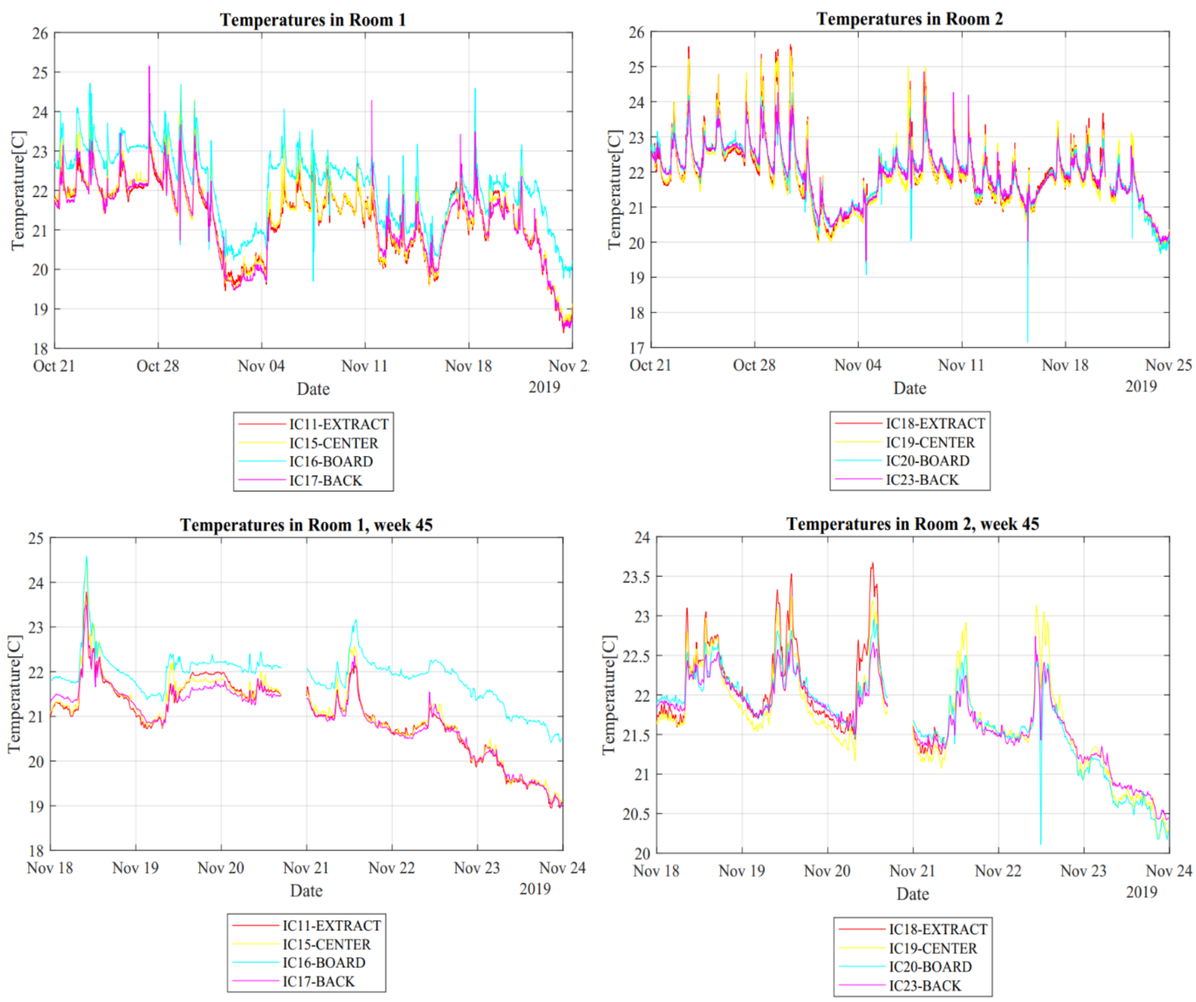


Figure 21 - Temperatures in room 1 & 2, all time & week 45, 10 min average with WT2, notice the difference in scales

Figure 21, 'Temperatures in Room 1' (top left) show that the IC 16 was generally 1°C above the rest of the sensors. This does not occur in room 2 (top right), which gives rise to suspecting that the IC 16 in room 1 was subjected to a very local temperature increase. Therefore, this IC meter was not used in the averaged data. Looking at a more detailed graph which is 'Temperatures in Room 1, week 45' (bottom left), it can be seen clearer that most of the time the IC 16 close to the board is showing 0,5 to 1,5°C higher than the rest of the IC meters. This could be caused by the fact that IC 16 was placed on an electrical circuit, which can be subjected to higher loads, causing the IC 16 to heat up.

Also, in the 'Temperatures in Room 2' (top right), there are some strange occurrences of large temperature drops. For example, between Nov. 11 and Nov.18 the IC 20 shows a temperature almost 3°C lower than the other lowest showing IC meter. This can also be seen in 'Temperatures in Room 2, week 45', where the drop is closer to 1,5°C from the nearest other IC meter. This could be caused by the manual opening of the window nearest to the board, causing a cold breeze of outside air to pass by the IC meter. Because of this, IC 16 and IC 20 were not included in the average of the room temperature.

Otherwise there was not a larger deviance in the temperatures in the different points in the rooms, indicating that there is generally a good mixing of the air in the rooms.

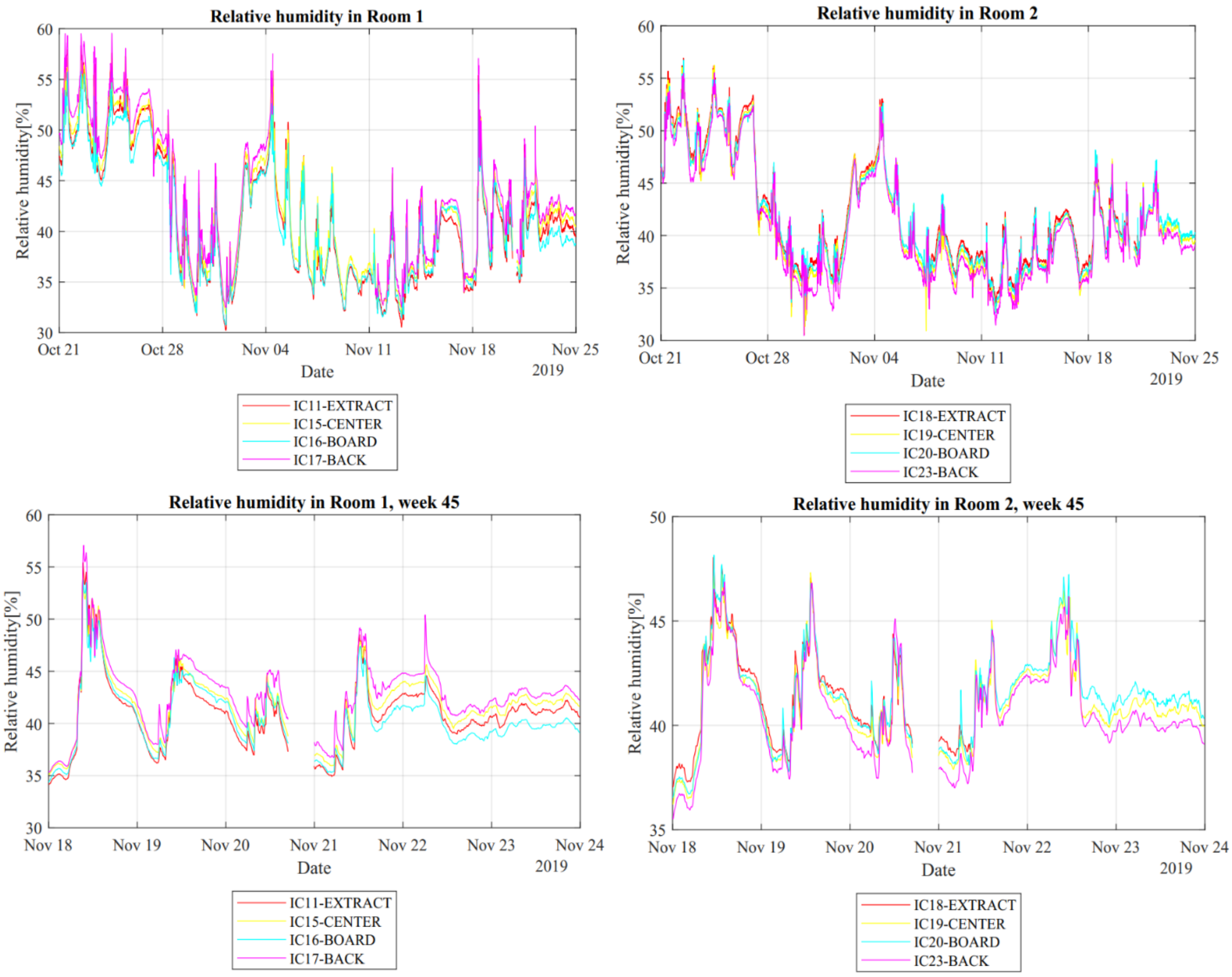


Figure 22 - Relative humidity in Room 1 & 2, all time and week 45, 10 min average with WT2Figure 23 - Relative humidity in Room 1 & 2, all time and week 45, 10 min average with WT2, notice the difference in scales

Figure 22 - Relative humidity in Room 1 & 2, all time and week 45, 10 min average with WT2Figure 23 shows the relative humidity in both rooms and generally shows similar values between the IC meters in the room. Therefore, all IC meters were used to make the average for the room.

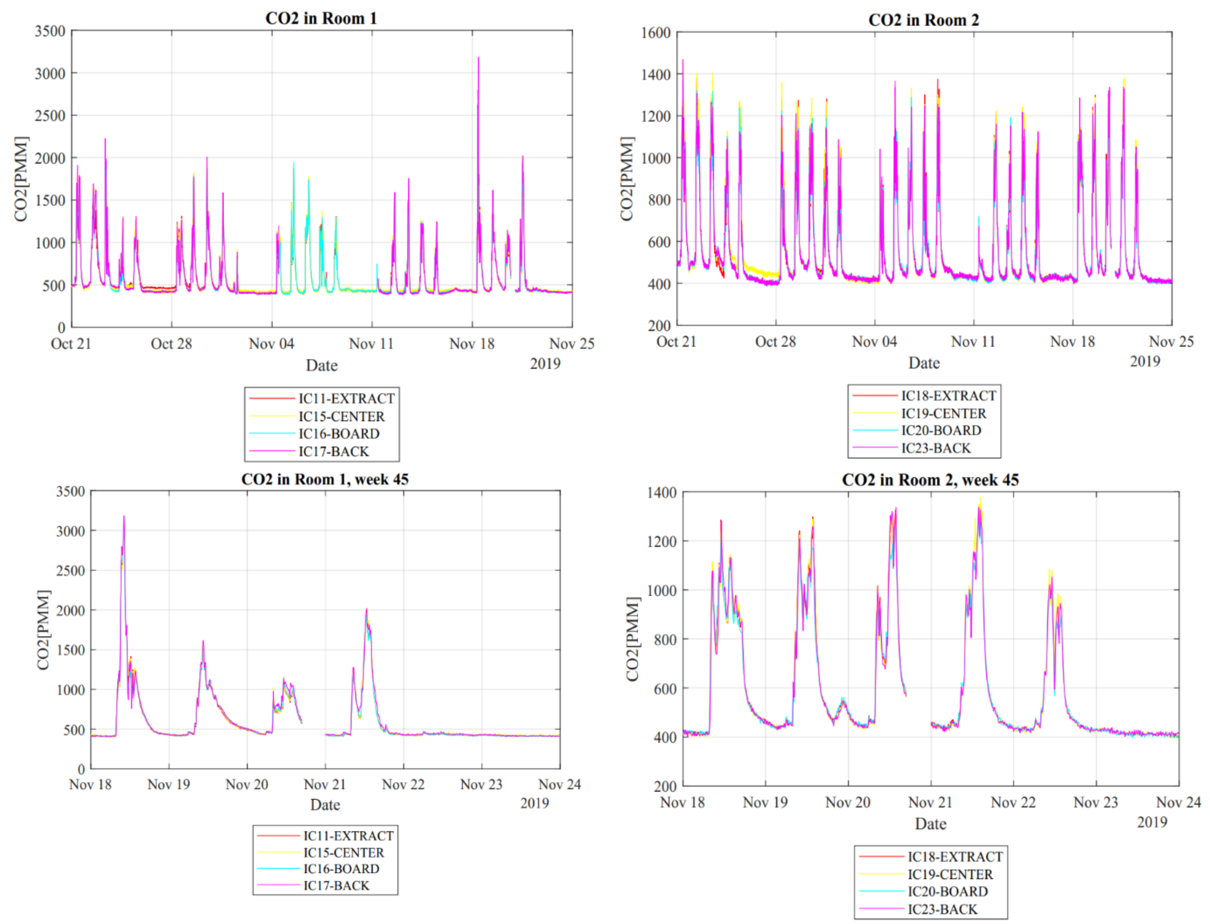


Figure 24 - CO2 for room 1 & 2, all time and last week, with 10 min average with WT2Figure 25 - CO2 for room 1 & 2, all time and last week, with 10 min average with WT2, notice the difference in scales

In Figure 24 - CO2 for room 1 & 2, all time and last week, with 10 min average with WT2Figure 25, the CO_2 concentration in the rooms over the measuring period can be seen. Also, the CO_2 levels seem to be quite similar in the different parts of the room. This means that all IC meters were included in the average of the rooms.

In order to achieve a quantitative grasp of the influence of the averaging, the maximum values of the IC 15, which was in the center of room 1, and the IC 19, which was in the center of room 2, and the averages of the rooms have been compared to see the difference. These two IC meters were chosen because they were in the position of the IC meters used in the previous investigation. The results are displayed in Table 8.

	IC15 R1	**IC19 R2**	**Averaged R1**	**Averaged R2**	**Difference R1**	**Difference R2**
Max CO2 [ppm]	2981	1472	3070,8	1426	2,92%	3,01%
Max Temp [°C]	24,64	25,48	24,19	25,01	1,93%	1,83%
Max RH [%]	57,46	56,45	57,44	56,13	0,02%	0,32%

Table 8 – Results in differences after averaging between the IC meters in each room with WT2

As it can be seen in Table 8, the averaging between the IC meters in each room had not made a larger effect than 3% on the maximum measured values in the rooms.

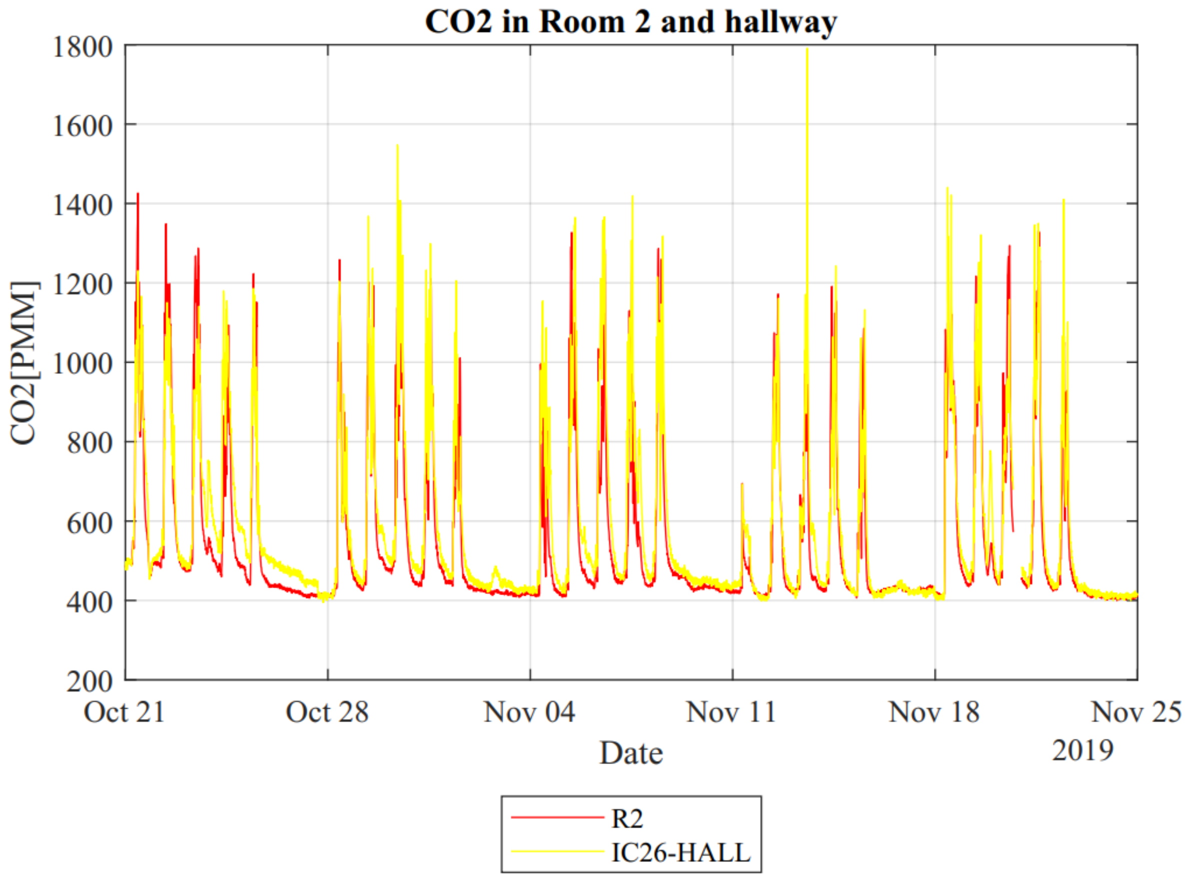


Figure 26 - Comparison between the average of Room 2 and the IC meter in the hallway IC26 with WT2

From Figure 26 it can be seen that the CO_2 level in the hallway was very similar to the CO_2 level in room 2. The hallway reaches higher levels, even reaching 1800 ppm. This indicates that the hallway was very influenced by the occupancy even though most of time the occupants should be in the classrooms. It was assumed that the CO_2 level in the hallway would be lower than the classrooms and could be used to indicate when the door was open by reducing the CO_2 level in the exhaust, since the exhaust is right by the door leading to the hallway. Looking at Figure 26 this does not seem to be the case.

4.1.1 Comparison of the indoor environment

In this chapter several factors that describe the indoor environment will be investigated and compared to the previous investigation of the school. This is to see what differences there are in the indoor environment that could be caused by the change in the design of the ventilated window.

CO2 concentration

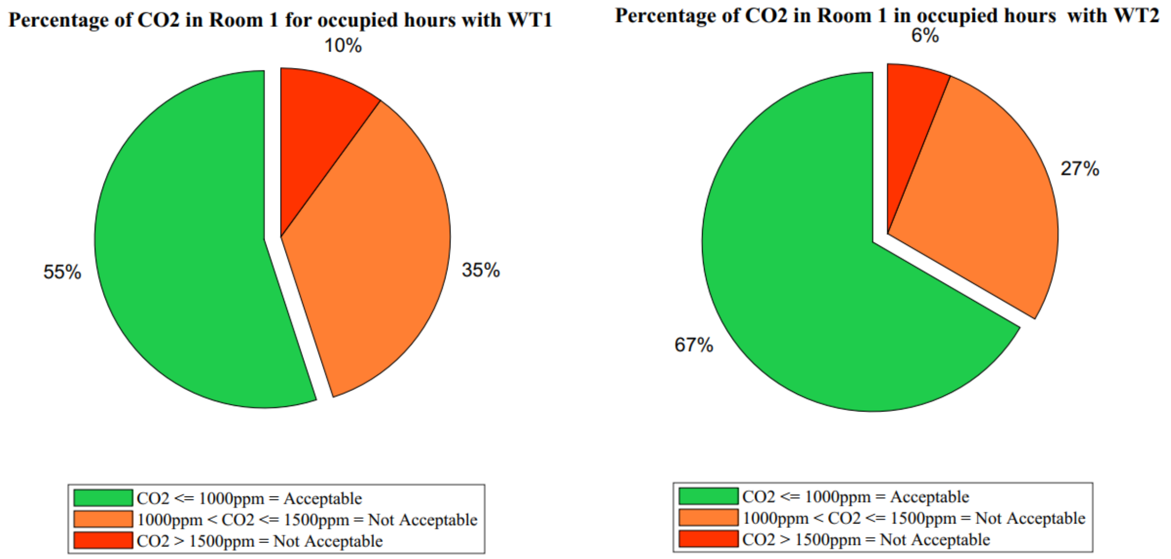


Figure 27 – CO_2 levels in Room 1 – Natural ventilation with WT1 (Left) and WT2 (Right) during occupied hours with 10 min average data

Figure 27 shows the CO_2 levels in Room 1 with WT1 (left) that has acceptable levels below or equal to 1000 ppm for 55% of the occupied time and unacceptable levels above 1000 ppm for 45% of the time. For 10% of the time there are unacceptable levels of the CO_2 where it is above 1500ppm.

For WT2 (right) it can be observed that 67% of the time the CO_2 levels are at the acceptable level below or equal 1000 ppm and 33% above the acceptable levels. For 6% of the time there are unacceptable levels of the CO_2 where it is above 1500ppm.

By comparing the two pie charts in Figure 27, it can be deduced that the time that the CO_2 levels in Room 1 is acceptable has increased by 12% from WT1 to WT2. Furthermore, the time at levels above 1500 ppm is reduced by 4%.

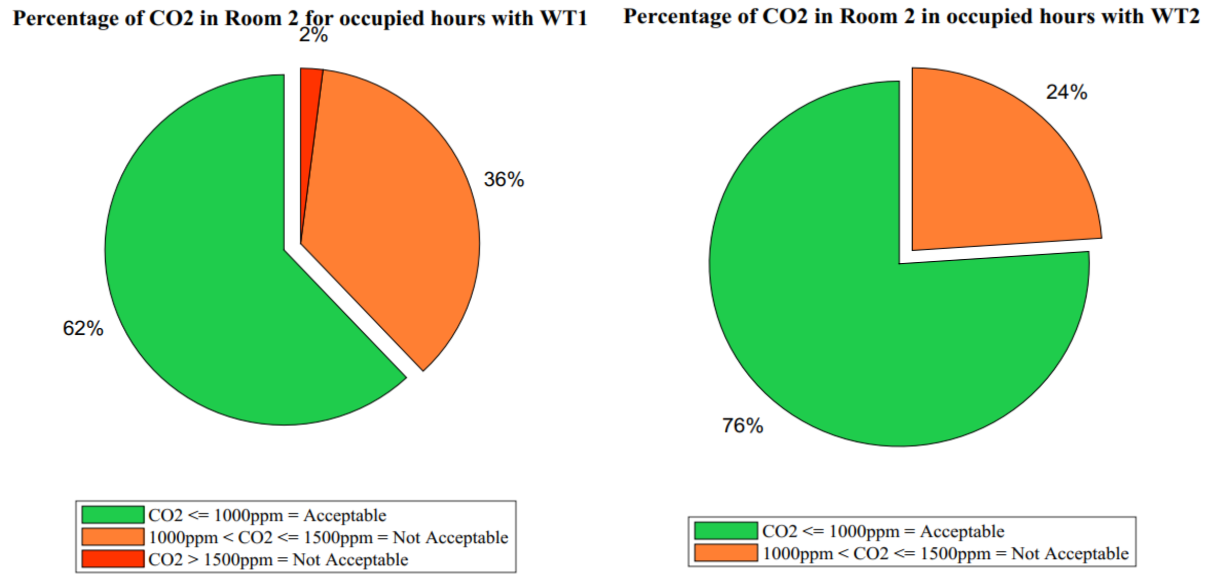


Figure 28 - CO2 levels in Room 2 – Mechanical ventilation with WT1 (Left) and WT2 (Right) during occupied hours with 10 min average data

In Figure 28 it can be observed that the CO_2 levels in Room 2 with WT1 (left) that has acceptable levels below or equal to 1000 ppm for 62% of the occupied time and unacceptable levels above 1000 ppm for 38% of the time. For 2% of the time there are unacceptable levels of the CO_2 where it is above 1500ppm.

For WT2 (right) it can be observed that 76% of the time the CO_2 levels are at the acceptable level below or equal 1000 ppm and 24% above the acceptable levels. For 0% of the time there are unacceptable levels of the CO_2 above 1500ppm.

By comparing the two pie charts in Figure 28, it can be deduced that the time that the CO_2 levels in Room 1 is acceptable has increased by 14% from WT1 to WT2.

To compare the CO_2 levels in Room 1 and Room 2 it can be seen that the acceptable CO_2 levels have increased for 12% of the time in Room 1 and by 14% of the time in Room 2. Assuming the pollution production is the same during the investigated period for the WT1 and WT2 this reduction could be caused by the fact that the new design of the ventilated window has been able to supply more fresh air to the rooms.

To examine this further, the extract flowrate was compared to the measurements from the investigated period for the WT1 and WT2.

Extract flowrate

In order to understand what caused the change in the CO_2 levels, the extraction flowrate for each of the rooms were measured. This was done for both rooms in the same duration as for the rest of the measurements, but the flowrates was investigated for all of the hours, not just the occupied hours. This was done for the reason that it was noticed that the window has been supplying air at all hours. This makes it interesting to then see the flowrates from the exhausts in the rooms and how they acted in this time. In the previous investigation of the indoor environment in the school it was investigated what the theoretical exhaust rate should be for the rooms using the dilution equation. Since several of the conditions were similar, such as the maximum expected occupants, scheduled weekly lessons, systems operation, it was assumed that the dilution calculations were still valid for this investigation. This was therefore also used for comparison in Figure 29 and Figure 30, to see how close the measured results were to the theoretical minimum flow need.

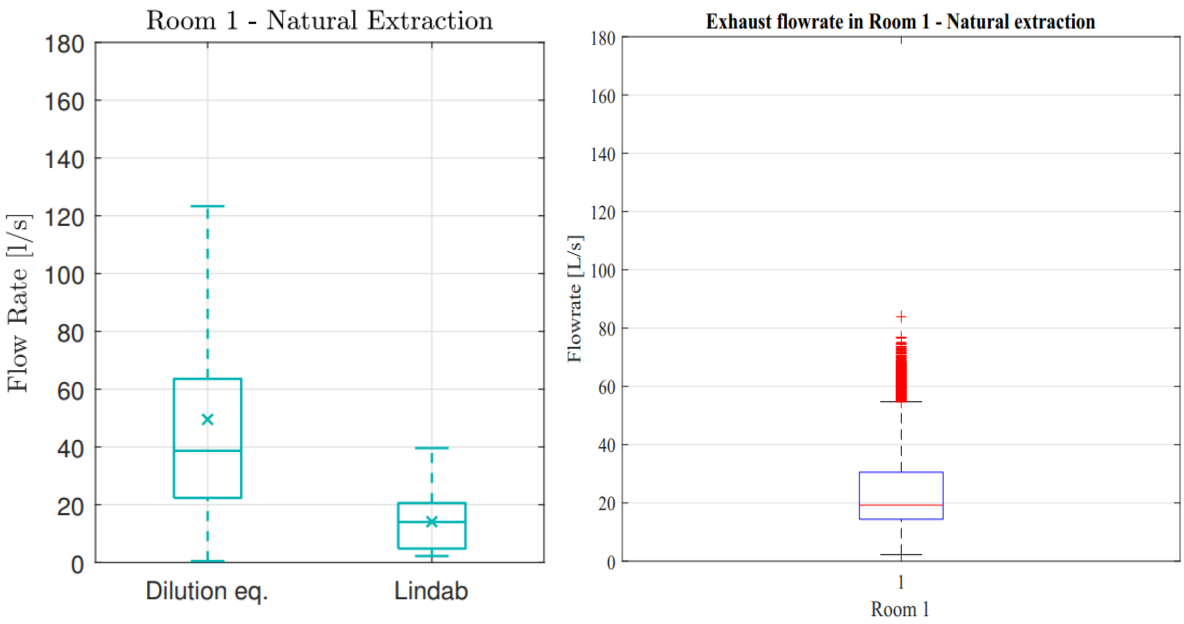


Figure 29 - Comparison of exhaust rates from the two investigations and the dilution equation in room 1 (Lindab is from the previous investigation WT1, Room 1 is from the current investigation WT2 from Lindab sensor. (Left figure is from previous investigation; right is from the current investigation).

As seen in Figure 29 there was generally higher extraction in room 1 in the current investigation than in the previous investigation. 75% of the WT1 airflow measurements were below 20 L/s while in the WT2 measurements 50% of the measurements were above 20 L/s. It can further be observed that the mean of WT1 to WT2 measurements was increased by 6 L/s.

This could help explaining why there was a 12% lower percentage of time with CO_2 levels above 1000 ppm. This is assuming that a higher exhaust means a higher ventilation airflow from the WT2. The measured values from the current investigation was still less than the dilution equation. The increase in airflow could indicate that WT2 had a lower pressure resistance than WT1.

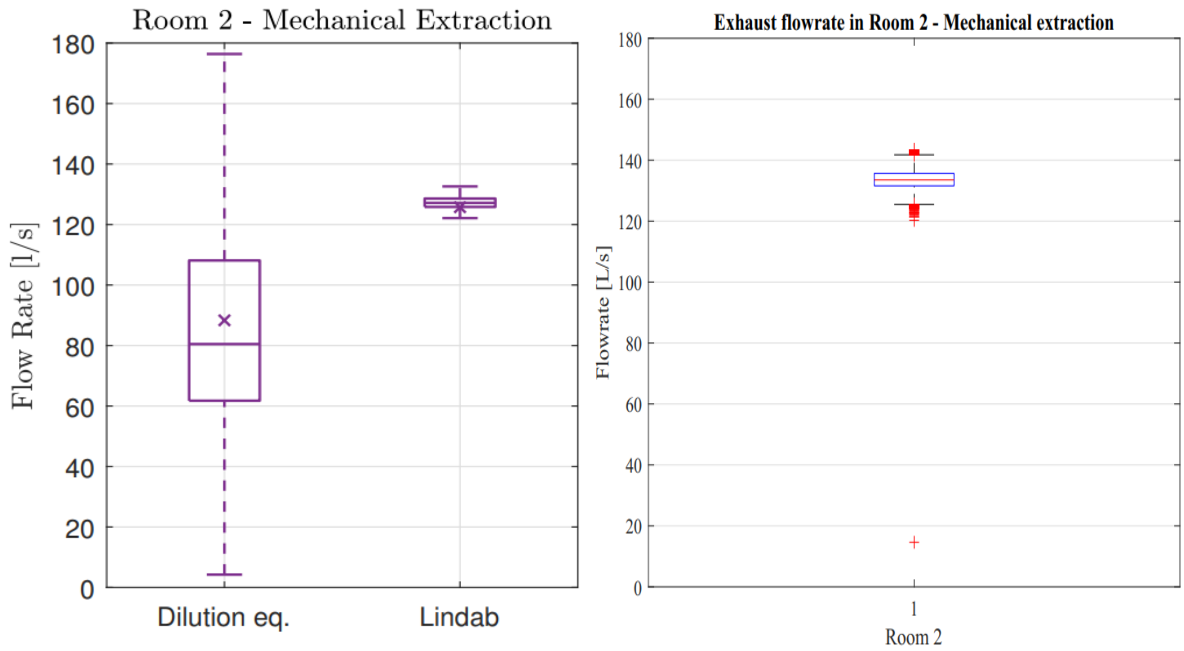


Figure 30 - Comparison of exhaust rates from the two investigations and the dilution equation in room 2 (Lindab is from the previous investigation WT1, Room 2 is from the current investigation WT2 Lindab sensor. (Left figure is from previous investigation; right is from the current investigation).

From Figure 30 it is observed that the mean of the airflow rates from WT1 had increased from 127 L/s to 132 L/s, resulting in an increase of 5 L/s. This could explain the improved CO_2 levels that were reduced by 14% in room 2. The increase in the mean flowrate was 5 L/s, but it was still not enough to achieve the levels calculated by the dilution equation. The increase in maximum flowrate is 10 L/s.

Relative humidity

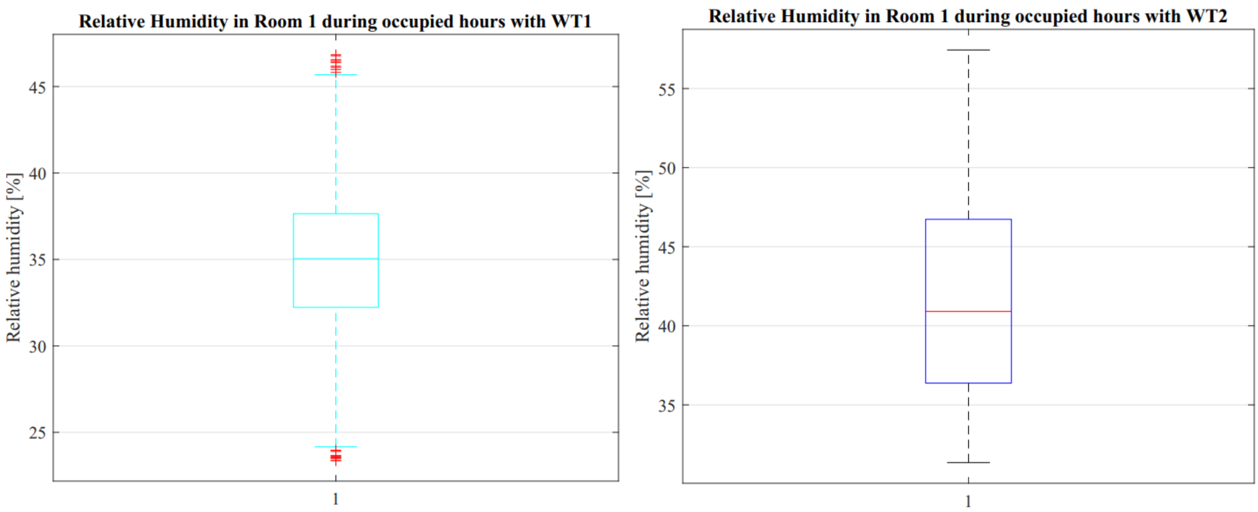


Figure 31 - Relative humidity in room 1 – Natural ventilation with WT1 (Left) and WT2 (Right) 10 min averaged of occupied hours, notice the difference in scale

In Figure 31 it can be seen that with WT1 (left) the relative humidity in room 1 is 100% of the time between 22 – 47%, resulting in category III according to DS 15251. The mean is 35% and is within category I.

For WT2 (right), the relative humidity is 100% of the time between 31 – 58% resulting in Category II. The mean is 41% and is within category I.

The WT1 measurements results in a lower category than WT2 caused by the relative humidity level being below 25%.

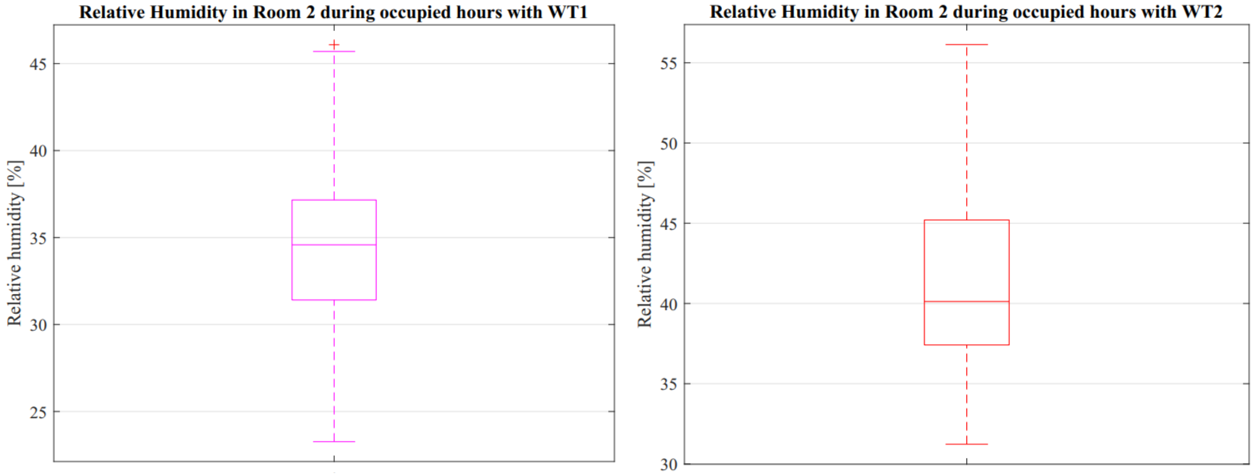


Figure 32 - Relative humidity in room 2 – Mechanical ventilation with WT1 (Left) and WT2 (Right) 10min average of occupied hours, notice the difference in scale

In Figure 32 it can be seen that with WT1 (left), the relative humidity in room 2 is 100% of the time between 23 – 46% resulting in category III according to DS 15251.

For WT2 (right) the relative humidity is 100% of the time between 32 – 56% resulting in Category II. The mean is 40% and is within category I.

The WT1 measurements results in a lower category than WT2 caused by the relative humidity level below 25%. The mean is 34.8% and is within category I.

Comparing the relative humidity in Room 1 and Room 2 it can be observed that both rooms during WT1 measurements had similar values, resulting in category III. Both rooms had relative humidity levels in the WT2 measurements resulting in Category II. The mean of both rooms and both WT1 and WT2 was within category I.

The observations of the relative humidity levels in the rooms, can be explained by the difference in season of the WT1 and WT2 measurements. The WT2 measurements were performed earlier in the winter season with warmer temperatures, causing a higher absolute moisture in the air. This moisture is then transported into the rooms through the window, causing higher relative humidity during WT2.

Temperature

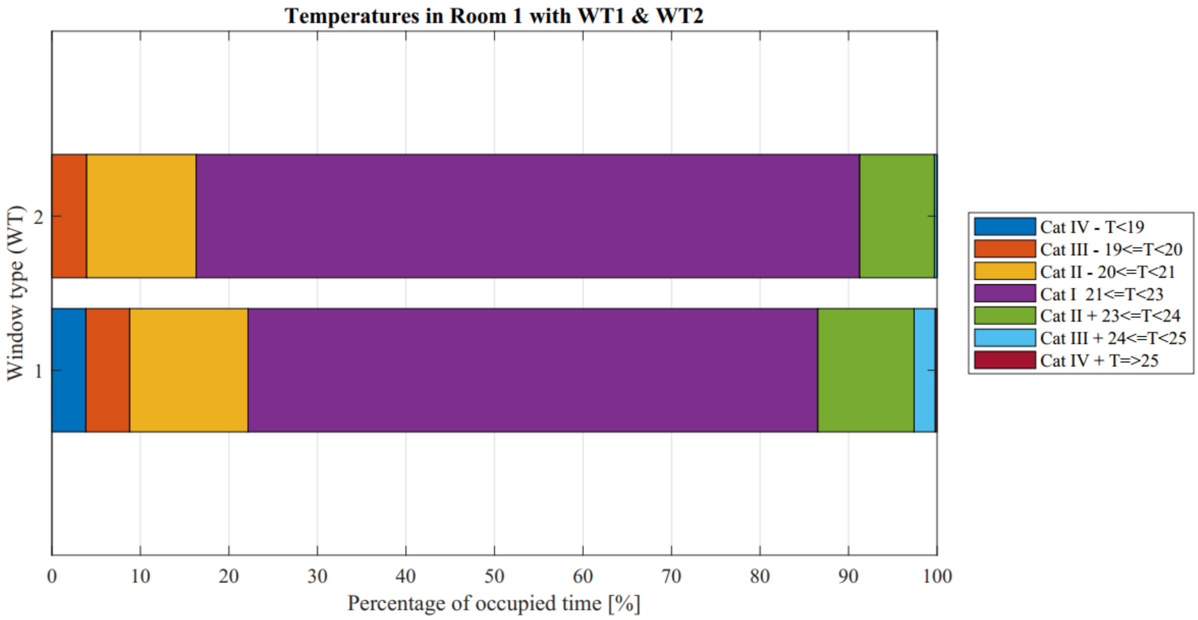


Figure 33 - Percentage of Temperature within categories in Room 1 for WT1 (Bottom) and WT2 (Top) 10 min average of occupied hours

It can be observed in Figure 33 that the temperatures during measurements with WT1 in room 1 are in the between category -II and -IV 22% of the time, within Category I 65% of the time and within category +II to +IV 13% of the time.

For the temperatures during measurements with WT2 in room 1 are in the between category -II and -IV 16% of the time, within Category I it is 76% of the time and within category +II to +IV 8% of the time. It can furthermore be observed that there is no time where the temperature is below 19°C placing it in Category IV. It can also be observed that there is less than 1% above 24°C meaning it never reaches category III or above.

Comparing the distributed temperatures in room 1 has changed within category -II and -IV with a reduction of 6%, within Category I it is 11% and within category +II to +IV a reduction with 5%. It can be observed on Figure 33 that none of the measurements reaches above 25°C which means neither are in category IV.

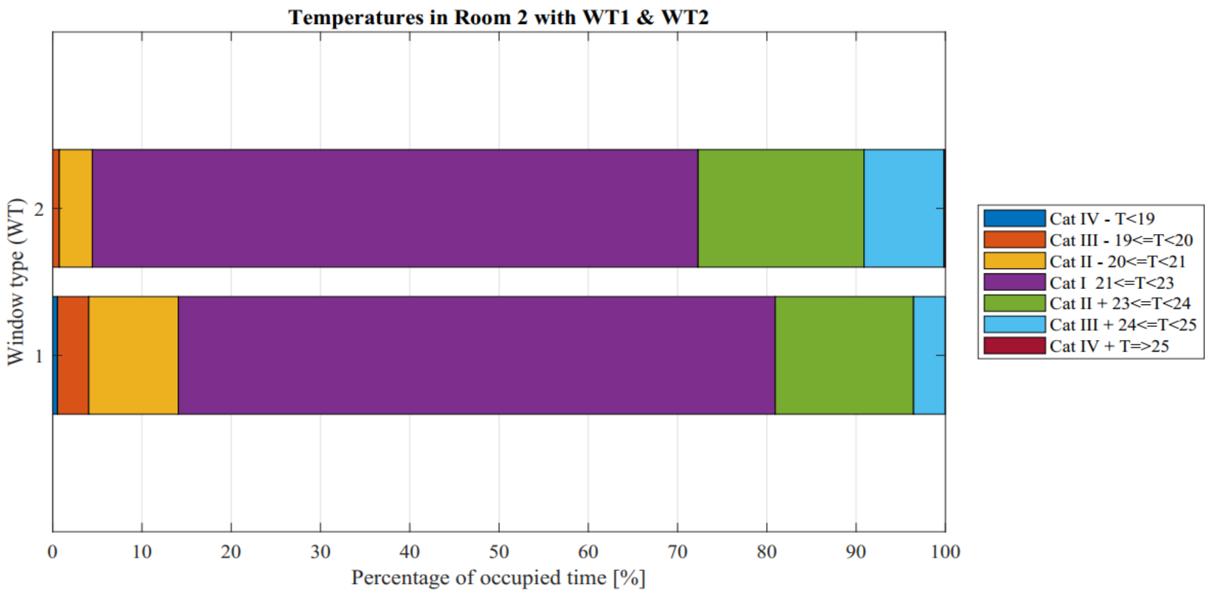


Figure 34 - Percentage of temperature within categories in Room 2 for WT1 (Bottom) and WT2 (Top) 10 min average of occupied hours

It can be observed in Figure 34 that the temperatures during measurements with WT1 in room 2 are in between category -II and -IV 13% of the time, within Category I 68% of the time and within category +II to +IV 19% of the time.

For the temperatures during measurements with WT2 in room 1 are in the between category -II and -IV 4% of the time, within Category I it is 68% of the time and within category +II to +IV 28% of the time.

Comparing the distributed temperatures in room 1 has improved within category -II and -IV with a reduction of 9%, within Category I it is 0% and within category +II to +IV it has increased with 9%. It can be observed on Figure 34 that none of the measurements reaches above 25°C which means neither are in category IV.

Both Room 1 and Room 2 has seen reduced time within the colder temperatures since the WT1 was replaced with the WT2. For Room 1 more time has been within category 1 comparing for WT2 where the rest of the measurements show similar time in category 1. Room 2 shows more time within the higher temperature categories than Room 1.

The observation in temperature distribution between the categories can be explained in theory by the two following conditions:

1. The outside temperatures were different because of the difference in season between the two measurement periods.
2. Room 1 is in the corner where it has two external walls compared to room 2 that has 1 external wall, meaning room 2 shares more walls with heated rooms.

There are several factors that support conditions 1, which are the following.

On the 13th of December at 7:48 in the morning the janitor called the authors of this report saying that it felt very cold in Room 1 with natural ventilation and it was discovered that the temperature by the exhaust (IC 11) in Room 1 was at 18,1°C. This indicates that colder temperatures were occurring in the rooms from December.

In order to assess how much the outside temperature had been different during the two measurements, which could affect the indoor temperatures, a comparison of the two outside temperature measurements was performed.

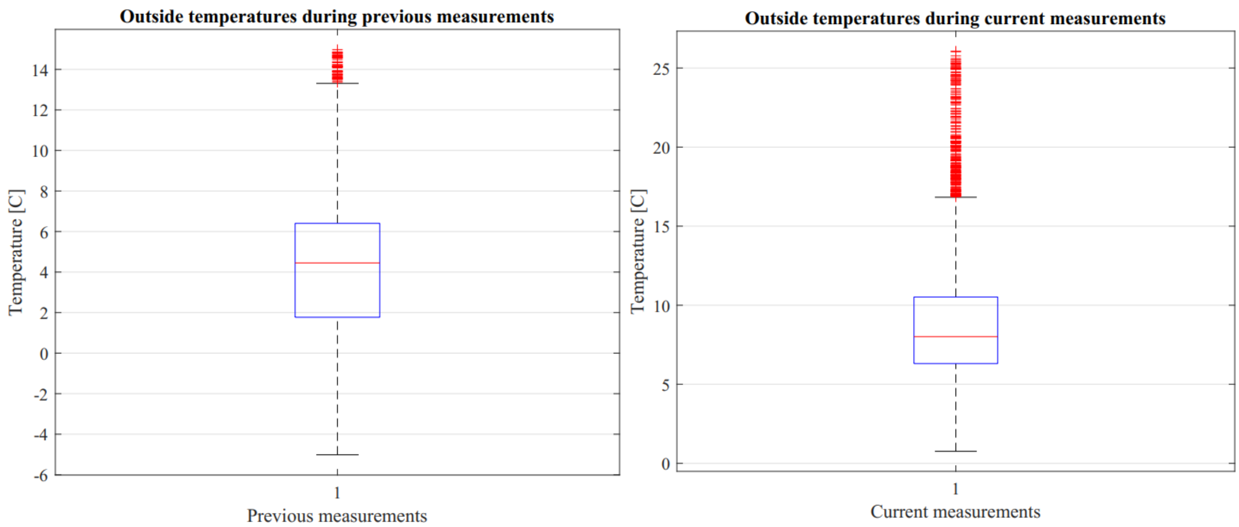


Figure 35 - Boxplot of outside temperatures during measurements with WT1 (Left) and current measurements WT2 (Right) notice the difference in scale.

In Figure 35 the comparison between the outside temperatures during the measurements can be seen. It is clear to see that on the current investigation measurements (right), there was 3°C higher in the mean temperatures than on the previous investigation measurements (left). It has to be noted that the IC meter measuring the outside temperature during the current investigation was not shielded from solar radiation and therefore did not always portray the true outside air temperature. But still, the temperature never went below 1°C in the current measurements, but it reached as low as -5°C in the previous measurements.

The outdoor temperatures can affect the indoor thermal comfort in colder temperatures by having colder temperatures supplied by the window. If the heating system is slow in response and even under dimensioned this could be causing the colder indoor temperature during the WT1 measurements.

4.1.2 Summary of the comparison

Generally, the indoor environments have shown improvements since the last investigation occurred. It is however difficult to say how much of this was caused by the installation of the new window design WT2 test.

To compare the two investigations, it can be seen that the CO_2 levels in the current investigations improved by 12% in Room 1 and by 14% in Room 2. This could be caused by the change in design, since there have also been observed higher ventilation rates in the extraction of the rooms. In room 1 it was observed that with WT1, 25% of the extract flow rates were above 20 L/s and 50% with WT2 test. For Room 2 it was observed that the mean flow rate increased by 5 L/s from WT1 to WT2 tests and the maximum flow rate increased by 10 L/s. This could indicate that WT2 test caused a lower pressure to drop than WT1 test resulting in higher air flows through the window.

The relative humidity changed from always being between 20 - 52% to 32 - 58% which is a change from category III to category II. This is possibly caused by the warmer air temperatures during the WT2 test, making the air able to contain more moisture. This could be investigated further by comparing the absolute humidity during WT1 and WT2 tests.

Temperatures changes from WT1, being within Category I 65% of the time, to WT2 being within Category I at 76% of the time. This is an increase in time within Category I of 11%. This is possibly caused by the higher temperatures outside during WT2 test compared to WT1 test, which is confirmed to be an increase of 3°C of the mean outdoor temperatures.

4.2 Window performance

4.2.1 PT100 sensors investigation in rooms 1 and 2

Based on the data collected by the PT100 sensors it was chosen the days 29th and 30th of October to display the highest air temperature registered at the top cavities 1, 3 of the WT2 in the investigated rooms.

Figure 36 presents the gradient temperature between the different PT100 sensors placed at the window for the room 1. In these days the air temperature measured at the top cavity 1(P1) and top cavity 3(P7) was the highest, registering 55 °C and 57.43 °C, respectively for the 29th and 30th of October for the room 1. For the room 2 it was registered 54.15 °C and 58.36 °C for the same period.

The outside air temperature ‘molded’ the pattern of the air temperature registered inside the air cavities of the WT2 by all PT100 sensors.

After this step, the investigation focused on the air temperatures measured at the top cavity 1 for the WT2 in the 2 studied rooms during weeks 43 and 47, as presented in Figure 37 and Figure 38.

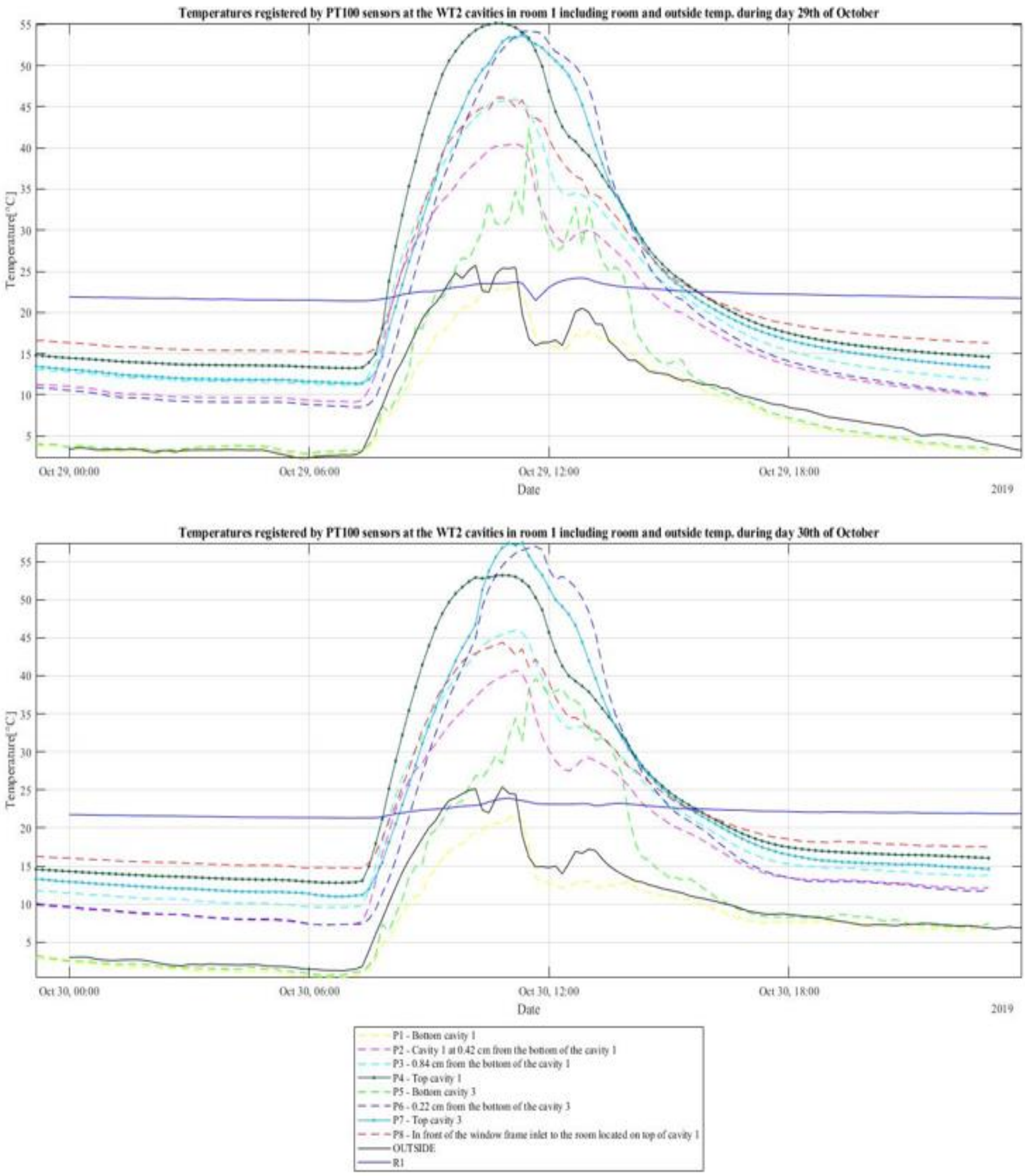
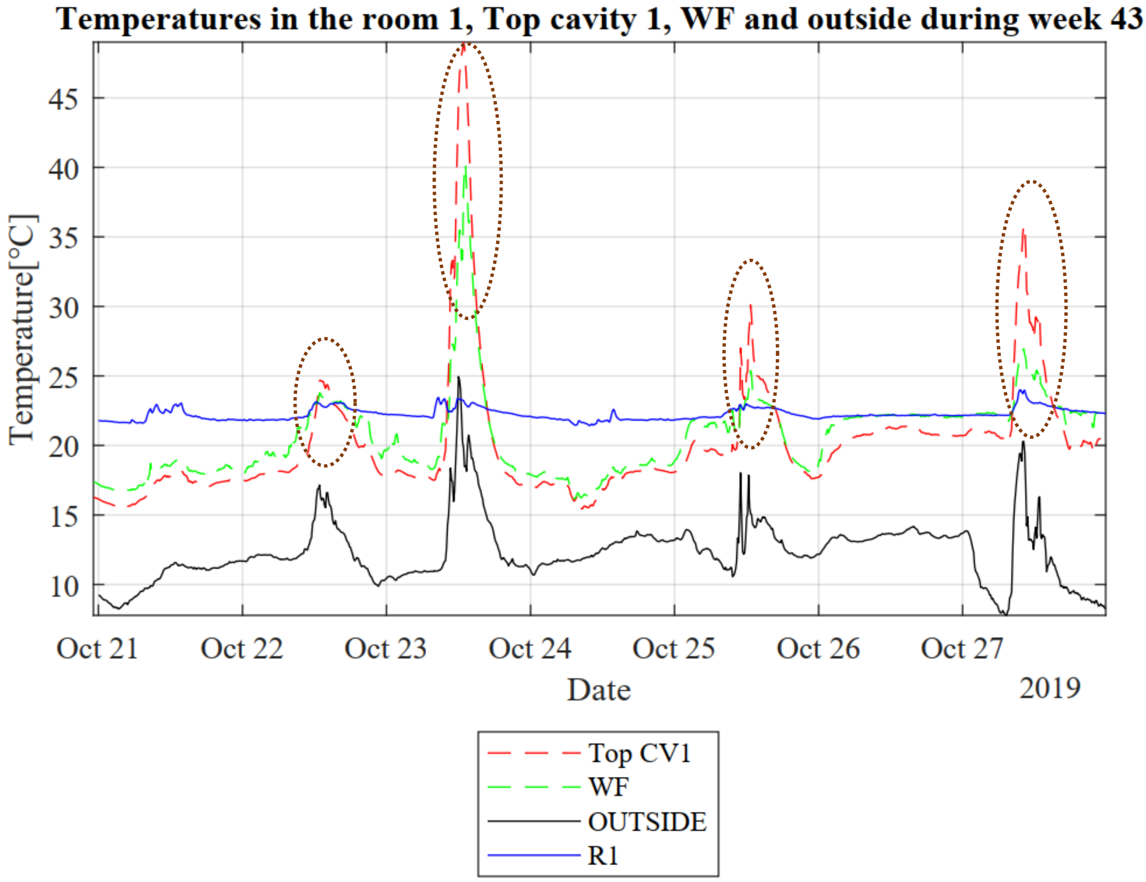


Figure 36 -- Temperatures registered by the PT100 sensors located at the WT2 cavities 1, 3, window frame including room and outside temperature during the 29th and 30th of October for room 1

As expected, the outside air temperature had influence on the air temperature measured at the WT2 top cavity 1 and window frame(P8) in both rooms, showing similarities in the behavior pattern, as can be seen in the figures below. The desired air temperature in the room was 22 °C, but oscilations occurred, especially during week 47 due to the decrease in the outside air temperature. Most of the time the air temperature measured at the window frame (P8).during the week 43 had higher values than in the top cavity 1(P4), but in some periods during the 22th, 23th, 25th and 27th of October the opposite happens (marked with a dashed brown line).

In Figure 38 it can be seen that there is a gap (missing information) in the plotting of the room and outside temperatures during some hours on the 20th of November due to a glitch in the IC meters storage cloud.



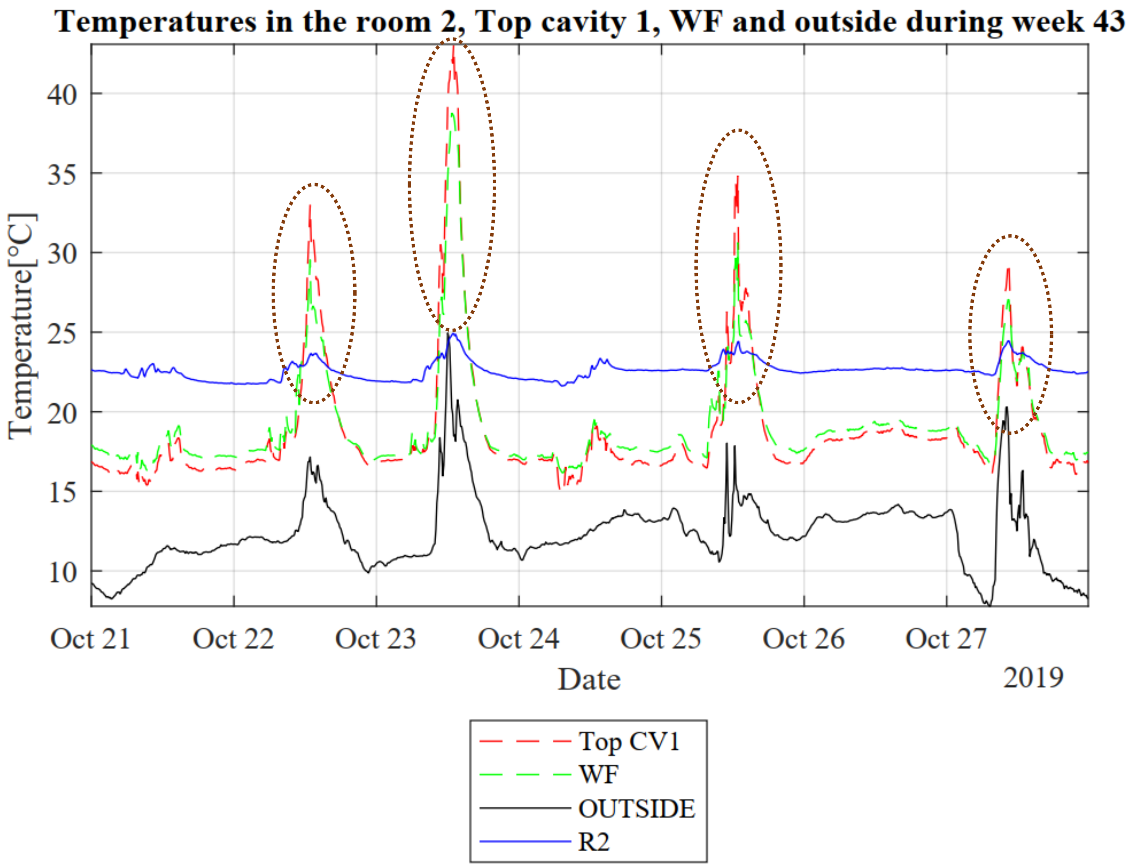
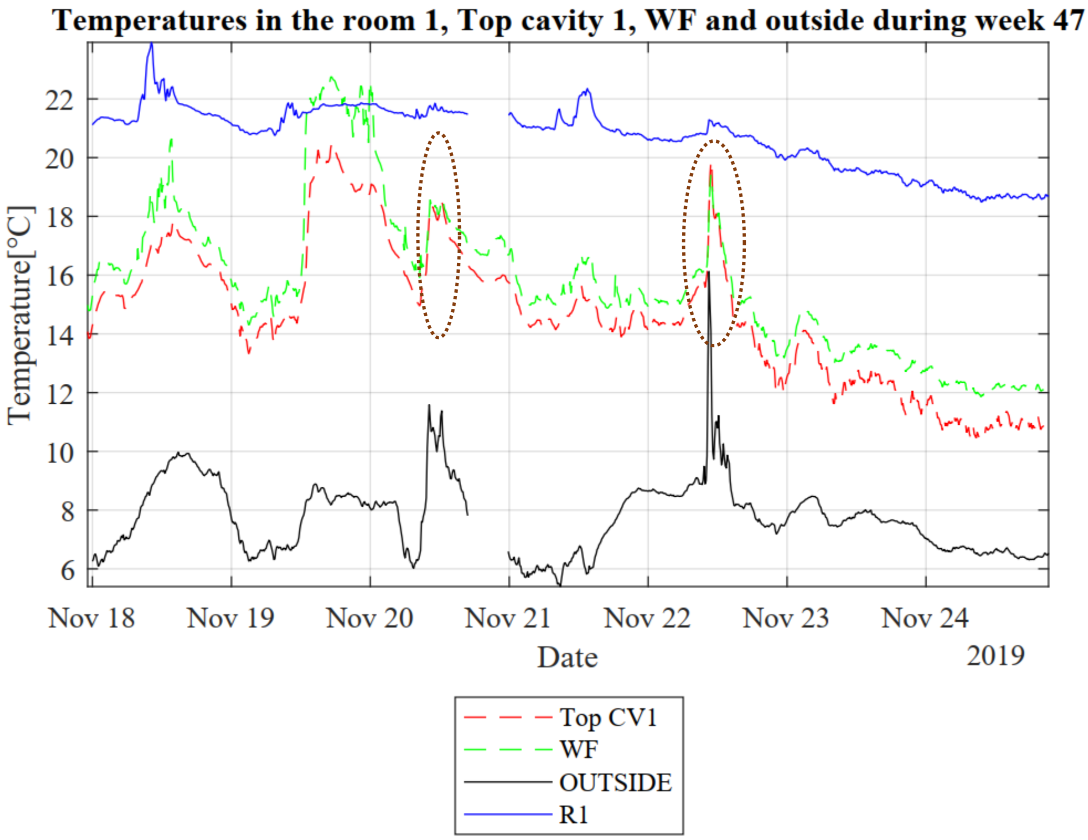


Figure 37 - Temperatures registered in the rooms 1, 2, Top cavity 1(P4), WF(P8) and outside during the week 43



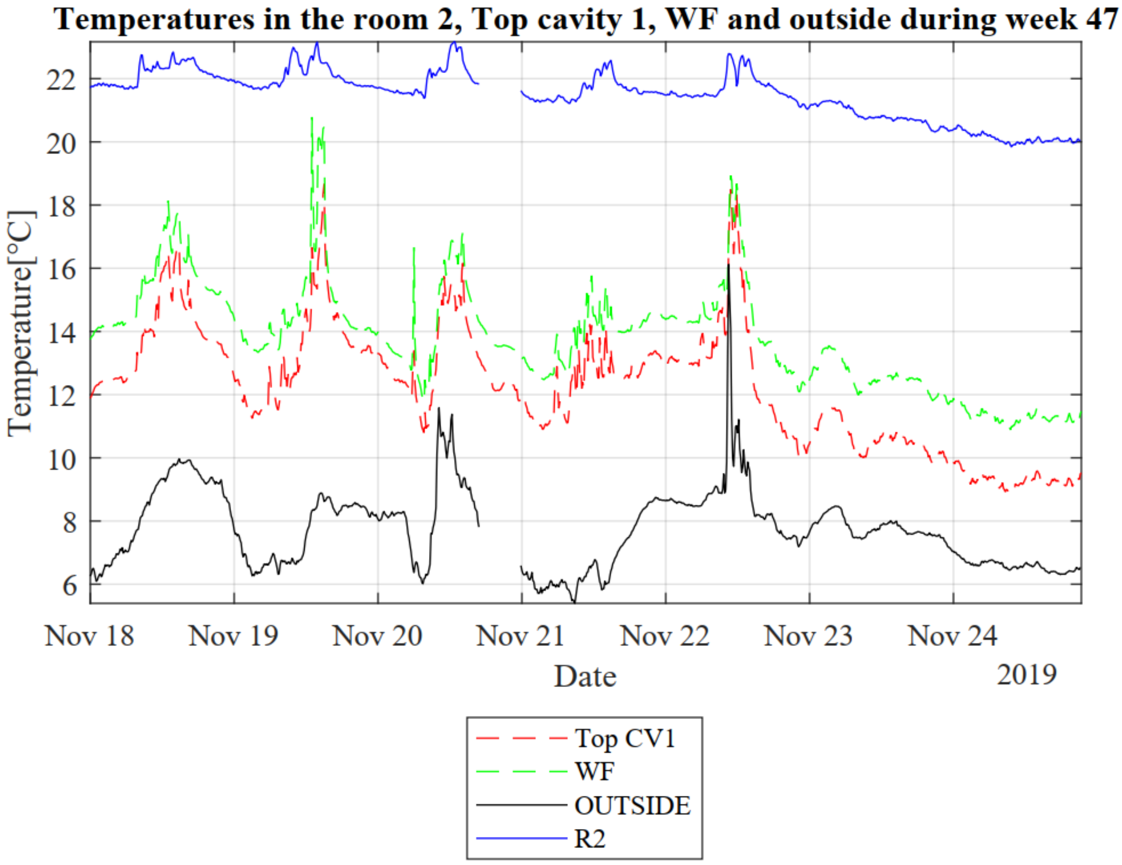


Figure 38 -- Temperatures registered in rooms 1, 2, Top cavity 1(P4), WF(P8) and outside during the week 47

During the week 47 shown on Figure 38 the air temperature measured at the top of cavity 1(P4) never overcame the air temperature measured at the window frame (P8) for the room 2 but for the room 1 it did very briefly during the 20th and 22th of November (marked with a dashed brown line).

A daily investigation was then conducted during those days to find out when and why this happened. It was chosen to present the figures of the day 27th for room 1 and 25th of October for the room 2. The reason for choosing these days was that the largest air temperature difference between the top cavity 1(P4) and the window frame(P8) was present on these days: 8.89 °C for room 1 and 4.69 °C for room 2 as presented in Table 9, Table 10, Figure 39 and Figure 40.

In appendix 8.5 can be found the investigation done for the other days.

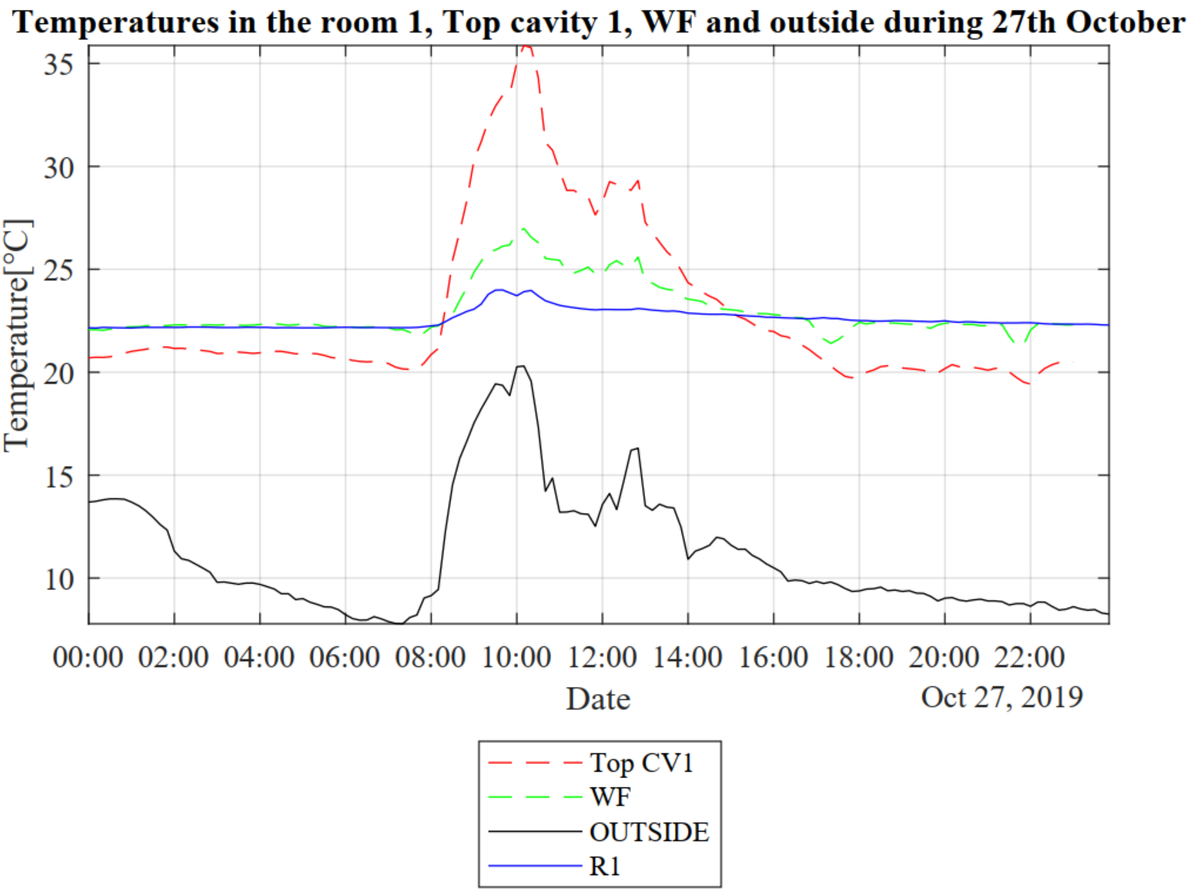


Figure 39 - Temperatures measured in the room 1, Top cavity 1(P4), WF(P8) and outside during the 27th of October

Table 9 present the periods during the 27th of October when the air temperature measured in the top of cavity 1 was higher than the one measured at the window frame in room 1 (including the air temperature outside and in the room), based on the plot displayed in Figure 39.

Temperatures [°C] measured in room 1				
Period	Outside	Top cavity 1	Window frame	R1
27/10/19 at 08:17	11.23	22.39	22.39	22.39
27/10/19 at 10:10	**20.30**	**35.87**	**26.98**	**23.91**
27/10/19 at 14:56	11.72	23.05	23.05	22.80

Table 9 - Temperatures measured in the room 1, at the top cavity 1, window frame and outside

This happened due to the influence of the sun radiation that hit the window pane, contributing to the increase of the air temperature in the window cavity.

Figure 40 exhibits the same behavior pattern for the room 2.

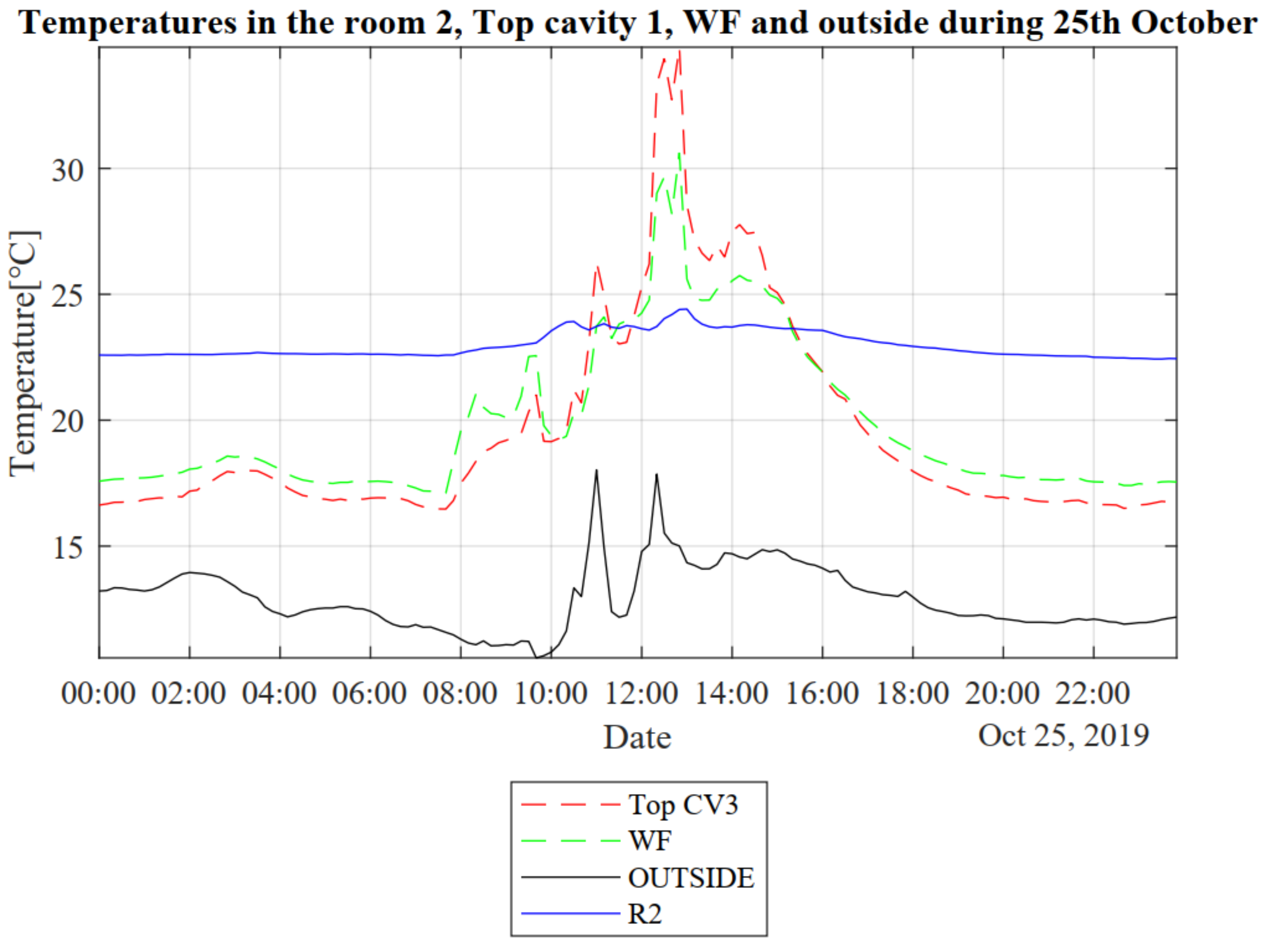


Figure 40 - Temperatures measured in room 2, Top cavity 1(P4), WF(P8) and outside during the 25th of October

Temperatures [°C] measured in room 2				
Period	Outside	Top cavity 1	Window frame	R2
25/10/19 at 10:10	11.09	19.22	19.22	23.74
25/10/19 at 11:20	12.39	23.24	23.24	23.70
25/10/19 at 11:50	13.22	23.99	23.99	23.72
25/10/19 at 12:30	**15.52**	**34.36**	**29.67**	**24.03**
25/10/19 at 16:00	14.12	21.91	21.91	23.57

Table 10 - Temperatures measured in room 2, at the top cavity 1, window frame and outside

The following step was to investigate when if ever the ventilated windows was supplying air to the rooms.

A correlation between the air temperatures measured at the top inside of cavity 1 and at the inlet to the room at the top of cavity 1 (P8) in the rooms 1 and 2 during weeks 43 until 47 was investigated and plotted in Figure 41. The correlation was strong, since the R^2 value was near to 1. The temperature at the top cavity 1 and at the room inlet (P8) are acting in the same way indicating that the ventilated window was supplying air most of the time.

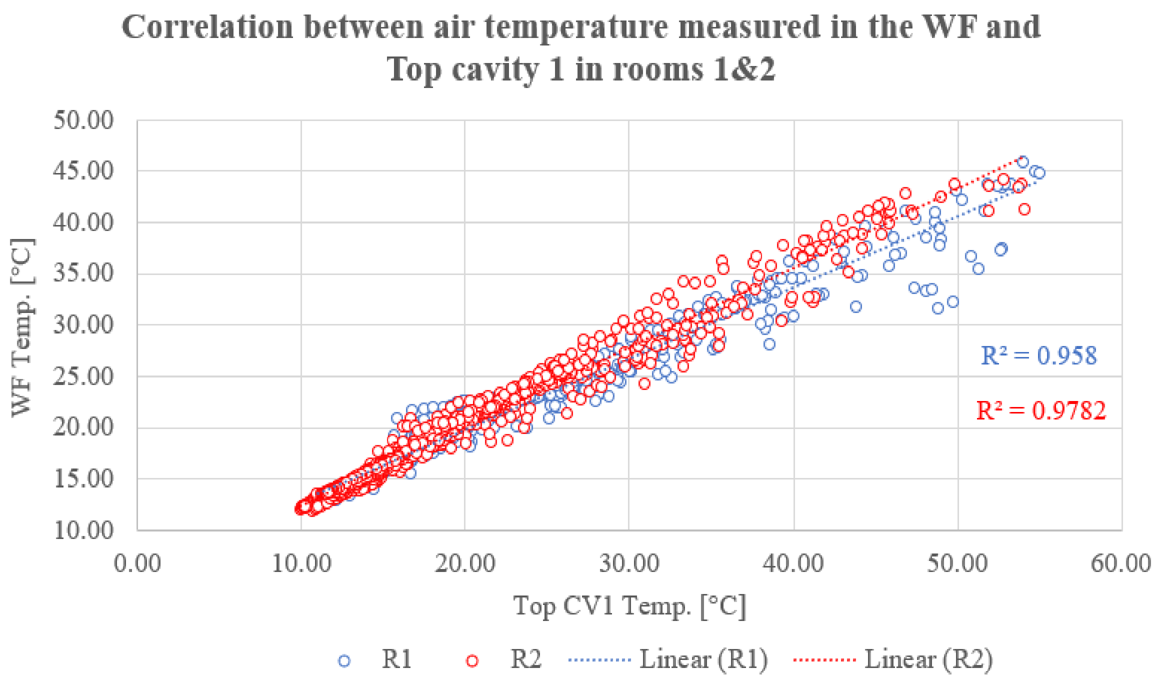


Figure 41 - Correlation between the air temperature measured in the window frame(P8) and the top cavity 1(P4) in rooms 1&2 during the W43-47

The same analogy was done for the correlation between the air temperatures measured at the inlet to the room at the top of cavity 1 (P8) and in the rooms 1 and 2 for the same investigated period, as presented in Figure 42. In this figure the correlation between the temperature at the window room inlet(P8) and the rooms temperature registered different linearity based on R^2. This indicates whatever it is affecting the temperature in the rooms is not affecting in the same way the temperature at the window room inlet(P8).

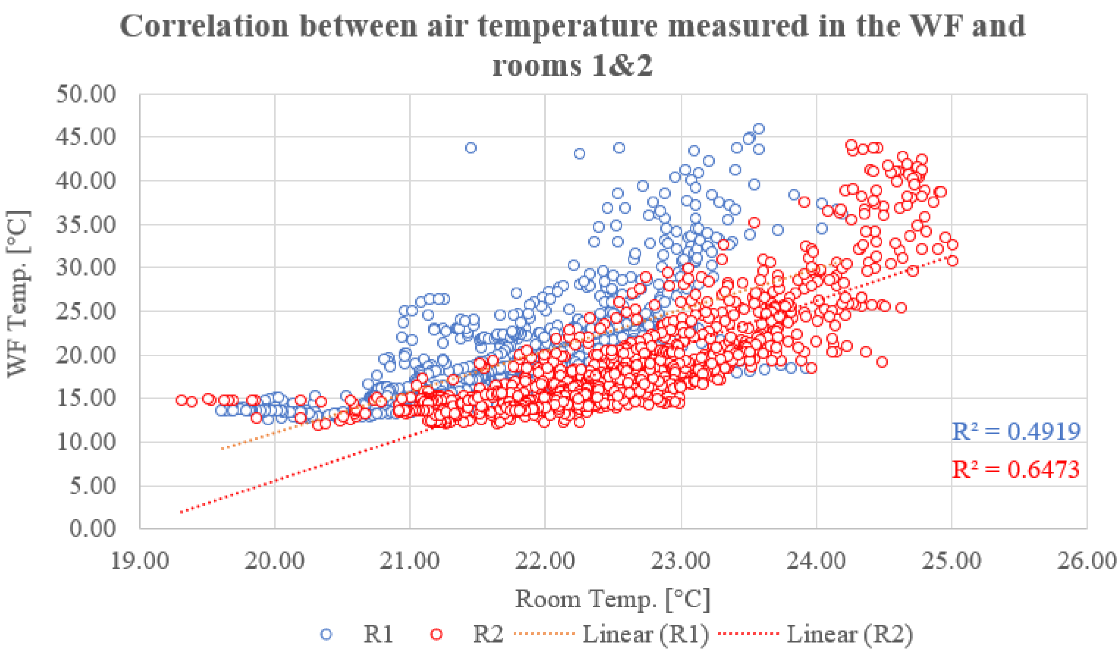


Figure 42 - Correlation between the air temperature measured in the window frame(P8) and the rooms 1&2 during the W43-47

Assuming that the convection from the ventilated window was the main factor contributing to the similarity between the temperatures in Figure 41 give an indication that the ventilated window is supplying air during the all investigated period.

4.2.2 Heat recovery

This quote from the comparative study described the definition of heat recovery:

"Heat recovery is the capability of the window to supply air at higher temperature than the inlet fresh air from the outside. It only occurs when preheating mode is in use. Fresh air goes through the cavity driven by buoyancy and wind forces while it is heated due to solar or/and internal heat contributions. This allows the window to supply warmer air than the outside temperature avoiding uncomfortable temperatures". (Bonet Arbos et al., 2019)

The heat recovery for the top cavities 1 and 3 of the WT2 was calculated based on the following equation:

$$HR = \frac{\Delta T_{Top\ cavity - OUT}}{\Delta T_{Room-OUT}}$$

Equation 4.1 - Heat recovery at the top of the window cavity

$T_{Top\ cavity}$ – Temperature supplied to the room based on top cavities 1 and 3[°C]

T_{OUT} – Temperature outside [°C]

T_{Room} – Indoor temperature in the room [°C]

The comparative study had calculated the heat recovery based on the same principle, but for the WT1 in the room 2. Since the design of the WT1 has 2 cavities with the same area and layout it was assumed that the heat recovery would be the same in both cavities.

The heat recovery was calculated for the top cavity 1 of the WT1 for the room 2 (based on the data collected from the comparative study) and compared with the top cavities 1 and 3 of the WT2 for rooms 1 and 2.

The heat recovery was plotted in function of the difference between the room temperature and the outside temperature, as presented in.Figure 43, Figure 44, Figure 45, Figure 46 and Figure 47. In the plotting of the heat recovery results the data was averaged for a 10 min period and was filtered based on:

- The occupation time from 08:00 until 17:00.
- Outdoor temperature (marked in blue, green and red according to the different temperature ranges in the figures below).
- $HR_{Top\ cavities\ 1\ \&3} <= 4$.

For comparison of the results, the scale used on y-axis was chosen according to the maximum heat recovery result obtained for the top cavity 1 for the WT1.

In Table 11 the maximum values calculated for the heat recovery for all window typologies (WT1 and WT2) for each cavity can be seen.

Figure 43 presents the investigation period of the heat recovery for the top cavity 1 for the WT1 in room 2, performed between the 18th of December 2018 to the 1st of March of 2019, which falls within a different period of the heating season then in our study.

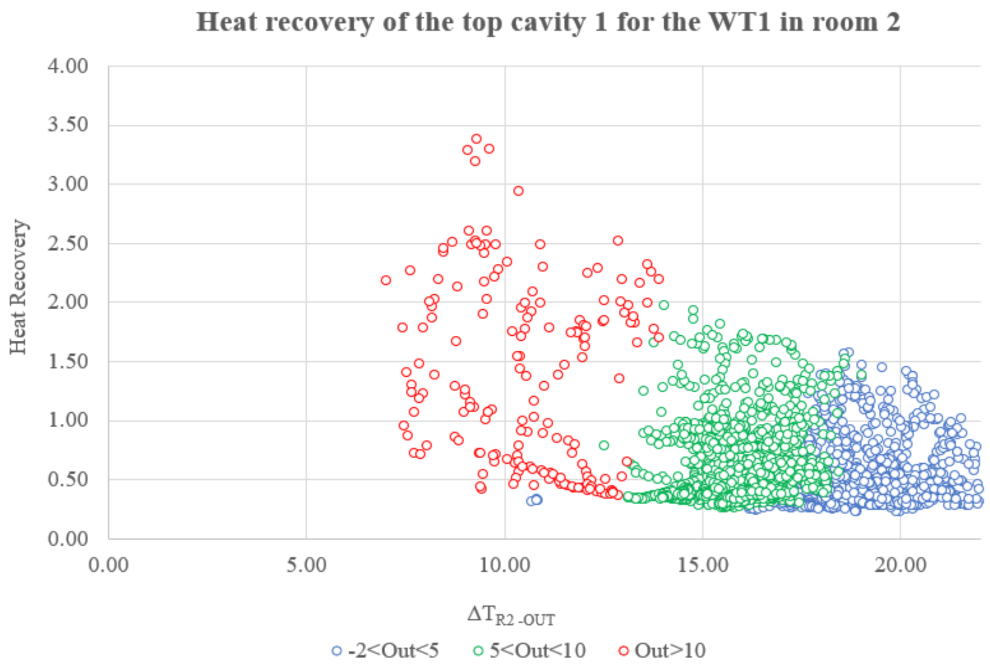


Figure 43 - Heat recovery of the top cavity 1 for the WT1 in room 2 with 10 min averaged data plotted in function of $\Delta T_{R2\text{-}OUT}$ (Bonet Arbos et al.*, 2019)*

As expected, the largest heat recovery occurred when there was the lowest difference between the outside and room temperature, meaning that when the outside temperature was above 10 °C (marked in red) the heat recovery reached the maximum of 3.38.

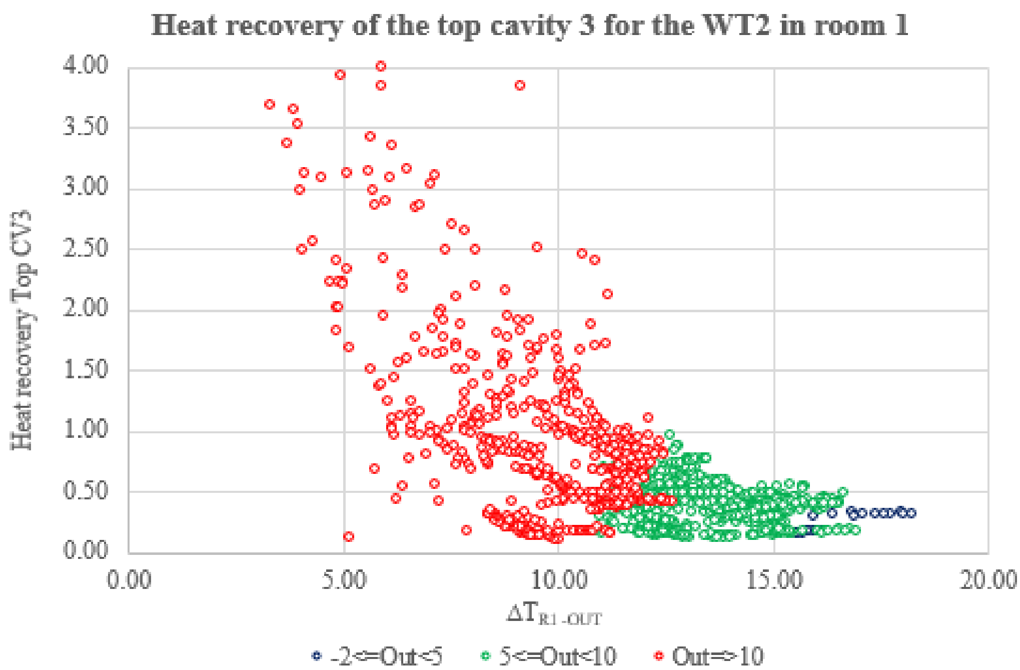


Figure 44 - Heat recovery of the top cavity 3 for the WT2 in room12with 10 min averaged data plotted in function of ΔT_{321OUT} (Bonet Arbos et al.*, 2019)*

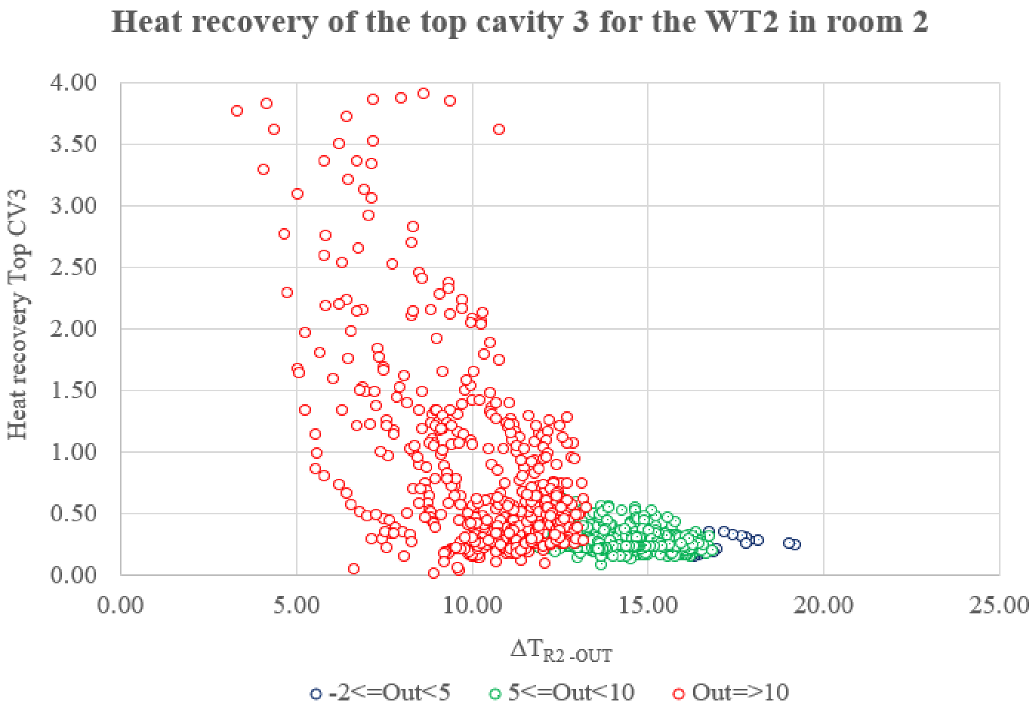


Figure 45 - Heat recovery of the top cavity 3 for the WT2 in room 2 with 10 min averaged data plotted in function of $\Delta T_{R2\text{-}OUT}$

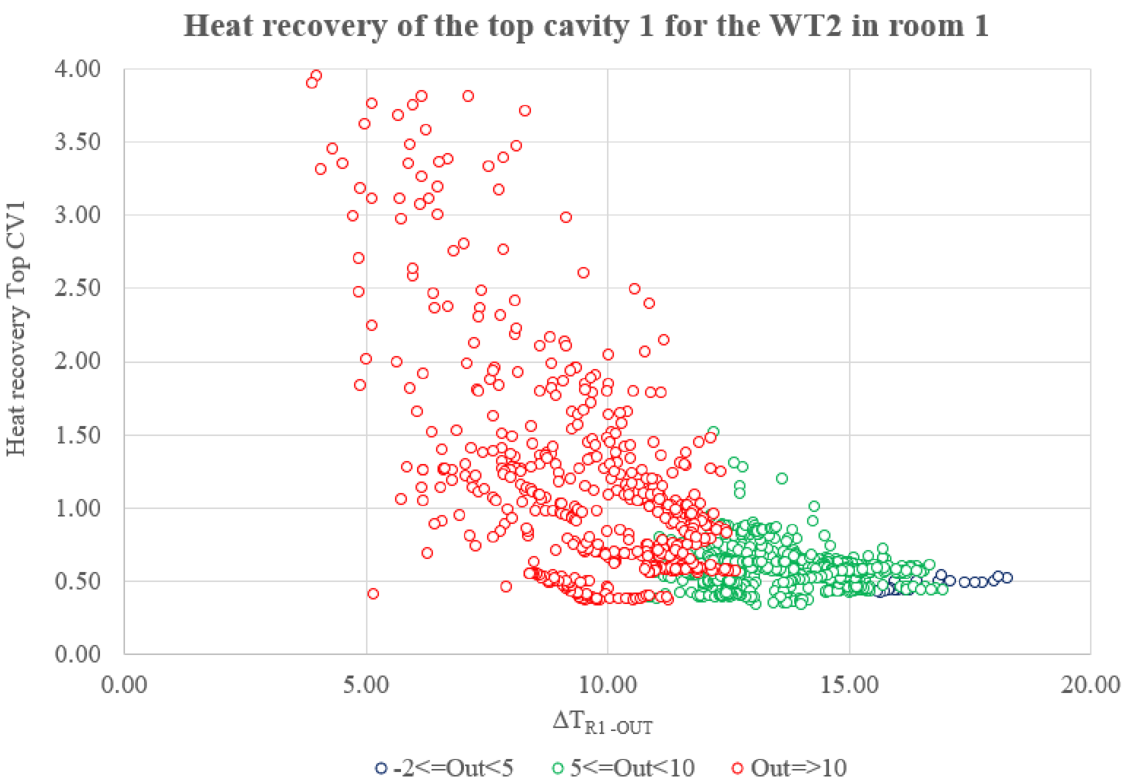


Figure 46 - Heat recovery of the top cavity 1 for the WT2 in room 1 with 10 min averaged data plotted in function of $\Delta T_{R1\text{-}OUT}$

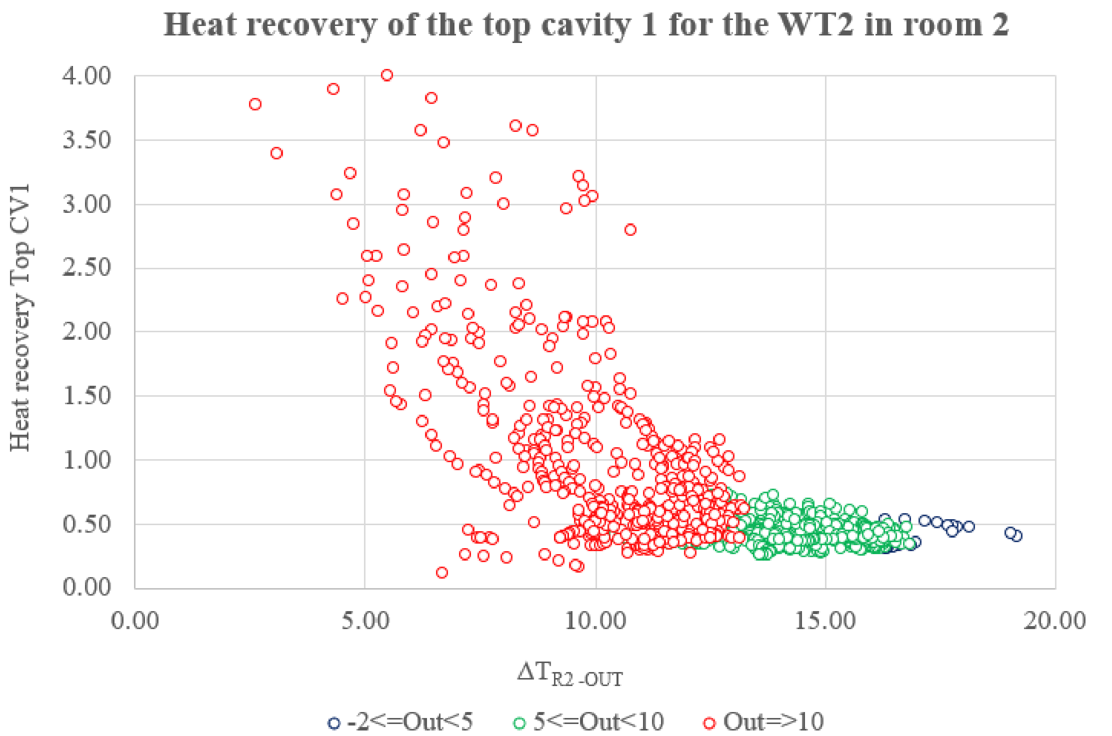


Figure 47 - Heat recovery of the top cavity 1 for the WT2 in room 2 with 10 min averaged data plotted in function of $\Delta T_{R2\text{-}OUT}$

	WT1	WT2	
Heat recovery	Room 2	Room 1	Room 2
Top cavity 1	3.38	241.46	98.16
Top cavity 3		145.91	158.88

Table 11 – Heat recovery calculated for the top cavity 1(P4) in WT1(P8) and top cavities 1&3 for WT2

The highest heat recovery calculated for the investigated period for the WT2 for cavities 1 and 3 was achieved when the outside temperature was very similar to the room temperature in both rooms (as seen marked in red for outside temperatures above 10 °C).

An explanation for this high heat recovery rate could be that the PT100 sensors placed in the window cavities were not effectively shielded from the influence of solar radiation striking the window pane, affecting the measurements of the sensors at the window cavities.

To confirm the impact of the solar radiation in the measurements of the window cavities a pyranometer should be used to record those measurements.

The best way to evaluate the heat recovery for both window types was to plot the heat recovery in function of the outside temperature, as exhibited in Figure 48. A different set of colors was chosen than in the rest of the figures in the chapter to emphasize that the comparison was done between the two windows types.

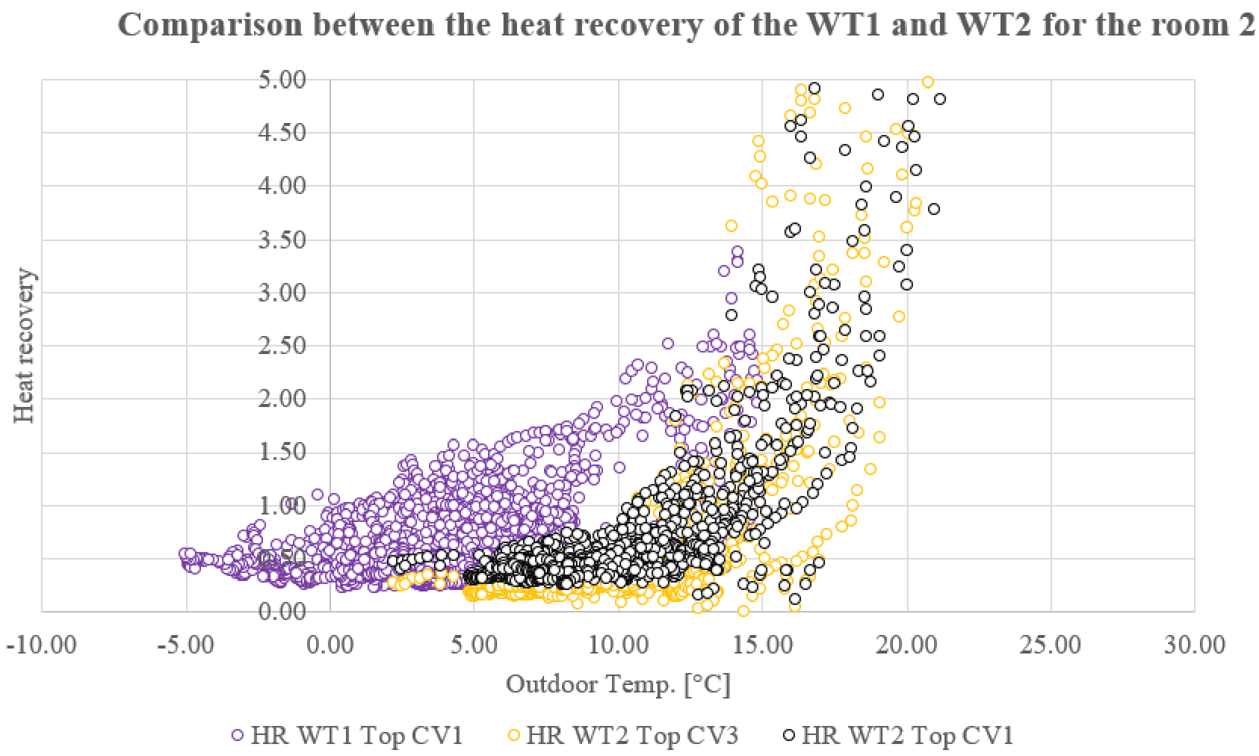


Figure 48 - Comparison between the heat recovery of the top cavity 1 of the WT1 and the top cavities 1&3 of the WT2 for room 2 (Bonet Arbos et al., 2019)

The top cavity 1 for the WT1 exhibits higher heat recovery for lower outside temperatures, as opposed to the top cavities 1 and 3 for the WT2 that has higher values for the higher outdoor temperature. An example of this heat recovery trend can be observed when:

- the outside temperature was 5°C:
  - the top cavity 1 in WT1 is between [0.35 - 1.5]
  - top cavity 3 in WT2 is between [0.15 - 0.29]
  - top cavity 1 in WT2 is between [0.31 - 0.37]

- the outside temperature was 15°C (maximum value registered in the previous study):
  - top cavity 1 in WT1 is between [1.24 - 2.18]
  - top cavity 3 in WT2 is between [0.34 - 4.02]
  - top cavity 1 in WT2 is between [0.38 - 3.08]

The explanation behind the difference of heat recovery observed between the two ventilated window types can reside on the higher flow rate observed in the WT2.

With higher flow rates the outside air supplied to air cavities would have less time for the air molecules to be heated up by the internal heat losses from the room towards the air cavity and the influence of the sun radiation hitting the window pane.

5 Sensors investigation

In order to investigate how well the chosen sensors for the window control are showing the indoor environment it is important to fully understand how the sensors work. By getting an understanding of the fundamental workings of the sensor, one can have a better understanding of what can affect the measurements of the sensor. Therefore, in this part of the report the BME680 sensor which is used to describe the indoor environment in the school is investigated. Also, since the VOC and how they are measured is not common knowledge this will also be shortly described in this part of the report.

5.1 Volatile Organic Compounds (VOC)

In this chapter the VOC sensors for the ventilated window will be investigated and questions such as: What are organic compounds? How do they affect human health? How do they occur? And should they be used in the ventilated window to achieve demand-controlled ventilation? In short, this chapter will investigate if the VOC sensors should be used in the ventilated window or if another solution such as using CO_2 sensors should be implemented. This is to achieve the necessary understanding when investigating the use of VOC sensors for the control of the ventilated windows.

5.1.1 What are Volatile Organic compounds and where do they come from?

A volatile organic compound is a carbon-based molecule that will evaporate at living room temperature. A more specific description from the European Union directive 2004/42/CE is "any organic compound having an initial boiling point less than or equal to 250°C measured at a standard pressure of 101,3 kPa" and “Organic compound means any compound containing at least the element carbon and one or more of hydrogen, oxygen, sulphur, phosphorus, silicon, nitrogen, or a halogen, with the exception of carbon oxides and inorganic carbonates and bicarbonates.”

This means that are thousands of compounds that fall under this description that can come from many different sources such as:

- People’s breath and odors
- Building materials
- New furniture and carpets
- Copy machines and printers
- Cleaning detergents and disinfectants
- Paints
- Smoke from cigarettes and fires
- Car exhausts

Source:(*Volatile Organic Compounds (VOCs): Your Environment, Your Health | National Library of Medicine*, 2019)

This list only contains a few of the sources of VOC that can occur in buildings and outside. Some of the VOC are known to cause both long- and short-term health issues for people and cause other serious issues such as infertility (*What is VOC Meter?*, 2019)

In BR18*(Bygningsreglementet.dk, 2020)* the focus of VOC’s is on the emissions from building materials, especially formaldehyde, which has been proven to be harmful to people. This means there are not any regulations that state the maximum concentration in a building but only maximum emissions from materials in the building. There are guidelines instead that suggests maximum concentrations in buildings. BR18 refers to EU-LCI which is the European lists of the maximum accepted concentrations of different VOC's indoors. The list contains, in July 2018, over 100 VOC's but is continuously updated with new compound concentrations (*uRADMonitor » Metal Oxide VOC Sensors*, 2019).

5.1.2 How does a VOC sensor work?

In order to investigate if the BME680 sensors are functioning properly it is necessary to have a fundamental understanding of how the sensor works and what can affect the measurements. Therefore, a general description of the sensor's functions, and their affecting parameters will be made in this part of the report.

A VOC sensor is a gas sensor, which can be calibrated to a specific gas and other gasses similar to the target calibration gas.

There are several different types of VOC sensors, but for this report the focus will be on the type that is used in the school to better evaluate its performance by having a general idea of its function. This type is called a Metal Oxide (MOx) sensor. The MOx's electrical resistance is affected by the presence of different gases.

The way a MOx sensor is sensing the air pollution is by having a metal oxide layer on top of a heating plate, with an electrical circuit. The heating plate heats normally between 200 – 400° causing the surrounding gas to ionize and this affects the electrical resistance of the metal oxide layer which can be measured. The metal oxide is a pourous material that has a lot of small tunnels that the VOC gasses can enter, become ionized by the heat and then affect the thermal resistance. This means that the more VOC's there are in the air the lower the electrical resistance will be, and the less VOC's the higher the resistance will be (*uRADMonitor » Metal Oxide VOC Sensors*, 2019).This means there is an inverse correlation between the air pollution and the resistance of the MOx layer.

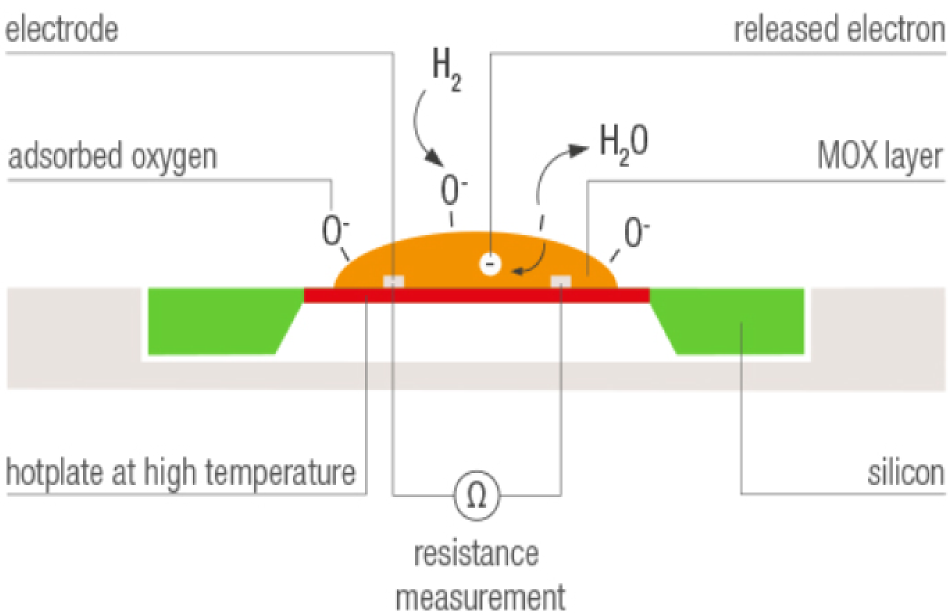


Figure 49 - MOx sensor function and parts (Multi-Pixel Gas Sensors SGP | Sensirion, 2019)

On Figure 49 a typical MOx sensor's parts can be seen. In the figure, dihydrogen is shown as an example of the gas that can be measured. The VOC sensor could be described as an "active" sensor in that its need to act before it can sense the VOC. This is more complex than the typical sensor like a resistance thermal detector (RTD) which is only needs to be placed in an environment to start sensing the influence of the environment.

5.1.3 Parameters affecting the VOC measurement

In order to understand what can affect the reading from the VOC sensor the datasheet of the BME680 *(https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors-bme680/, 2019)* has been studied in depth, to find explanations of the behavior of the measurements. Further investigations of reports about sensitivity and influencing parameters of the MOx sensors have also been made.

Looking in mentioned data the following influencing parameters were found:

- Relative humidity level/ Long term moisture exposure (*Metal Oxide Gas Sensors: Sensitivity and Influencing Factors*, 2019)
- Operating temperature of the heating plate. (*Metal Oxide Gas Sensors: Sensitivity and Influencing Factors*, 2019)
- Conversion, compensation and calibration algorithms. BME680 datasheet *(https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors-bme680/, 2019)*

Relative humidity and long-term moisture exposure

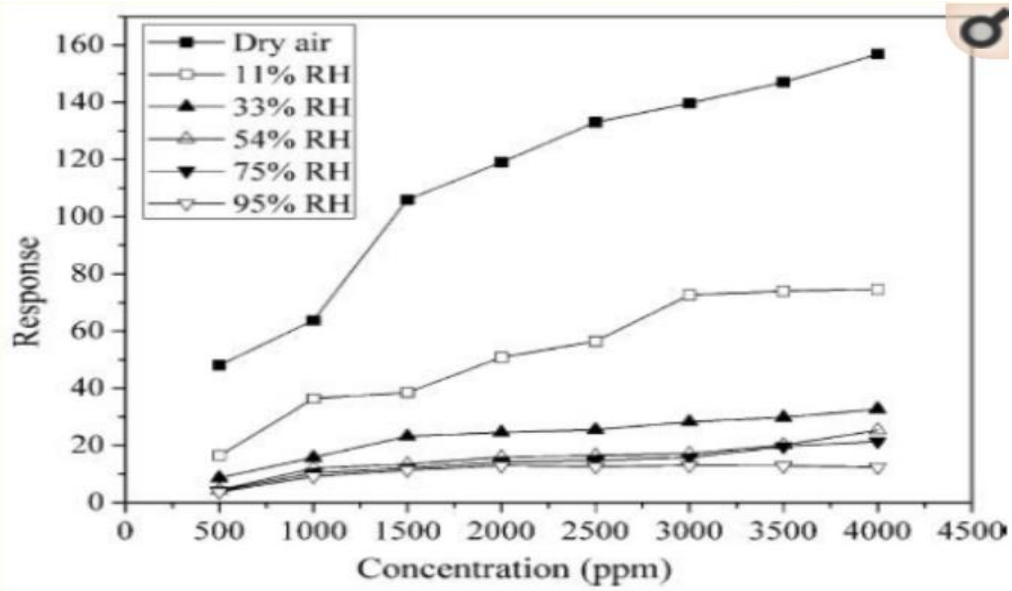


Figure 50 - Example of the influence of RH on the VOC measurement of MOx sensor (Metal Oxide Gas Sensors: Sensitivity and Influencing Factors, 2019)

On Figure 50 the influence of the relative humidity on the VOC measurement can be seen. The higher the humidity level the less sensitive the sensor becomes giving lower gas level results than reality. This is because the water molecules react with the metal oxide and sticks to the surface stopping the gases from affecting the sensor.

This can affect the measurements as seen on the figure but over long term this can accumulate over time. Assuming that the sensor, when becoming less sensitive, senses less VOC gases showing lower concentrations, it will look like the gas concentration is lower and lower over time. This can according to (*Metal Oxide Gas Sensors: Sensitivity and Influencing Factors*, 2019) be fixed by heating the heat plate to temperatures above 400°C which will remove the water molecules resetting the sensor to normal function.

BME680 datasheet

According to the datasheet for the sensor it is necessary to configure the sensor before using it. This includes things such as:

- Conversion algorithms that convert from the measured values e.g. resistance to the wanted readout value e.g. gas concentration.
- Compensation algorithms that compensate for the influence, of e.g. humidity, operative temperature and operation temperature of the hot plate, on the measurements.
- Calibration algorithms that calibrate the individual sensors to remove any bias or other errors between the different sensors.
- Choice of measurements, the sensor can measure pressure, temperature, RH and VOC but it can be configured so that some of them should be skipped.

If these are not working properly it can affect the measurements, so that the measurements are unusable to measure the indoor environment.

By investigating the BME680 datasheet it was found that the standard measuring temperature that does not require compensation is 25°C. This means if the temperature is 25°C then the BME680 sensor shows the correct values for relative humidity, pressure, temperature and VOC, without the need for compensation.

From the investigation of the sensors from the previous investigation it was noticed that there were some errors in the measurements. These could be explained by the fact that there could be some issues with the configuration of the sensors.

An example of the fact that there are some issues with configuration of the sensors can be seen by studying Figure 51. This is a test from the previous investigation*(Bonet Arbos et al., 2019)* where the BME680 sensors were compared to a reference pressure sensor, and it was noticed that there was a correlation with the temperature. When the temperature is close to 25°C the pressure is close to the reference, but as the temperature increases the pressure measurement is reduced in an inversed manor that indicates issues with the configuration of the compensation algorithms.

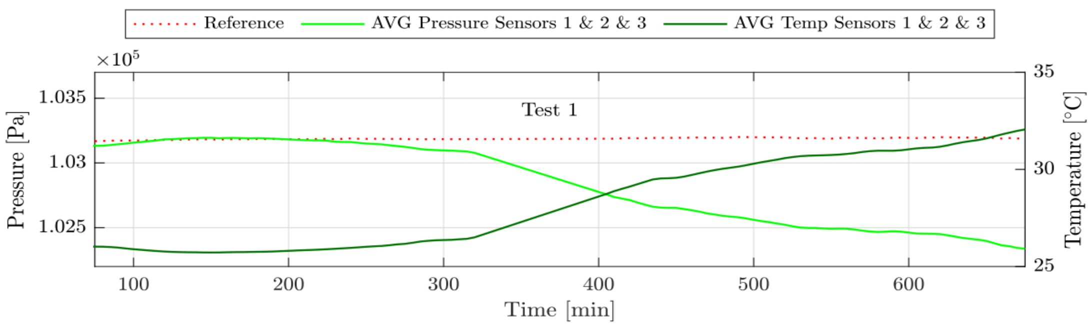


Figure 51 - Pressure measurement calibration test from previous investigation were the BME680 is mentioned as AVG sensor (Bonet Arbos et al., 2019)

5.2 VOC sensor investigation

The behavior of the sensors used for the automation of the control strategy applied in WT2 was tested and the results were compared to the results of the study by Bonet Arbos et al *(Bonet Arbos et al., 2019),* from here on in this chapter referred to as the comparative study.

As previously explained in the control strategy chapter, the sensor Bosch BME6980 is a 4-in-1 integrated sensor that measures different indoor climate parameters such as temperature, relative humidity, volatile organic compounds (VOC) and pressure.

The sensor behavior was analyzed, and the accuracy was compared to a reference sensor (IC meters), that would guarantee a reliable output result. A more detailed explanation of this will be presented later in the chapter.

The atmospheric comfort is based on the CO_2 concentration level present in a room. Due to the sensors used in the automation of the control strategy do not measure CO_2 concentration directly, an investigation of the possible correlation between the VOC readings from the Bosch BME680 sensor and the CO_2 readings from the IC meters was performed.

5.3 Sensor behavior analysis

Why is it important to test sensors?

The main purpose of testing the sensors was to confirm that it can measure a physical quantity properly. The output of the sensor response was compared to the reference sensor, that is considered to present with the “true” value of the measurand.

As stated in the report *Testing sensors for building applications* by Hicham Johra *(Hicham Johra, 2019),* the sensor behavior can be classified as:

- **Well-behaved sensors**: Good sensors which can be trusted and be used as is.
- **Poorly-behaved sensors needing correction**: They cannot be trusted or used as is, but can be useful with some correction such as recalibration, data treatment, signal filtering, etc.
- **Defective sensors**: They cannot be used because they present a major flaw which cannot be corrected by recalibration, data treatment or signal filtering of their output signal. They need to be fixed or replaced.

A well-behaved sensor example is represented by Figure 52 and Figure 53. In Figure 52 both the tested sensor (measurement) and reference sensor (measurand) follows the same pattern (“mimic each other”), indicating that the tested sensor is reliable.

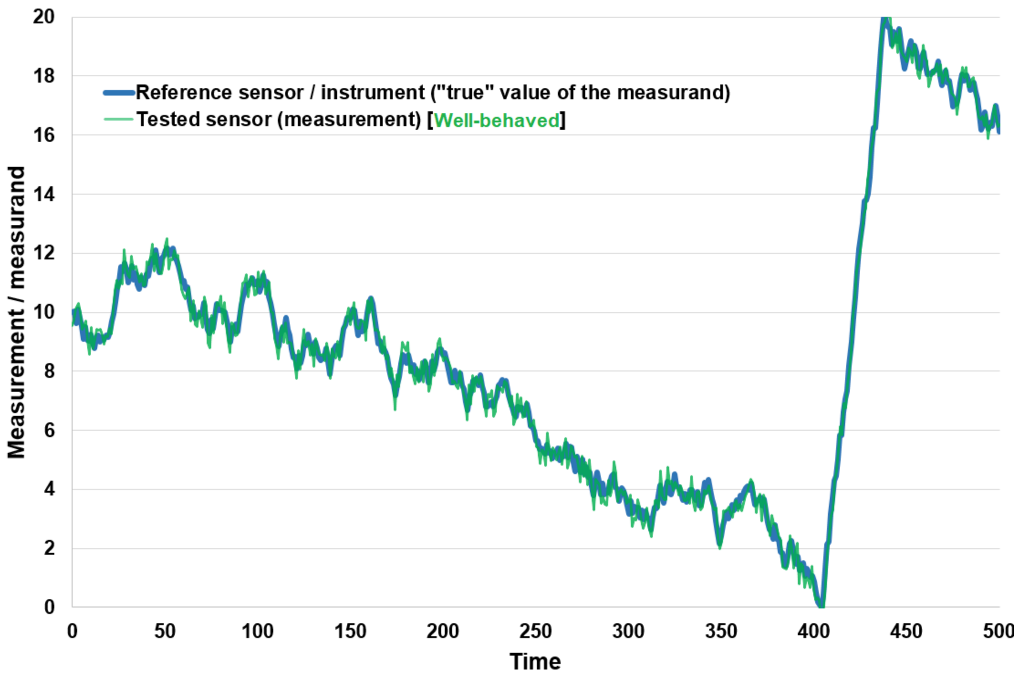


Figure 52 - Comparison between a very well-behaved sensor and a reference sensor / instrument which represents the true value of the measurand.(Hicham Johra, 2019)

Figure 53 presents a different kind of graph (reference vs. sensor). On the y-axis the values registered by the reference sensor/instrument are plotted, and on the x-axis the values registered by the tested sensor's output. All the data points are concentrated around the "Y=X" line drawn in the graph, indicating a very close relationship between the reference sensor/instrument and the tested sensor. I.e. this sensor can be trusted and used without recalibration or correction of its output response/signal.

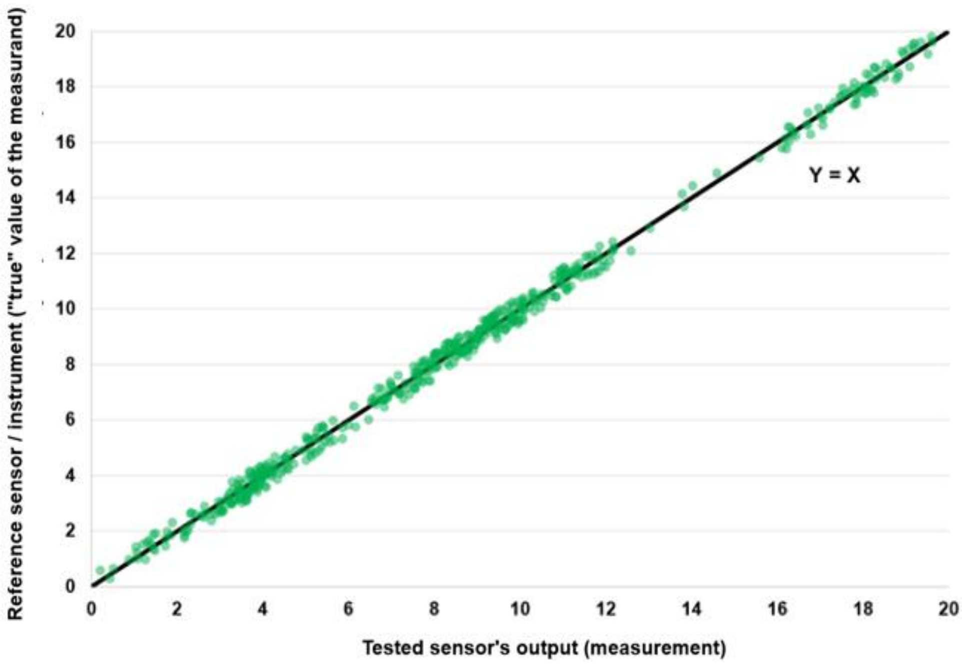


Figure 53 - Example of a very well-behaved sensor which can be used as is without any recalibration or correction.(Hicham Johra, 2019)

Figure 54 illustrates a sensor that requires recalibration.

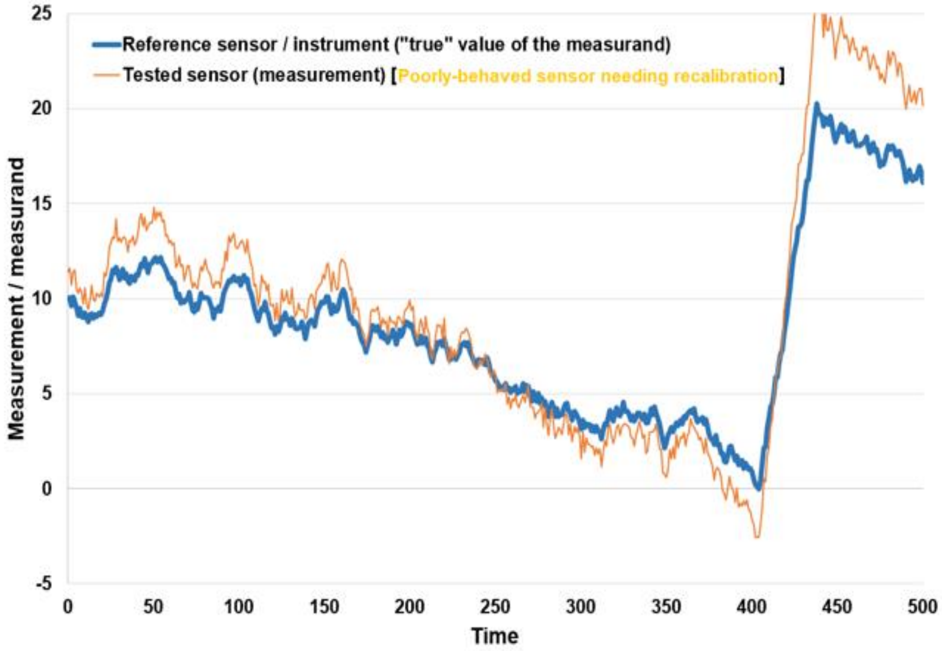


Figure 54 - Comparison between a poorly-behaved sensor needing correction (here recalibration) and a reference sensor / instrument which represents the true value of the measurand.(Hicham Johra, 2019)

Recalibration is needed because the tested sensor's output (measurement) does not "mimic" the reference sensor (true value of the measured). Figure 55 presents the divergence between the tested sensor and the true value of the measurand. The data points are not concentrated around the Y=X line anymore, but instead follow along the dashed green line, which is represented by the monotonic function Y = 1.4019X – 2.5052. The output of the tested sensor can be corrected with recourse of a calibration function:

- Calibrated output = (uncalibrated output + 2.5052)/1.4019 (*)

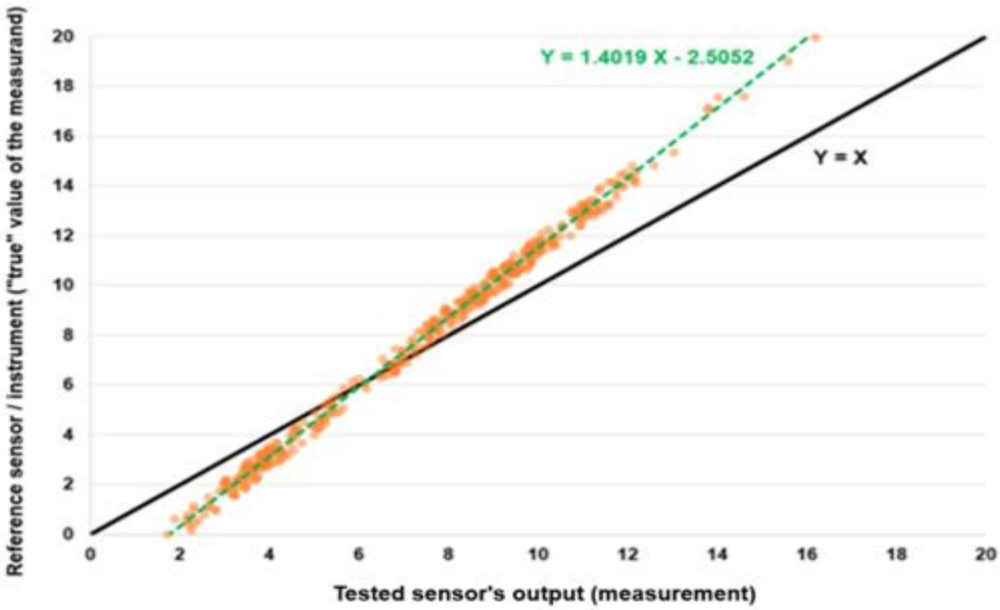


Figure 55 - Example of a poorly-behaved sensor needing correction (here recalibration.(Hicham Johra, 2019)

Figure 56 and Figure 57 exemplify that with the correction of the sensor´s output with the calibration function (*) the enhancement of the accuracy of the tested sensor is achieved.

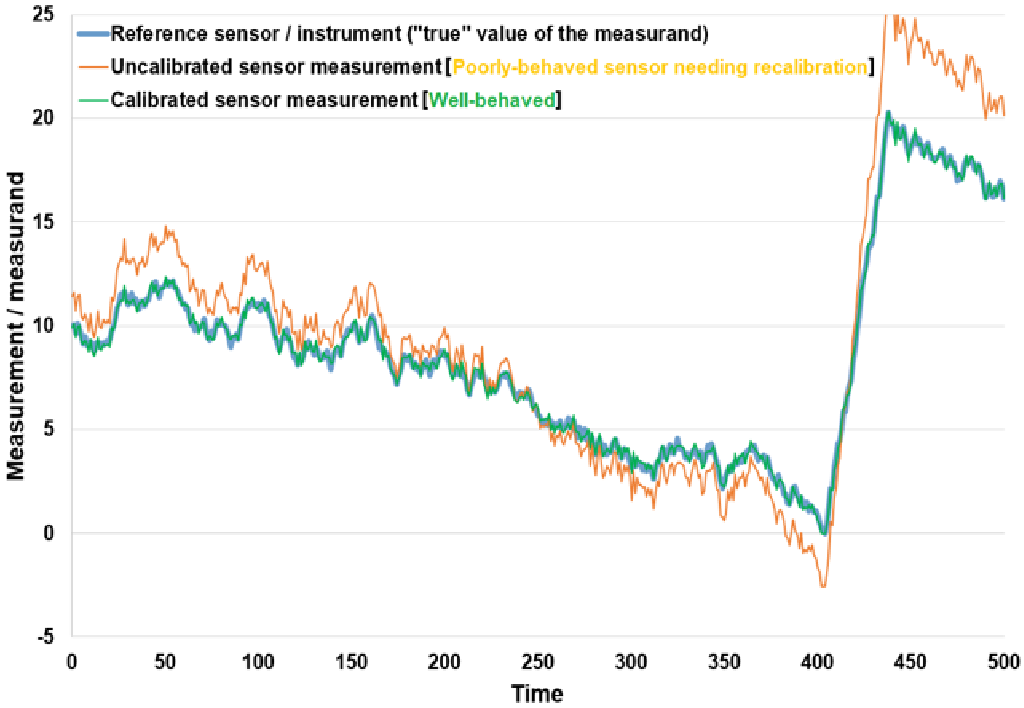


Figure 56 - Comparison between an uncalibrated sensor , a calibrated sensor and a reference sensor / instrument which represents the true value of the measurand.(Hicham Johra, 2019)

When applying the calibration function to the sensor´s output, the output signal becomes very similar to the reference sensor, as can be seen in the figure below.

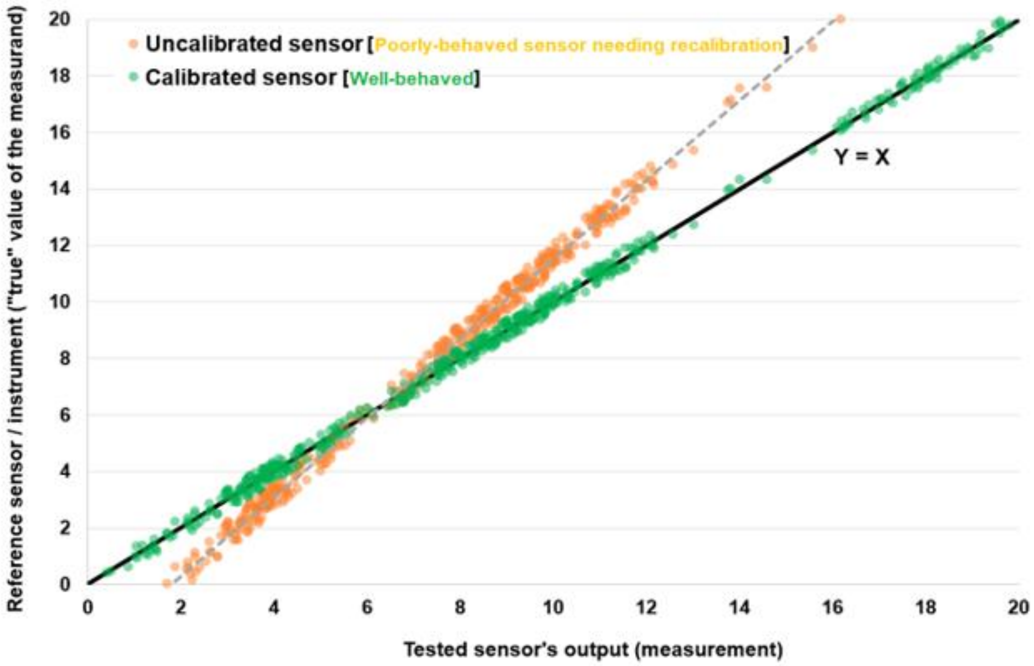


Figure 57 - Comparison between an uncalibrated sensor and a calibrated sensor(Hicham Johra, 2019)

5.4 Experiment performed in the previous research

In the research paper by Bonet Arbos et al, the authors performed five tests to evaluate temperature, relative humidity, pressure and CO_2, (Figure 58). The study also included a correlation analysis of the VOC readings and the CO_2 concentration.

The following quote describes the five tests performed: *"The Test 1 has been performed with the intention of testing temperature, relative humidity and pressure. The environment has been triggered to change with the radiator located in the room. Test 2 has been placed outside. During Test 3, Test 4, Test 5 the variable occupancy load has been applied. To check the influence of the Climawintech box where Bosch sensor is located, the case has been removed during the test 4 and test 5".(Bonet Arbos et al., 2019)*

	Test 1.	Test 2	Test 3	Test 4	Test 5
Date	18 April	25 April	25 April	14 May	16 May
Conditions	Radiator ON	Outdoor	Indoor	Indoor	Indoor
Focus	Temp RH P	Temp RH CO_2	Occ - CO_2	Occ - CO_2	Occ - CO_2

Figure 58 - Tests performed by the previous research paper.((Bonet Arbos et al., 2019)

All the parameters were tested in the laboratory room, except for the CO_2 analysis that was performed in a smaller room, varying the occupancy during the time of the investigation. Three Bosch BME680 sensors (named S1, S2 and S4) and four IC meters acting as reference sensor were used, as presented in Figure 59.

Figure 59 - Setup used for the sensors test.((Bonet Arbos et al., 2019)

PT100 sensors were also used inside the climawintech cases to assess if the air inside the case is preheated and evaluate the impact on temperature readings.

The Bosch BME680 sensors when measuring the VOC needs to be heated up until temperatures between 200 – 400 °C, which can affect the temperature readings *(https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors-bme680/, 2019)*

Figure 60 demonstrates the duration of the tests. All the data collected was averaged for periods of 5 minutes.

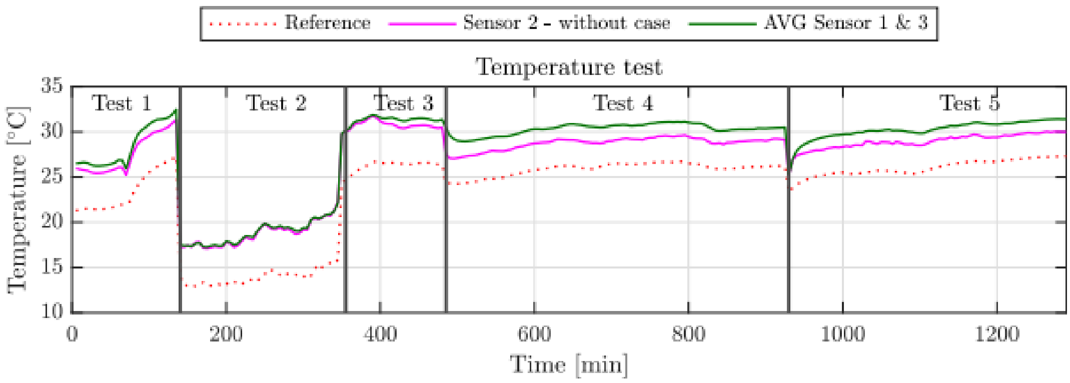


Figure 60 - Duration of the tests performed by the previous research paper.(Bonet Arbos et al., 2019)

5.5 The VOC experiment description

The experiment took place in a working room (room 1.312) on Thomas Manns vej 23 at Aalborg University, during the following days: 24th, 25th, 28th, 29th and 30th of October 2019. The following equipment was used: three Bosch BME680 sensors (named S1, S2 and S4) and two IC meters located in the middle of the room as well as two meters from the window, as illustrated in Figure 61.

Figure 61 - Experiment setup (IC meters – white devices and Bosch BME680 sensors – black devices)

The sensors named S1 and S4 were integrated in a case named climawintech and the sensor S2 was not encased. The ventilation diffusers were sealed to guarantee that the air supplied and extracted to the room wouldn't disturb the IC meter readings of CO_2. During the time of the experiment all the users of the meeting room registered their entry and exit of the room, and every time a door or window was opened was also registered. The occupation time schedule was between 07:00 AM until 17:30 PM. Knowing the occupation schedule of the room, as well as the number of times that the door and/or window was open, it was possible to investigate and achieve certain conclusions about the sensor behavior for the temperature, relative humidity and the study of the correlation between the VOC readings and the occupation.

In the following sections the results of our investigation will be compared with the results of the previous research.

5.5.1 Temperature behavior test

All the data registered by the two IC meters and the three different Bosch BME680 sensors were filtered according to the occupation time in the working room and plotted in the Figure 62, Figure 63, Figure 64 and Figure 65. The values used as the reference sensor were based on the average values collected by the two used IC-meters. The average was used because the measured values from the two IC-meters were very similar. The red line in all figures indicates the ideal linearity between the reference sensor and the tested sensor.

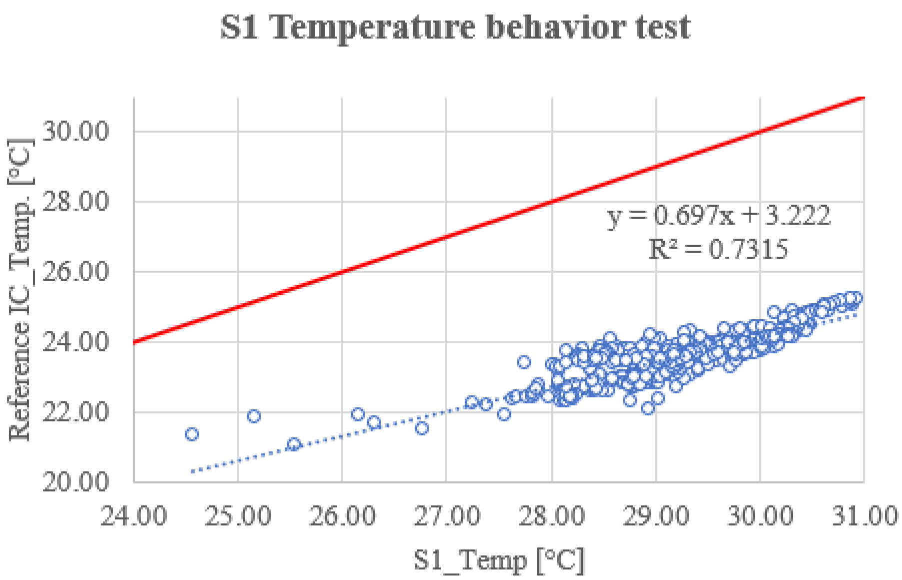


Figure 62 - S1 Temperature behavior test

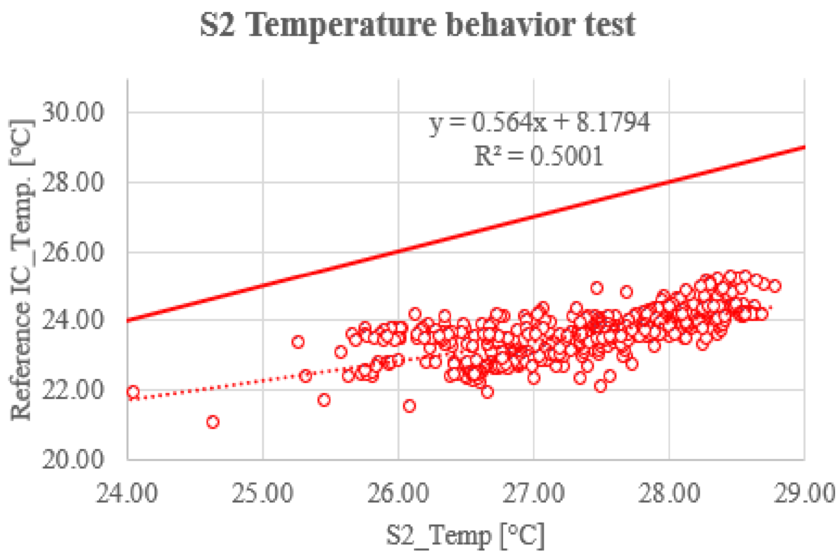


Figure 63 - S2 Temperature behavior test

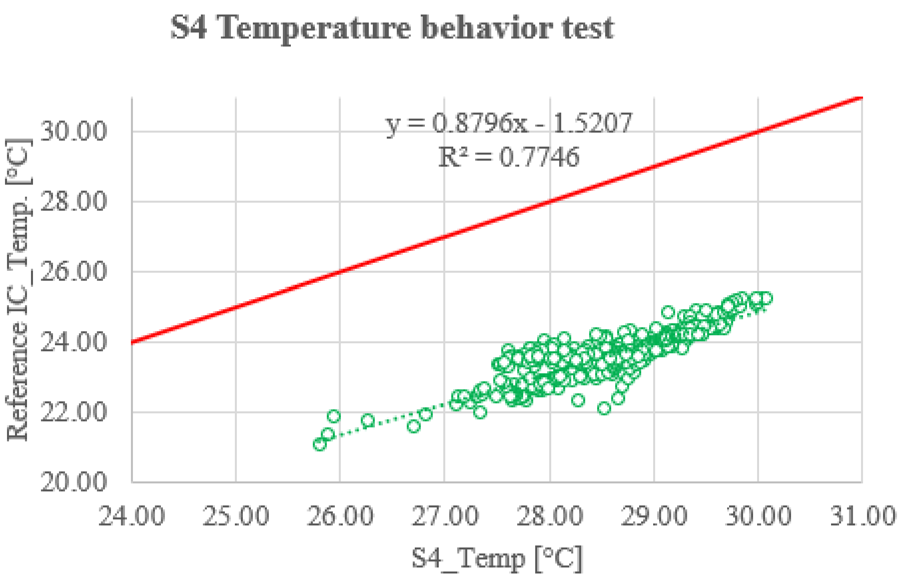


Figure 64 - S4 Temperature behavior test

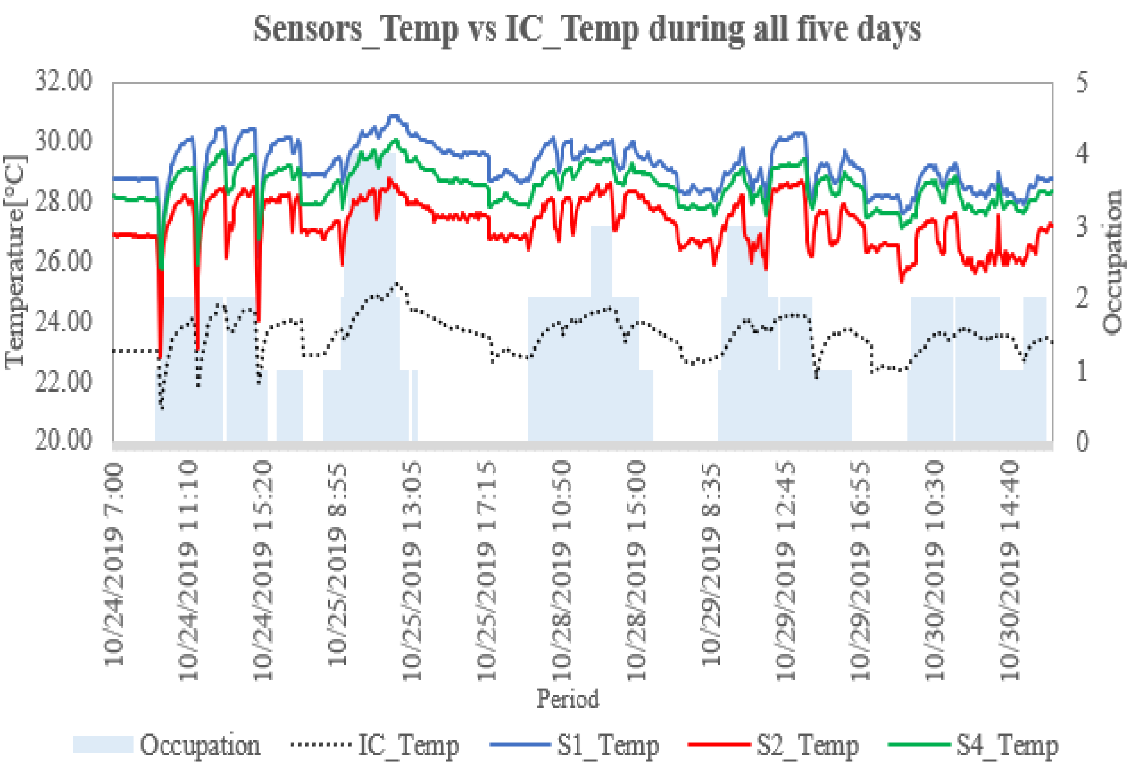


Figure 65 - Sensors (S1,S2 and S4) vs reference sensor (IC meters) measuring the temperature in the meeting room during all five days

All sensors showed a poor behavior, i.e. showing a need for recalibration, due to the data points not falling in the red line (ideal linearity). When using the calibration function applied to the sensor´s output the ideal linearity between the reference and tested sensor can be achieved. The coefficient of determination, denoted R^2, quantifies the degree of linear correlation between the reference sensor and the tested sensor. The R^2 range is between 0 and 1, being 1 and indication of the regression prediction perfectly fit the data*(Coefficient of determination - Wikipedia, 2019)*. S2 was the sensor with worst behavior, since the R^2 was equal to 0,5001.

Figure 66 presents the results of the behavior of sensors as presented in the comparative study.

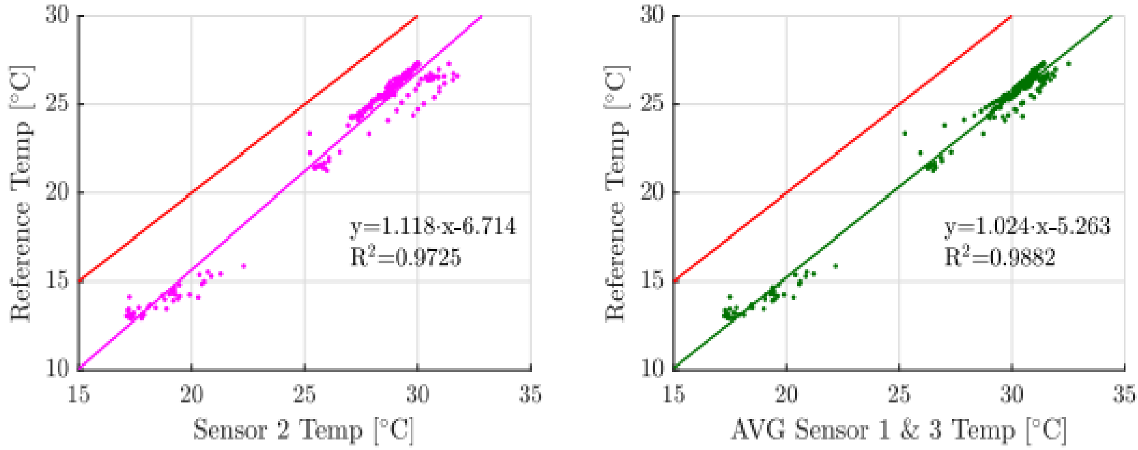


Figure 66 - Temperature behavior test done by the previous research paper(Bonet Arbos et al., 2019)

The temperature behavior test done by Bonet Arbos et al showed similar results but presented higher R^2 which can be explained by the lower sampling period of three hours compared to a week in our investigation.

5.5.2 Relative humidity behavior test

The same analogy was applied to analyze the tested sensors' output related with the readings of relative humidity as a function of the reference sensor (the average value of the readings of the two IC meters were used).

Figure 67, Figure 68 and Figure 69 have shown poorly behaved sensors, needing recalibration due to the data points not falling in the red line (ideal linearity). However, the readings of the relative humidity presented higher degree of linear correlation between the reference sensor and the tested sensor when compared to the temperature readings, reaching values near to 1.

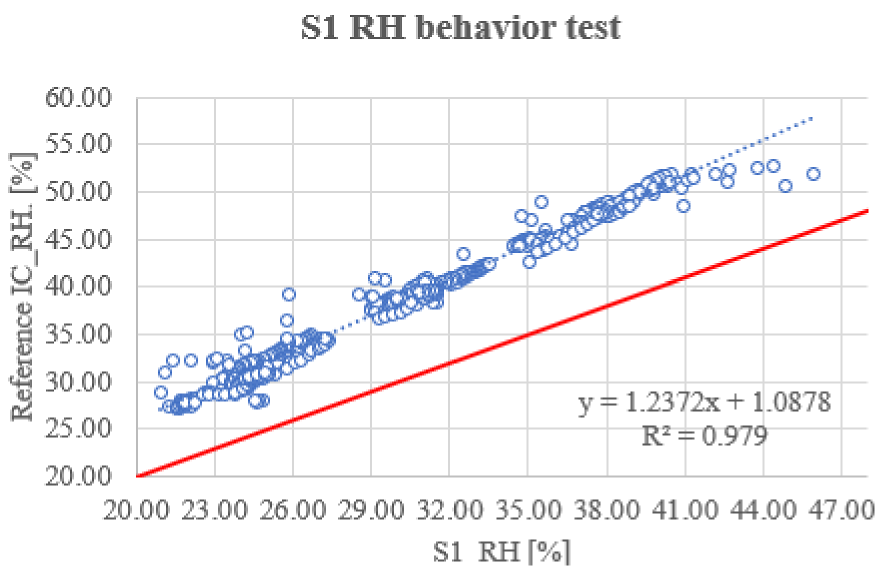


Figure 67 - S1 RH behavior test

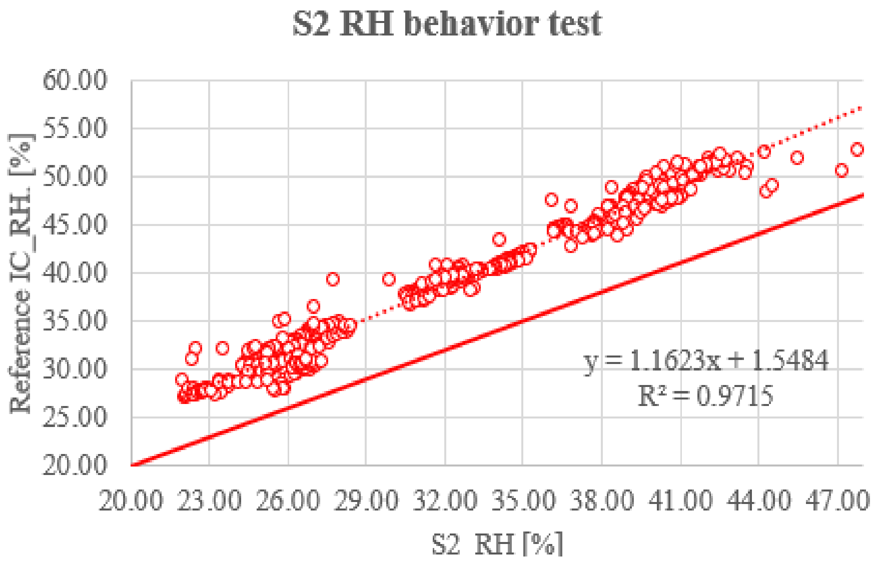


Figure 68 - S2 RH behavior test

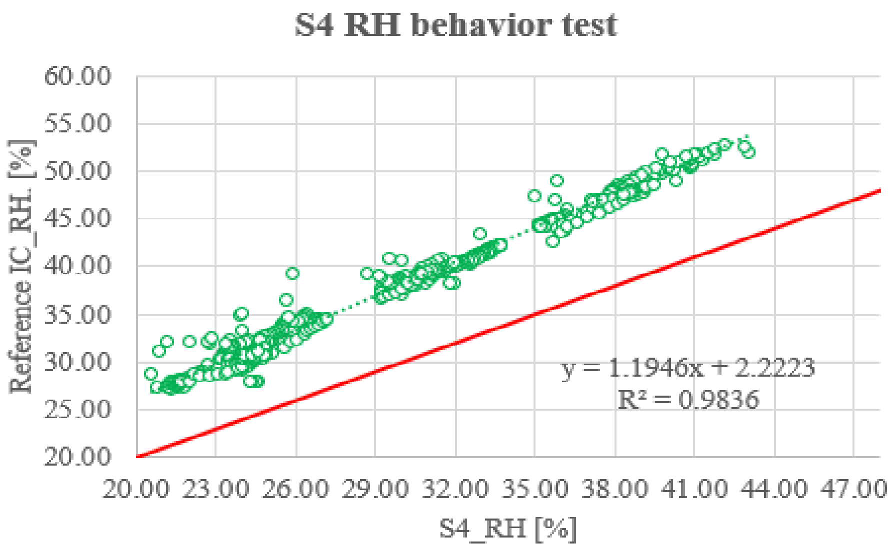


Figure 69 - S4 RH behavior test

In Figure 70 the relative humidity measured by all the tested sensors (S1. S2, and S4) is described, and the reference sensor based on the occupation of the meeting room during the all time of the experiment.

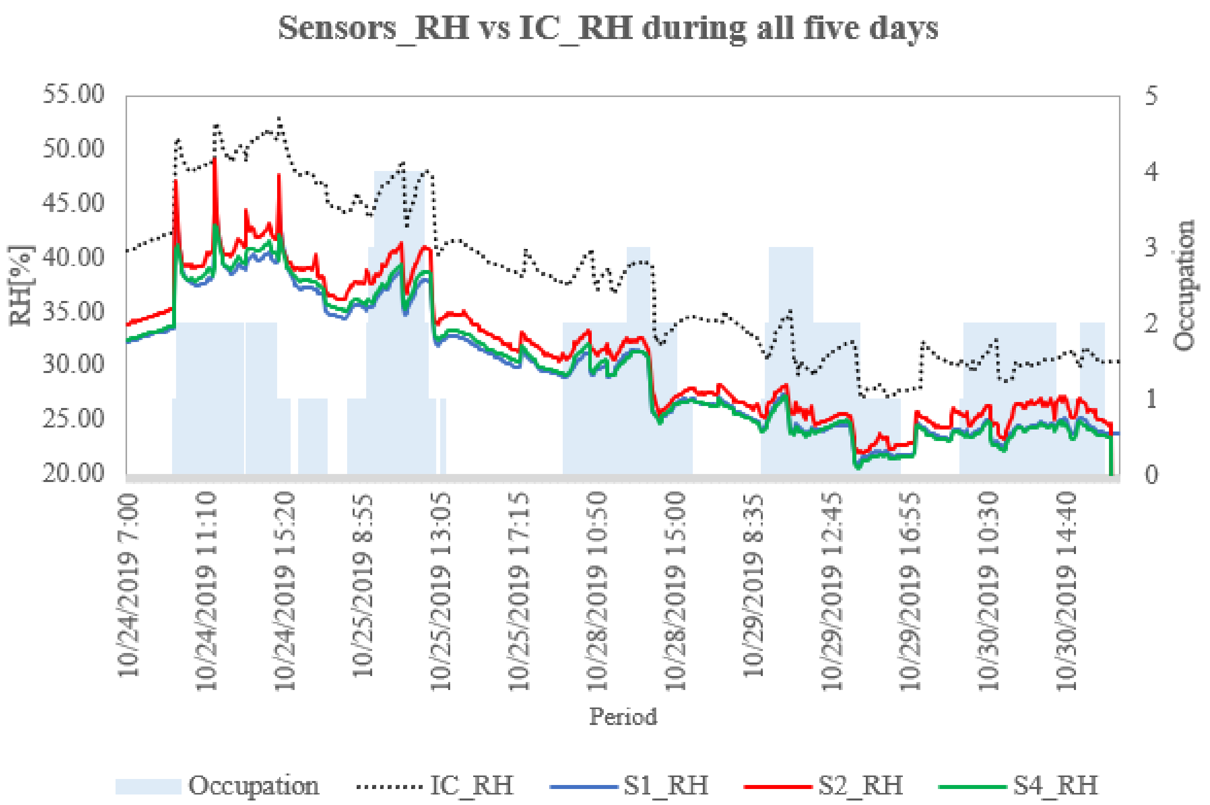


Figure 70 - Sensors (S1,S2 and S4) vs reference sensor (IC meters) measuring the RH in the meeting room during all five days

Figure 71 illustrates that the results of the relative humidity test in our study reach the same conclusion as the results in the comparative study.

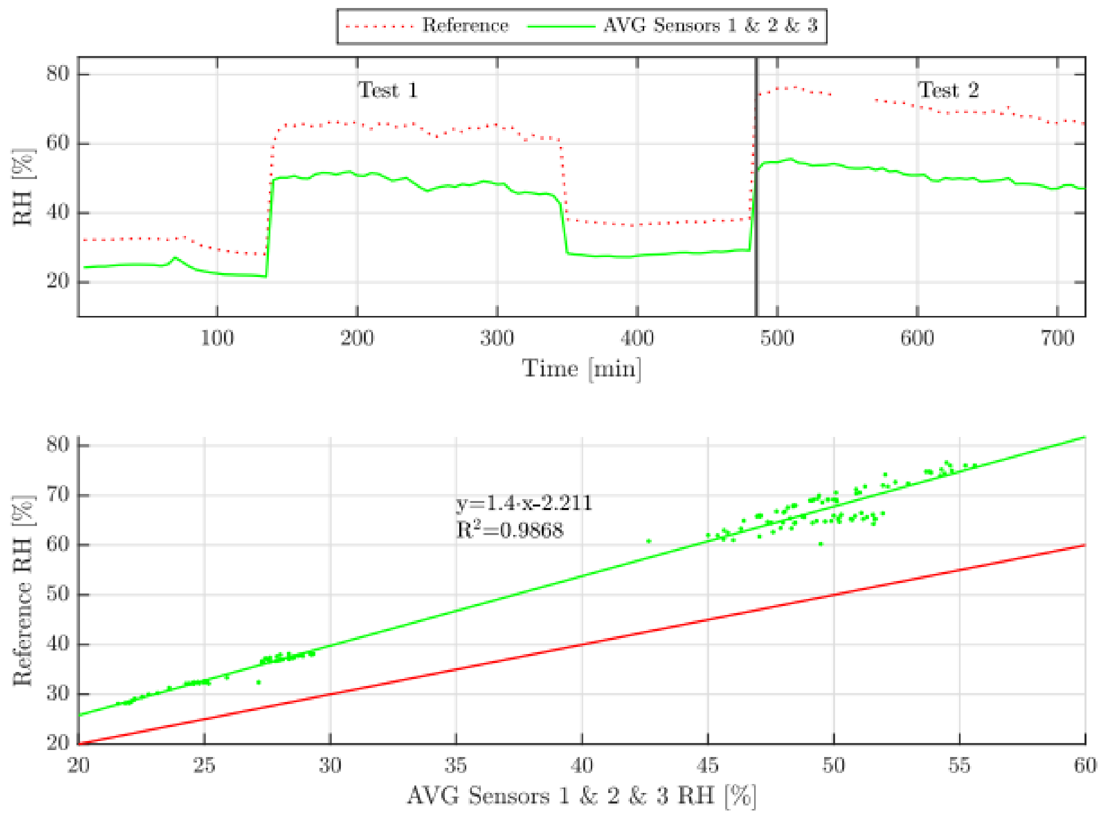


Figure 71 - Results of the relative humidity behavior test (Bonet Arbos et al., 2019)

5.6 Investigation of the correlation between VOC readings, CO_2 and occupation

In the control strategy of the WT2 chapter 2.4 it was explained that the first parameter examined is based on the CO_2 concentration (ppm) present in the room. The Bosch BME680 does not read this parameter directly, but instead reads the inverse of the VOC signal present in the room, measured in ohms (resistance). From here on in this chapter, wherever VOC readings are mentioned, it must be understood as the inverse of the VOC signal reading values.

The data collected during the five days of the experiment to study the sensor behavior was also used to investigate a possible correlation between the VOC, temperature, relative humidity, CO_2 and occupation of the meeting room. Figure 72 presents the VOC and CO_2 trend for all the days of the experiment, and the values of VOC are progressive increasing. As explained in the Bosh BME680 chapter 5.1.3, the moisture has a large influence in this results. The sensor S2 is the sensor that didn't have the case and the results of the VOC were less affected. The climawintech case used in the sensors S1 and S4 are made of plastic and due to the heating plate reaching temperatures between 200-400 °C the gas released could be encapsulated by the case, affecting the readings *(https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors-bme680/, 2019).*

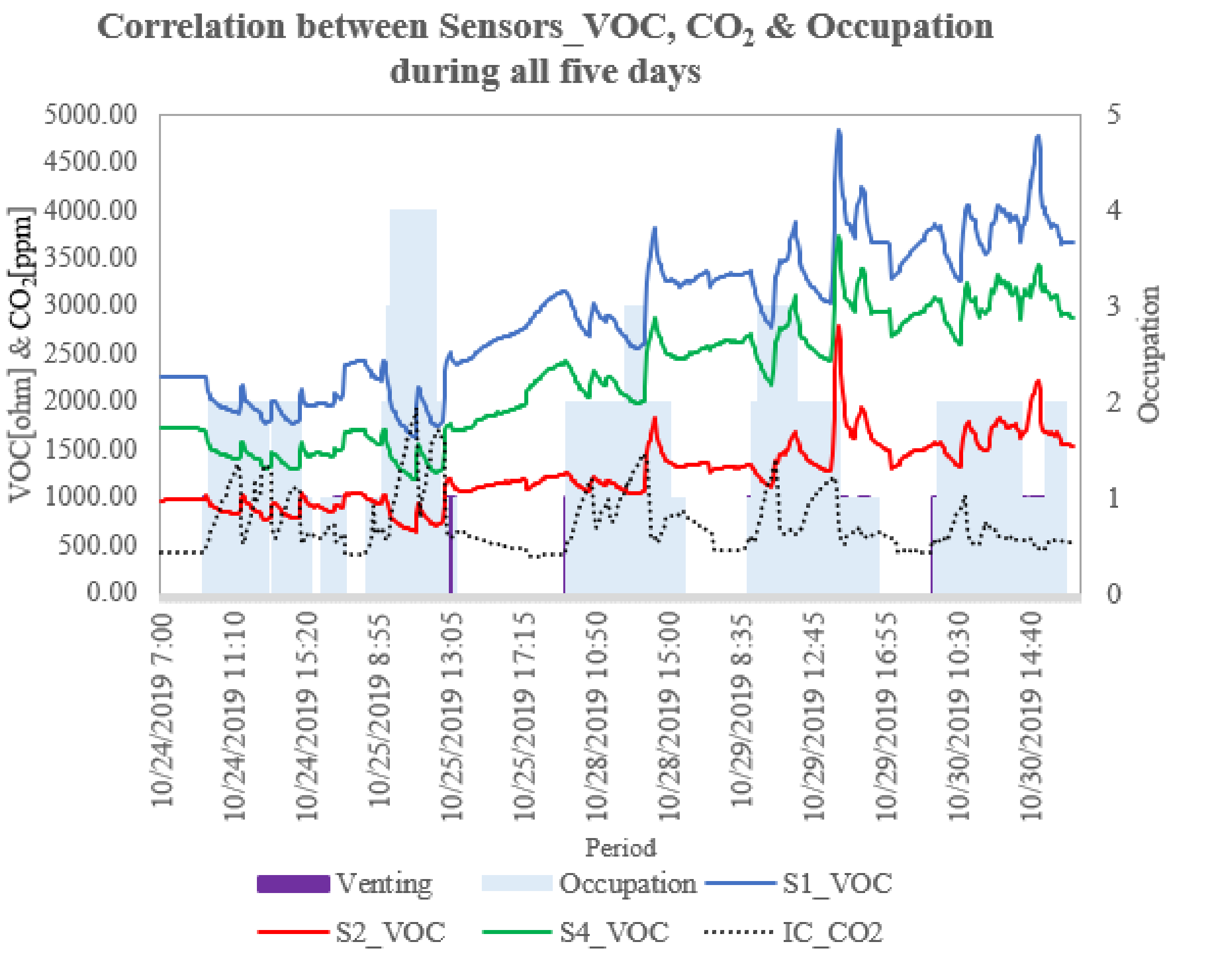


Figure 72 - Correlation between sensors (S1, S2 and S4) readings of the VOC present in the meeting room during all five days

5.6.1 Correlation between the CO_2 & Occupancy during the 1st and 5th day

Figure 73 presents the correlation between the CO_2 measured in the room and the occupation during the first day of the experiment. The peak of CO_2, marked with a dashed purple circle, is considered a random error because the number of occupants maintained the same, and the spike may therefore be explained by an occupant sitting near to the IC meters. As mentioned before, the value of CO_2 depicted in the figure is a result of the average value of the two IC meters used in the experiment. Apart from the random error, it can be seen that the level of CO_2 concentration increased every time that an occupant entered the room and decreased every time that the window or door were opened.

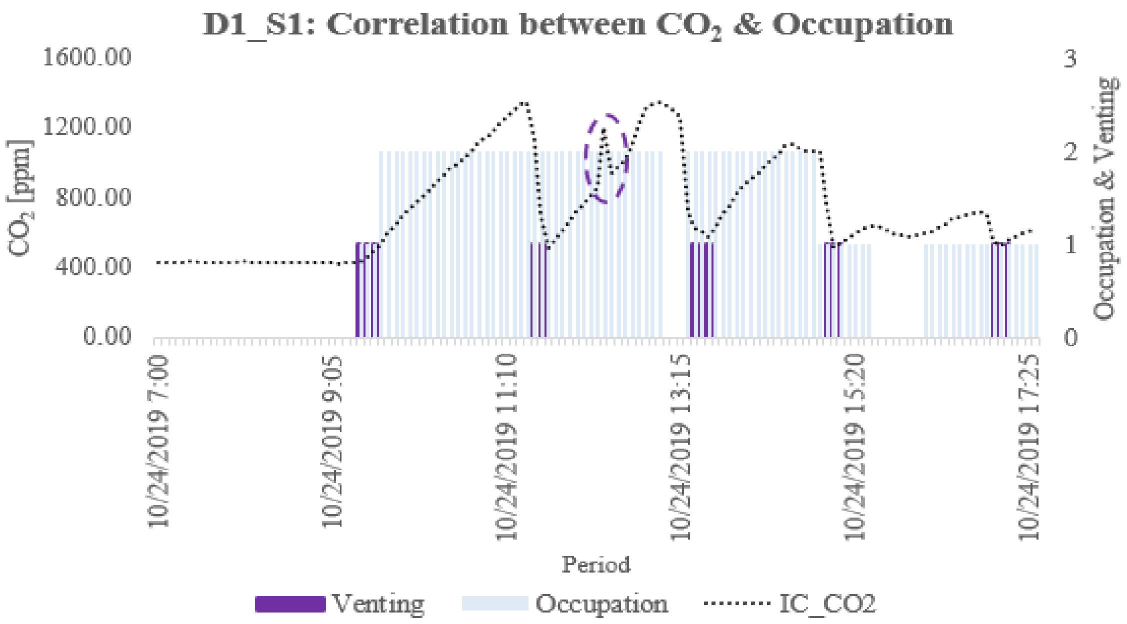


Figure 73 - D1_S1: Correlation between CO2 & Occupation

The 5th day of the experiment exhibits the same correlation behavior pattern as shown on the 1st day.

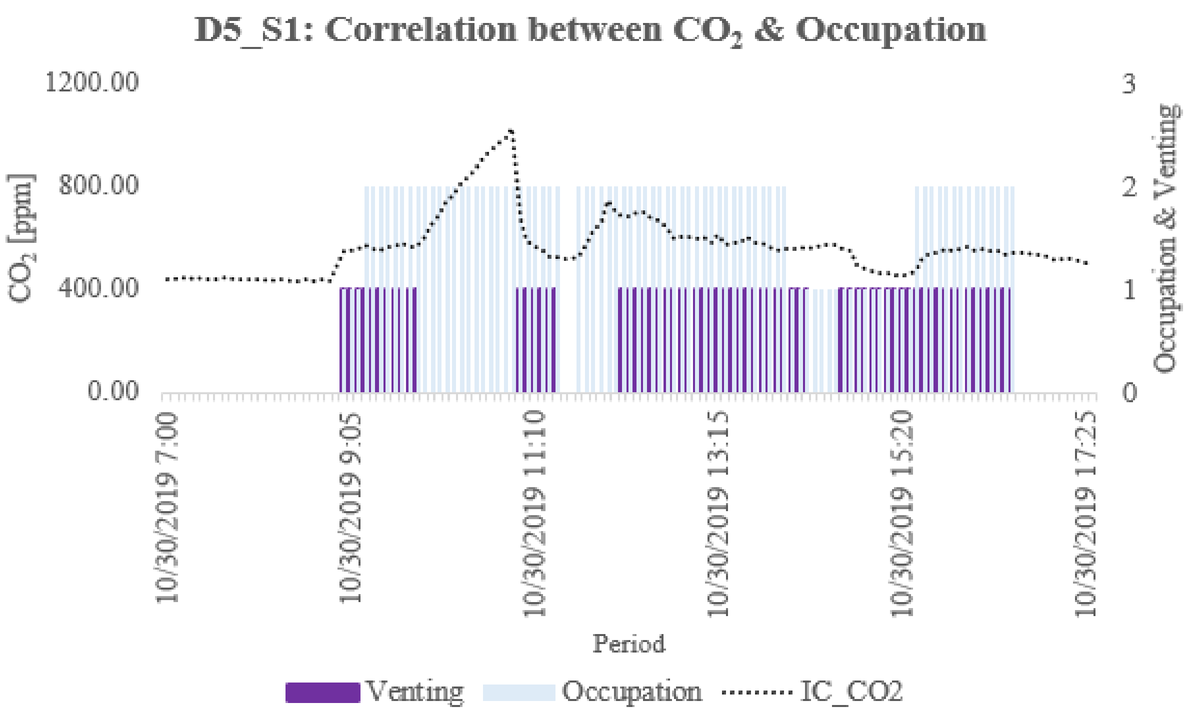


Figure 74 - D5_S1: Correlation between CO2 & Occupation

5.6.2 Correlation between the VOC & Occupancy during the 1st and 5th day

Figure 75 and Figure 76 presents the correlation between the VOC readings measured and the occupation in the room during the 1st and 5th day of the experiment.

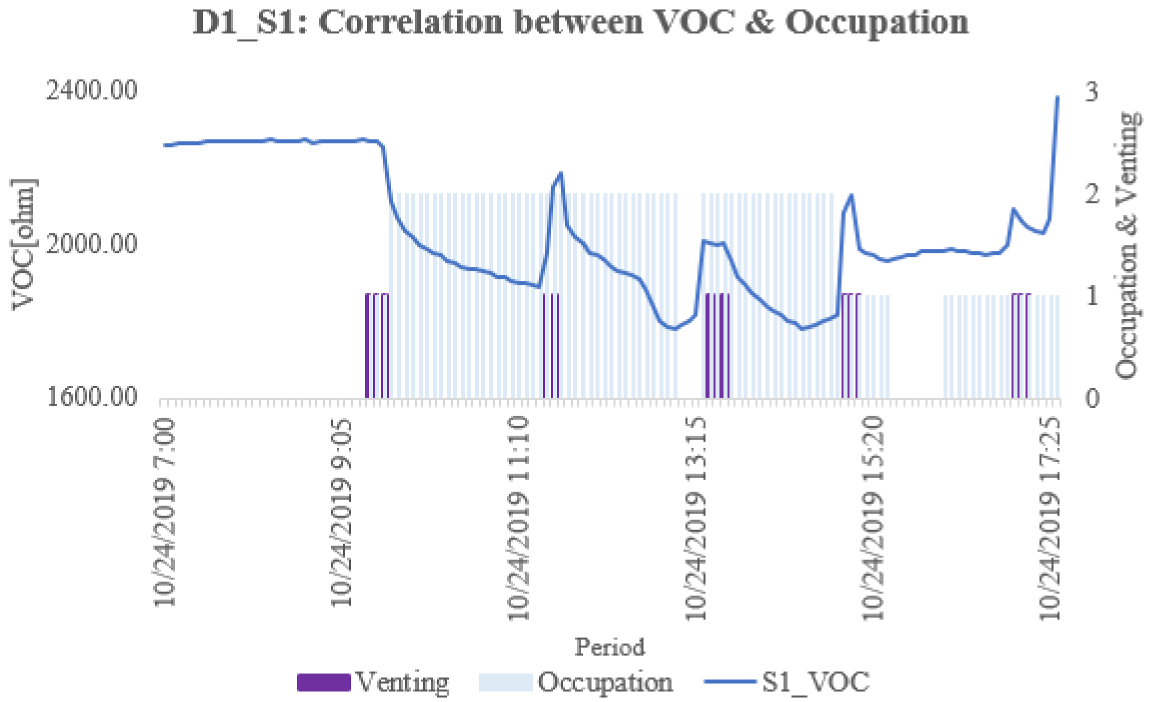


Figure 75 - D1_S1:Correlation between VOC & Occupation

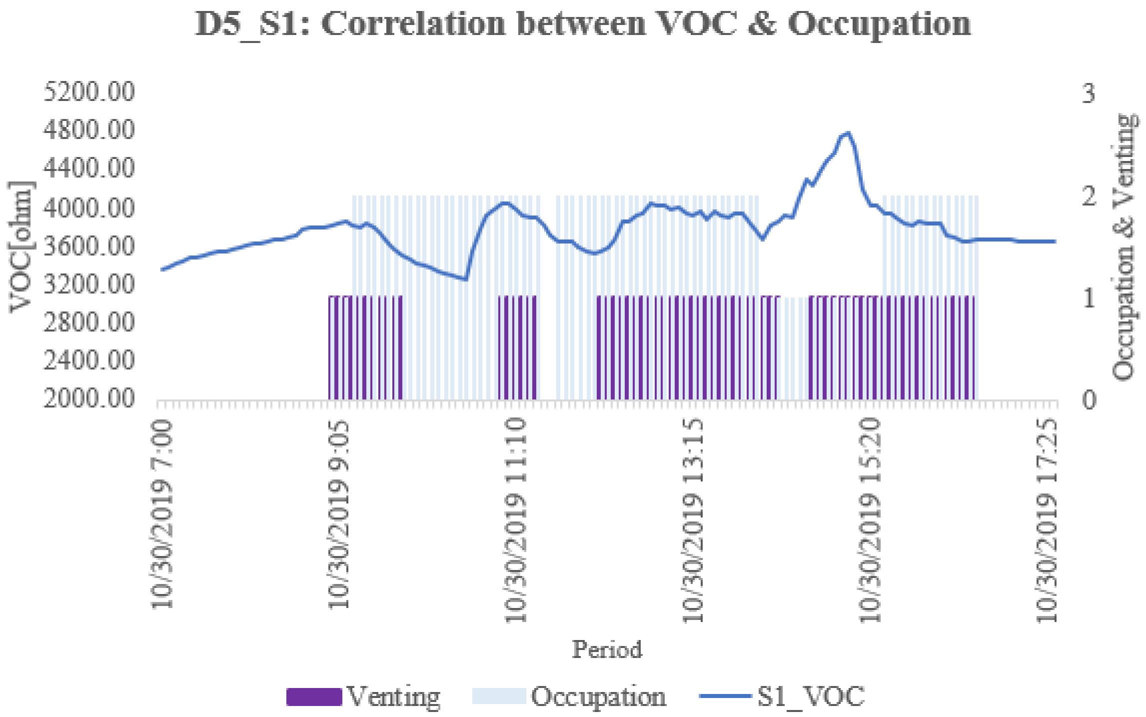


Figure 76 - D5_S1:Correlation between VOC & Occupation

Almost every time that an occupant entered the room, the VOC readings measured decreases and every time the room was vented by the opening of the window or door, the value increased.

5.6.3 Correlation between the CO_2 & VOC during the 1st and 5th day

Figure 77 depicts the average values of the two IC meters used in the experiment and the values of the VOC readings registered by the sensor S1 on the 24th of October during the occupation time (07:00-17:30). Because the diffusers of the ventilation system in the meeting room were sealed, and the occupation present the room is known, the values of CO_2 measured by the IC meters give a reliable representation of the pollution present in the room.

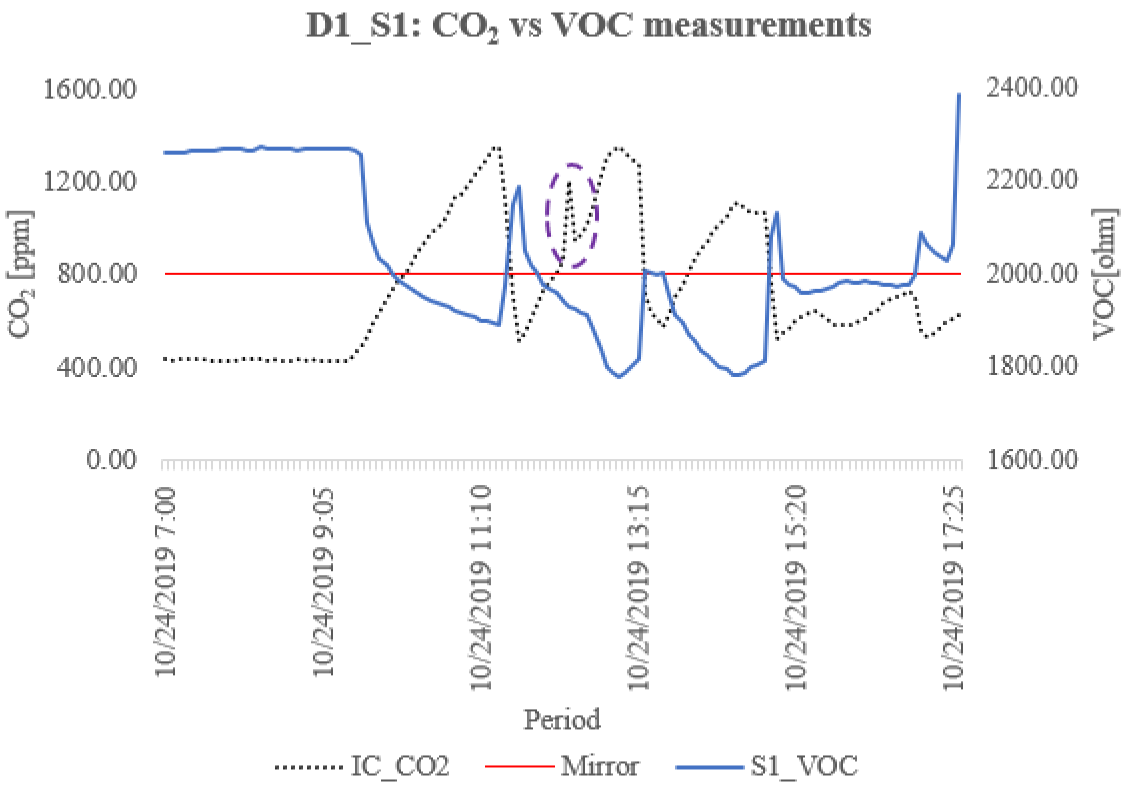


Figure 77 - D1_S1: CO_2 vs VOC measurements

According to the scale used in Figure 77, plotting the CO_2 and the VOC readings, it was possible to depict a red line denoted "Mirror" acting almost as a mirror effect between the two measured parameters.

During the whole investigation period the VOC values decreased, and the CO_2 values increased, including the previously mentioned peak of CO_2 (random error).

From day 1 until day 5 of the experiment, an increase in the VOC readings was seen, due to accumulation effect, reaching a maximum of almost 5000 [ohm] on day 5, as seen in Figure 78

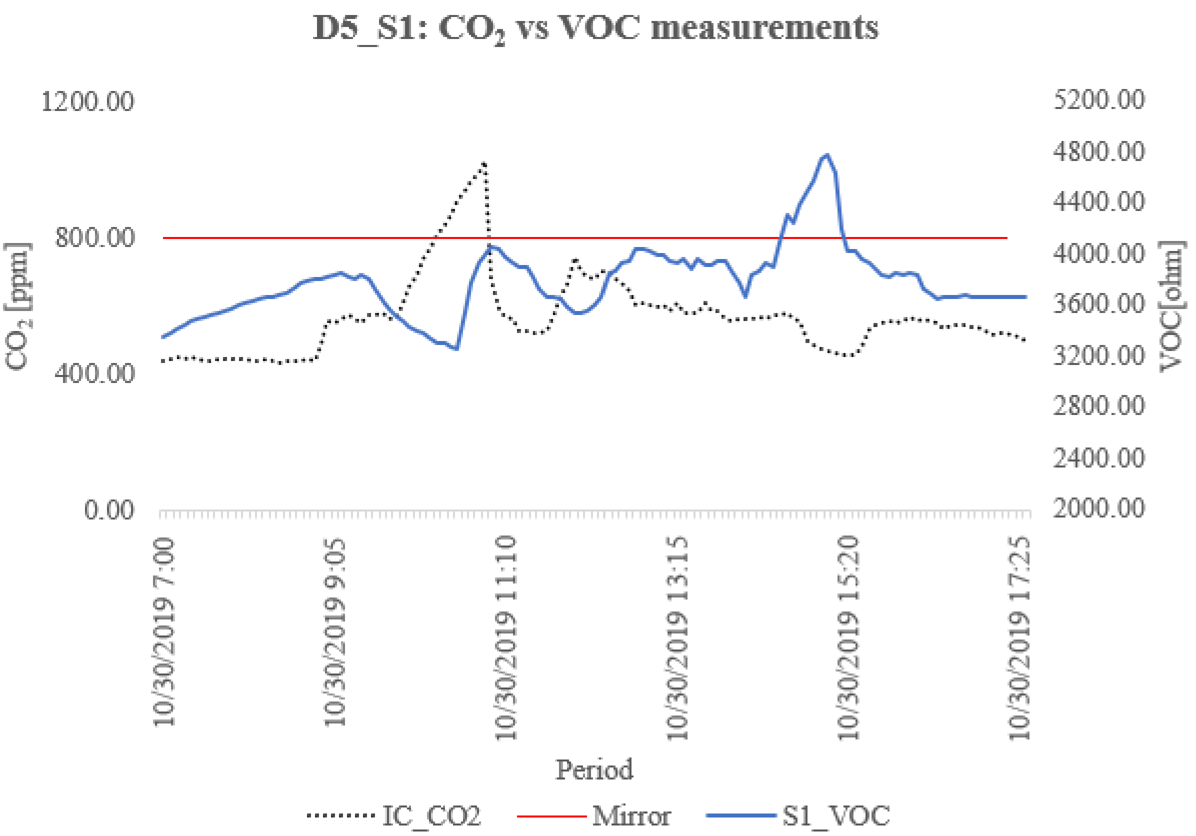


Figure 78 – D5_S1: CO_2 vs VOC measurements

In appendix 8.3 can be found the investigation for sensors S1, S2 and S4.

5.6.4 Correlation between the CO_2, VOC and Occupancy in the comparative study

This quote from the comparative study explains in more detail the features of Figure 79*:*

"As presented in the figure below, it can be seen that the reference measurements and the sensors behave differently when changing conditions. It can be noticed that reaction to the environmental change is observed for all of the sensors. The highest occupancy load is during test 4 and test 5. However, it cannot be concluded that the sensors are correlated with the reference measure. Additionally, the sensor 1, 2 and 3 are not even correlated between each other. For instance, during tests 1,2 and 3 the results from the sensors 1 and 3 are the same, while sensor 2 shows lower values, more related to the reference results. However, during the test 5, when exposed to higher occupancy load, the three of them give different results. The relationship between the sensors and the reference measurements is presented on the CO2 test, Figure 79 at the bottom. No linearity in the results is visible, obtaining the R2 close to 0. It is a wrong-behaved sensor, which should not be used for the measurement. The sensor behavior cannot be trusted and an actual CO2 sensor is recommended."(Bonet Arbos et al., 2019)

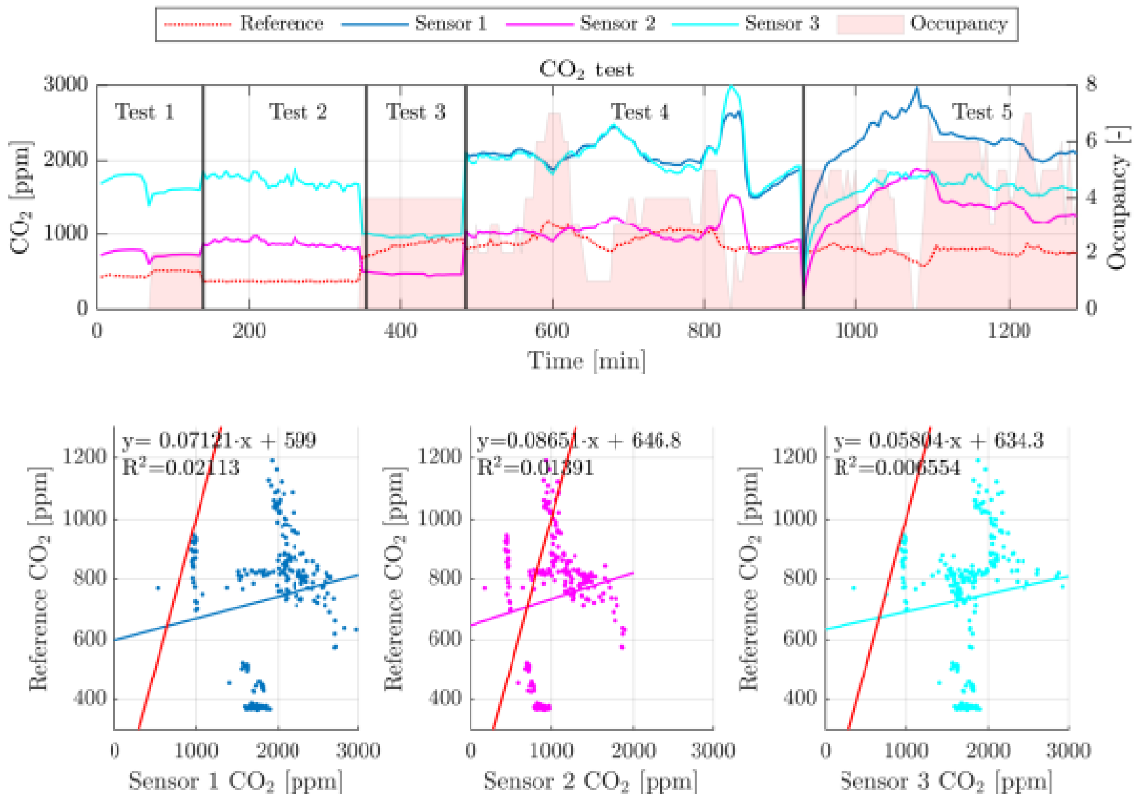


Figure 79 - Results of the CO2 calibration test(Bonet Arbos et al., 2019)

5.6.5 Further investigation of the correlation between VOC readings, temperature, relative humidity, CO_2 and occupation

The correlation between the VOC readings from the sensors S1, S2 and S4 and the temperature, relative humidity, CO_2 and occupation was investigated following the steps:

- **Step 1**: Study the correlations based on the raw data collected from all sensors;
- **Step 2:** The data was filtered based on when venting was off to evaluate the influence of this parameter on the VOC readings;
- **Step 3:** Normalization of the data from the VOC readings. Due to the values of VOC increasing successively, the daily difference between the final and initial values were subtracted. The reason for this accumulation effect was an accumulation of humidity in the sensors;
- **Step 4**: Filtering the data based on temperature between 23-24 °C and relative humidity between 40-45 % (to show the impact of this parameters on the VOC readings).

Summary of the investigation

The original data was plotted without being normalized or filtered, according to the venting (including the data when the door or window was open). In the following figures the correlation of the VOC readings with the temperature, relative humidity, CO_2 and occupation including the R^2 is presented.

In Figure 80 and Figure 81 the correlation between the sensor VOC readings and the IC meters readings (averaged values) for the temperature and relative humidity is presented. The R^2 presents a better linearity with the relative humidity (R^2 near to 1), than of the temperature readings (R^2 values closer to 0).

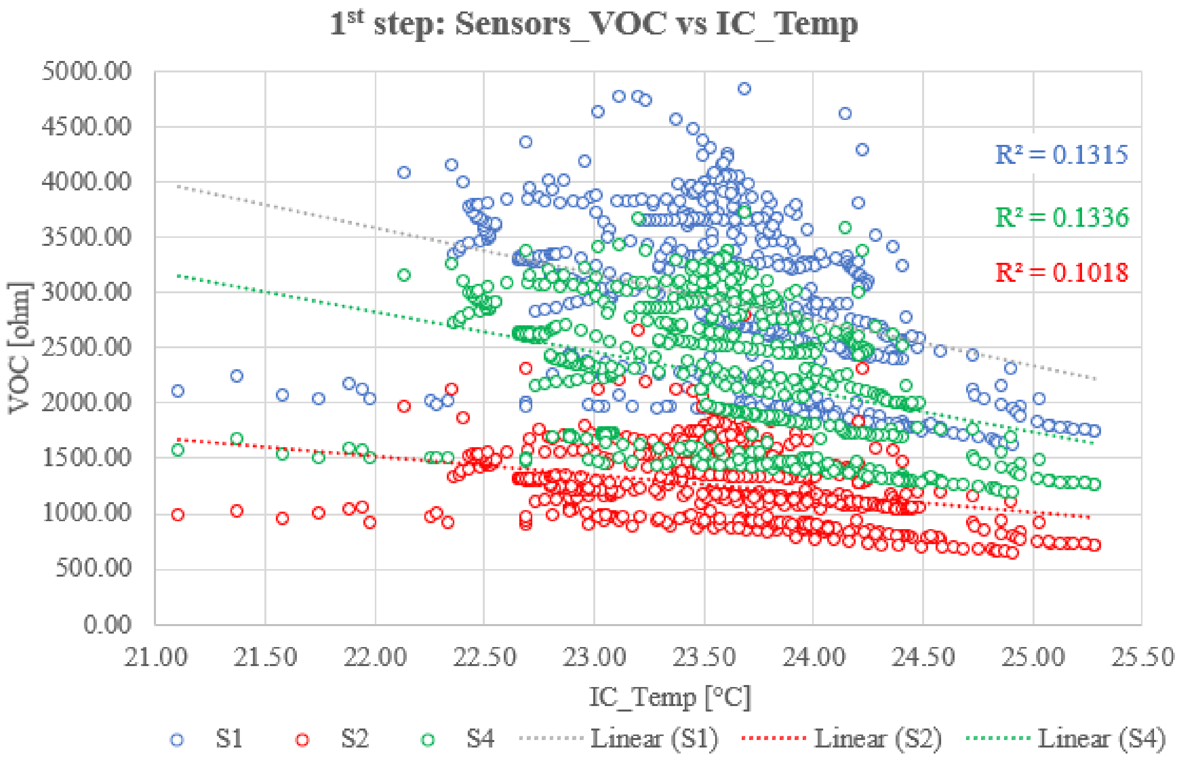


Figure 80 - Correlation of Sensors_VOC vs IC_Temp based on raw data

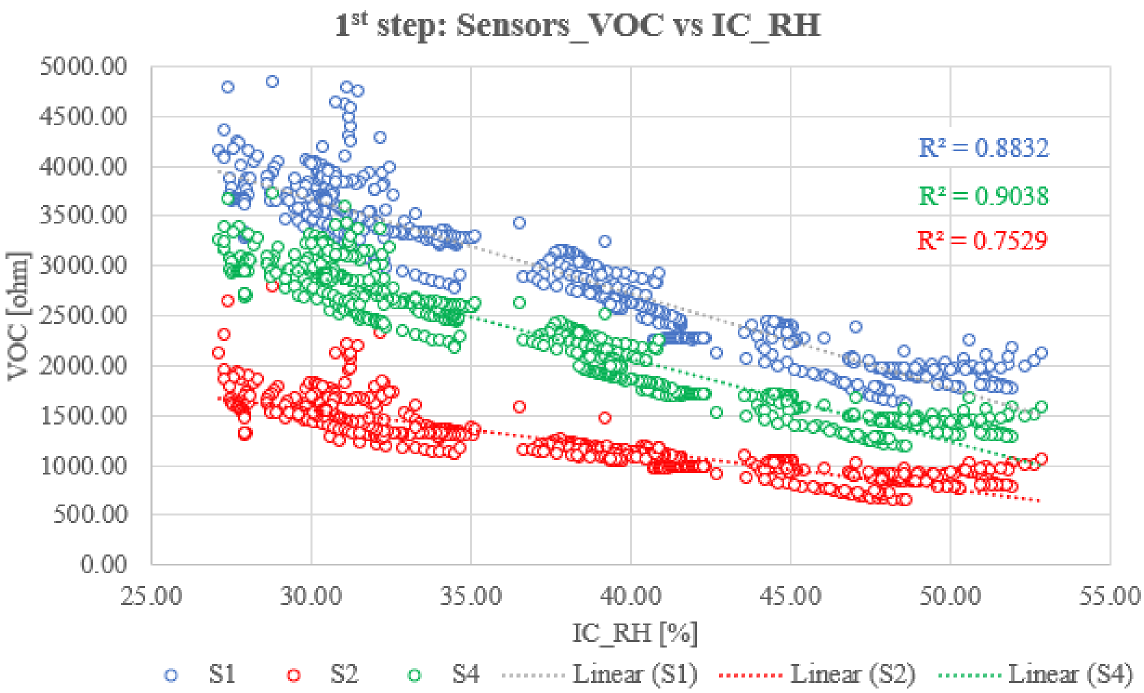


Figure 81 - Correlation of Sensors_VOC vs IC_RH based on raw data

In Figure 82 the correlation of the sensors' VOC readings with the CO_2 measured in the room is depicted. The values of R^2 are very low indicating a weak correlation.

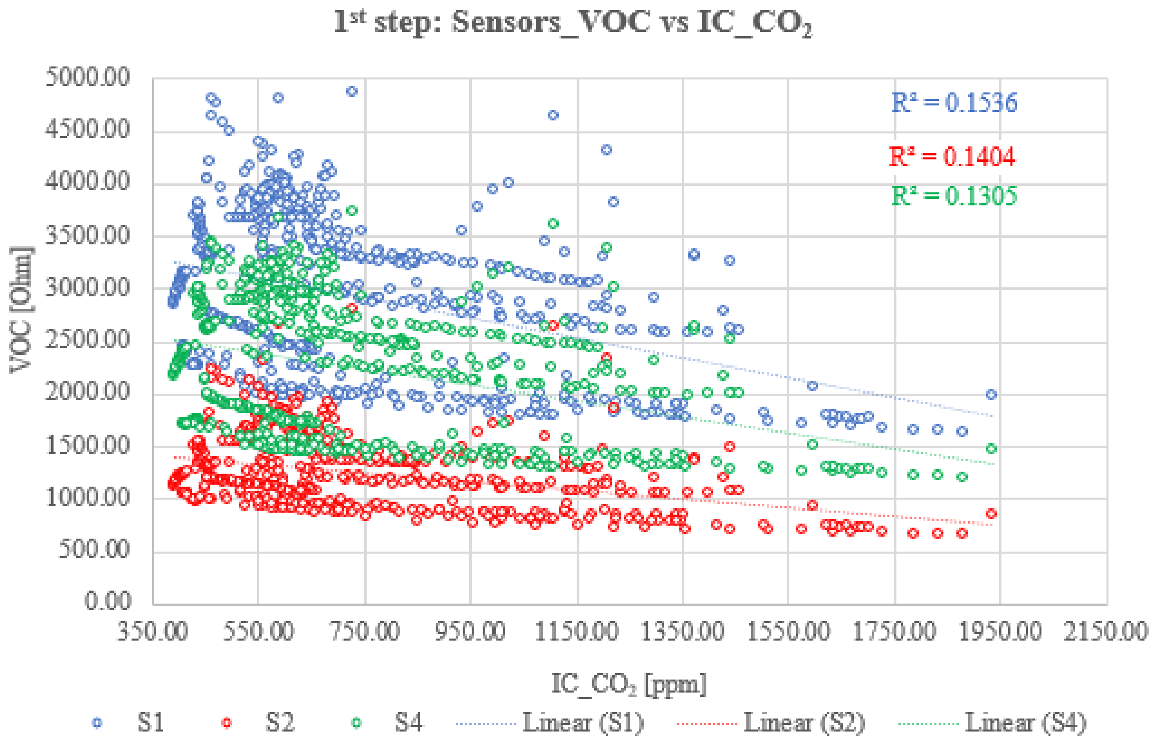


Figure 82 - Correlation of Sensors_VOC vs IC_CO_2 based on raw data

In Figure 83 the correlation between sensors' VOC readings based on the occupation in the room is presented. The level of pollution in the room increases with higher occupation and the opposite happens with the VOC readings. However, when there is no occupation in the room, the VOC reading logically should have registered the highest value, but that did not occur.

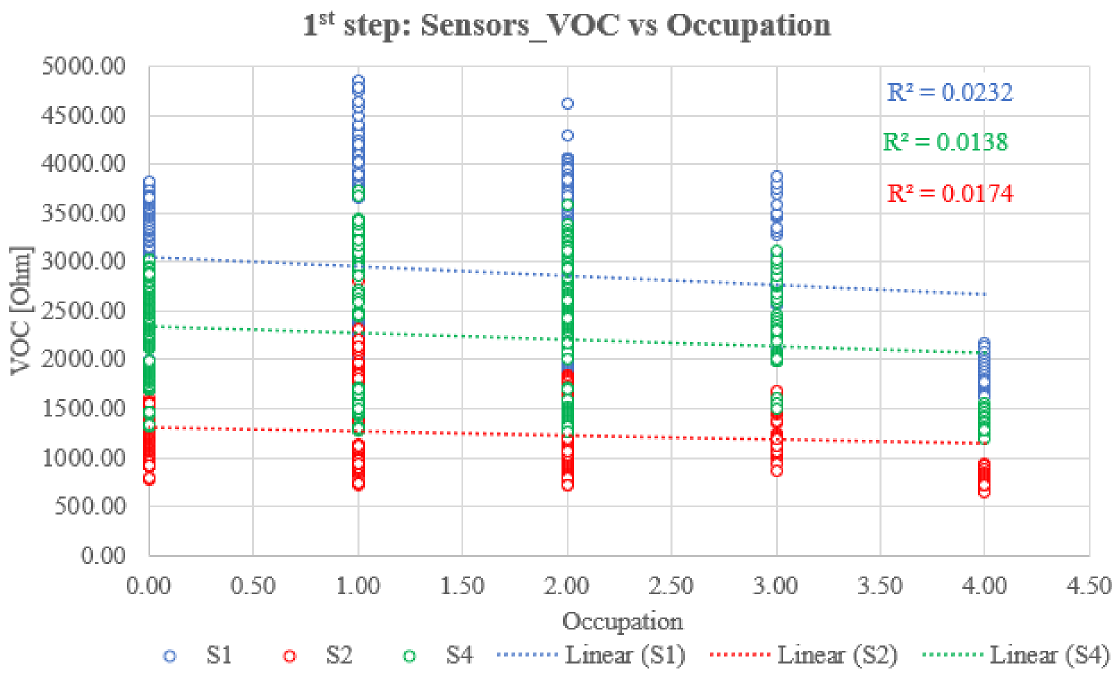


Figure 83 - Correlation of Sensors_VOC vs Occupation based on raw data

The R^2 registered in all sensors was very low with values near to zero, which indicates that no linearity can be seen.

This kind of sensor should be used together with a special software called Bosch Software Environmental Clusters (BSEC). This software algorithm handles the humidity compensation, baseline as well as long drift correction of the gas sensor signal (https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors-bme680/, 2019).

Different studies have shown that the readings of this type of sensor Bosch BME680 are greatly affected by the relative humidity and temperature. Our study did not include the use of the BSEC algorithm, meaning that the compensation formulas could not be applied. Instead, the data was filtered and normalized based on temperature and relative humidity between 23-24 °C and 40-45 %, respectively, to investigate the correlation between the VOC readings and temperature, relative humidity, CO2 and occupation as exhibited in Figure 84, Figure 85, Figure 86, Figure 87 .

In Figure 84 and Figure 85 presents a decrease in the correlation between the VOC readings and temperature and relative humidity, because the R^2 calculated registered worst values than the ones exhibited with the raw data. The largest decrease occurred in the correlation with the relative humidity.

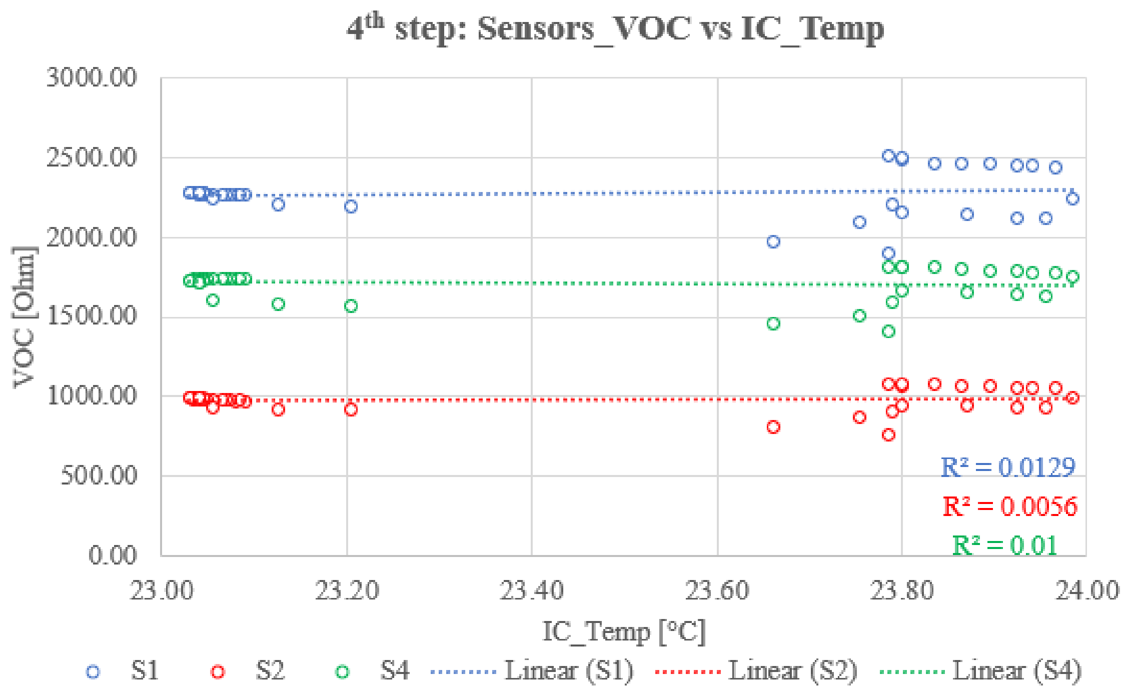


Figure 84 - Correlation of Sensors_VOC vs IC_Temp with filtered and normalized data (T:23-24 °C, RH:40-45%)

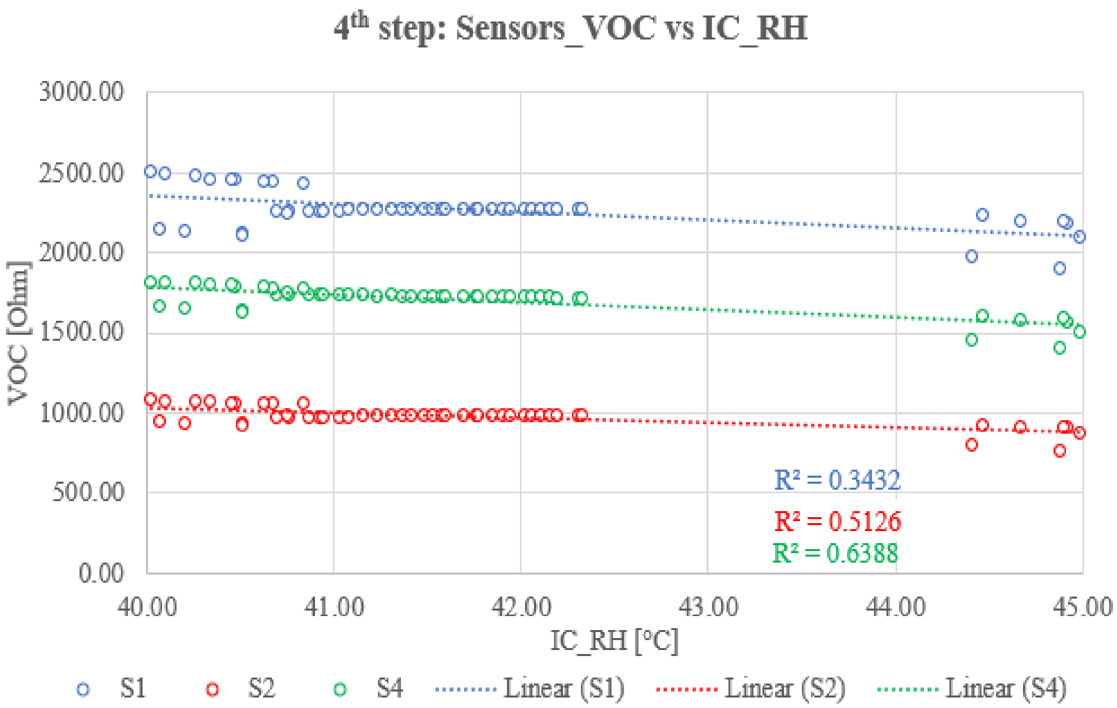


Figure 85 - Correlation of Sensors_VOC vs IC_Temp with filtered and normalized data (T:23-24 °C, RH:40-45%)

In Figure 86 a setback in the improvement of CO_2 correlation is shown, since the values of the R^2 had decreased in all sensors when compared with the raw data, with special emphasis for sensor S2. The CO_2 correlation has demonstrated not to be accurate and precise enough to manage proper control of the ventilated window.

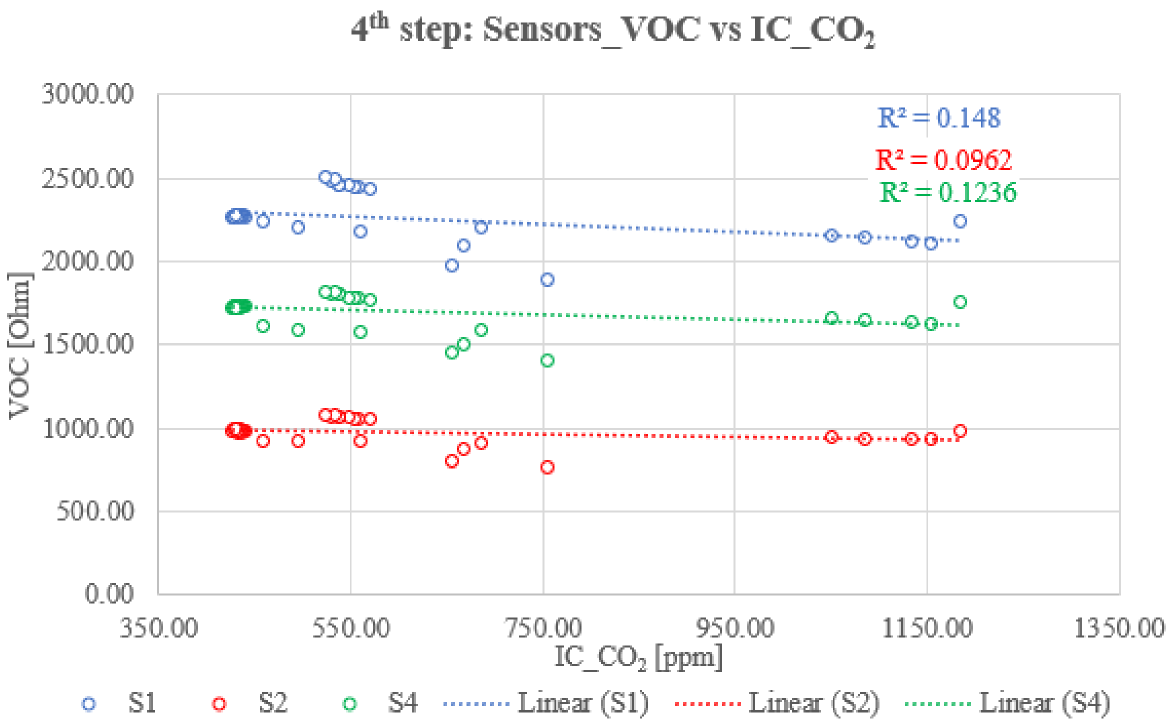


Figure 86 - Correlation of Sensors_VOC vs IC_CO_2 with filtered and normalized data (T:23-24 °C, RH:40-45%)

In Figure 87 is shown considerable improvement in the VOC resistance correlation vs the occupation. when compared with the values of R^2 calculated based on the raw data.

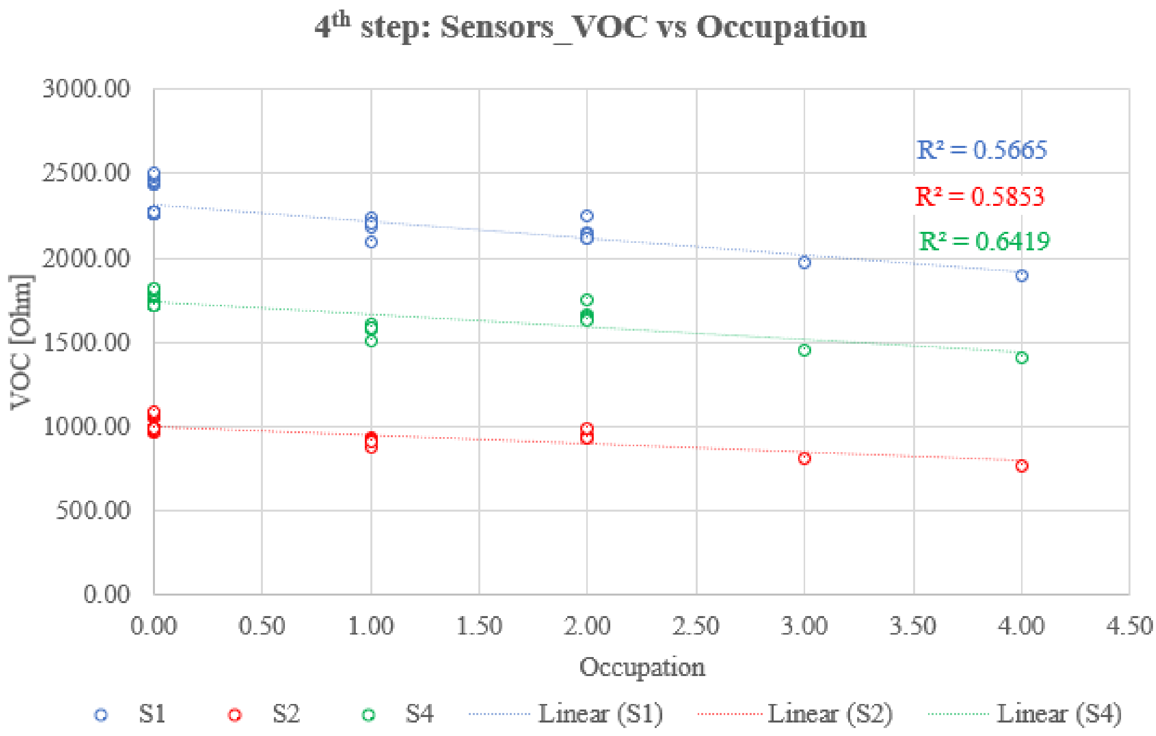


Figure 87 - Correlation of Sensors_VOC vs Occupation with filtered and normalized data (T:23-24 °C, RH:40-45%)

The results have shown that it is better to use the correlation of people´s detection instead, meaning that it is possible to estimate the number of people with this sensor if it has temperature and relative humidity compensation. However, it is not possible to transform this VOC readings into an accurate CO_2 level.

Conclusions

- After the steps described in 5.6.5 the correlation between the VOC readings and the:
    - Temperature disappeared since the R^2 calculated presented values near to 0 indicating no linearity observed.
    - Relative humidity decreased in a very significant way in counterpoint with the one observed in the raw data. The R^2 decreased in all sensors with special rate in sensor S1.
    - CO_2 decreased slightly for sensors S1 and S4, and drastically for sensor S2.
    - Occupation increased and improved considerably reaching R^2 values of 0.5665 for S1, 0.5853 for S2 and 0.6419 for S4.

6 Conclusion

6.1 The indoor environment

Since the change from window type 1 to window type 2, the indoor environment has improved. The temperature in Room 1 had an increased time within category I of 11%, while Room 2 did not have an increased time in category I. However, Room 2 had an increased time within category +II to +IV, it has increased with 9%.

The relative humidity changed from always being between 20 - 52% to 32 - 58%, which is a change from category III to category II 100% of the occupied time. However, the two improvements were caused by the differences in season during the measurements. The window type 2 measurements had a higher outdoor mean temperature of 3°C compared to the window type 1 measurements.

To compare, the two window types CO_2 levels below or equal to 1000 ppm improved by 12% in Room 1 and by 14% in Room 2. This could be caused by the different design, since it was observed that ventilation rates in the extraction of the rooms were 5-6 L/s higher.

The installation of the new window design WT2 resulted in an improved indoor environment, but not enough to be acceptable according to building standards and regulations.

The ventilated windows were found to always be supplying air during the measuring period. The heat recovery of the new windows was lower during the same outside temperatures. This could be because the new design was meant to increase the flowrate, but now has lower heat recovery due to the design.

6.2 The sensor for room conditions monitoring

The temperature and relative humidity tests performed on the sensor used to measure the indoor climate parameters in the room revealed a need for recalibration since the output of the sensor response was compared to the reference sensor and the results presented an offset.

The results of the investigated correlation between the inverse of the VOC signal readings, temperature and relative humidity, showed that these parameters had a large influence on the VOC signal. By narrowing the data related with temperature and relative humidity it was proven that the correlation could be improved.

The correlation between the inverse of the VOC signal readings, CO2 and Occupation showed that the VOC readings could be used for occupation detection on the condition that the proper control algorithm was used for the sensor, which was not the case here. The CO_2 correlation exhibited a weak correlation.

The previous study by Arbos Bonet et al did not find a correlation between the VOC readings and the CO_2, which is in line with our results after applying the steps mentioned in 5.6.5, but not in line with our raw data where we did indeed find a correlation, however weak.

6.3 Improvement suggestions and further study

The suggestions posed in this part of the report are meant as initial sparks of ideas that could sprout into solutions that help to improve the ventilated window project. The suggestions are based on theory and would need further investigation to prove.

6.3.1 The ventilated window and mechanical ventilation design

The new window design is not providing enough air flow to the rooms, even with the mechanical extraction. This means that a new design focusing on reducing the pressure resistance through the window could be made. Assuming that the window acts similar to a ventilation duct the following could be investigated to see if it would have an adequate effect on the pressure resistance.

- Increase the openings' size and shapes into less pressure resistant and let the valves modulate in openings for reducing and controlling airflow. There seems to be available area for increasing both the opening into the window cavity, the opening in the actual cavities and from the window into the room.
- Increase the thickness of the cavity to reduce the pressure resistance through the cavity.
- Decrease the length of the cavities, this would reduce the pressure resistance per meter.

These three parameters could influence the pressure resistance causing low flows. It must be kept in mind that these parameters could also influence other aspects of the windows performance such as energy consumption, daylight, structural integrity etc. But assuming the windows main function is to ventilate according to the need these changes could be necessary.

The room with the mechanical extraction shows preferred CO_2 levels compared with the room with natural ventilation. This could indicate that increasing the airflow of the mechanical extraction could improve the indoor environment further. A larger mechanical extraction could also be installed. As well it is necessary to install a mechanical extraction in Room 1 with natural ventilation. This is all assuming that the ventilated window cannot achieve lower pressure resistance which should result in higher flows. This would be preferred in case of energy efficiency.

6.3.2 The sensor for room monitoring

The sensor for room monitoring is now a complex sensor measuring volatile organic compounds, temperature, relative humidity and pressure. The sensors do not express its environment with its measurements very well. The issues could be rectified by applying the software for the sensor from the supplier or making the necessary lab work to find the calibration, conversion and compensation curves.

The sensors investigated are only the same type, not the exact sensors from the rooms. Therefore, it is necessary to access the data in the room and analyze it, to see if this would show similar results. As shown also by the study (Bonet Arbos *et al.*, 2019) it was found that the sensor cannot be used for measuring CO_2 correlation directly. This means a CO_2 sensor will need to be installed assuming that the CO_2 levels is preferred to monitor.

6.3.3 The control of the ventilated window

The control of the window could be improved by adding both the heating system, the blinds and the ventilation extraction system to the control. This way too cold inlet temperatures from the window could be heated up by the heating system before causing discomfort. The ventilation could then only be used when it was necessary caused by not enough natural forces for creating airflow. The blinds could then act as an additional improvement of the heat recovery since lab experiments done at Aalborg University has shown that a venetian blind rolled down with vertical blinds can increase heat recovery with direct solar radiation present. The blind could also act as a passive cooling measure in summer, but it would need further investigation if this is necessary at the school.

There could also be added a sensor that measures when the door is open or closed added to the control. Assuming the mechanical extraction is causing a lower pressure in the room resulting in higher air flow through the windows. Opening the door would then cause polluted air from the hallway to enter the room instead of the fresh air. This would result in, even with the ventilation on, the wanted air quality in the room would not be achieved.

6.4 Further investigation

The window type 2 now installed in the school shows different behavior during the same time of the day. This indicates that cavities are not all influenced by the same conditions at the same time. This could be further studied by making correlation graphs between the temperatures to see if they are affected by the same conditions.

There was no access to the Bosch software algorithm in this study, however, it is advised that future researchers in this area include it, to confirm if the sensor VOC readings with the CO_2 and occupation would be accurate and stable enough to be used in the current defined control strategy. The results may then be compared to ours, given that the experiment setup is comparable.

During the measurements it was not possible to get access to data from the window and rooms sensors. It could be accessed when possible to then see, first of all, if the sensor in the room is acting as the tested sensors. Furthermore, it could be studied if the control system is acting as it should.

The venetian blinds in the ventilated window is electrical, but manually controlled. Further study could include if there are too warm temperatures in the summer that a control strategy of the blinds could prevent.

When an optimal ventilated window has been designed and installed at the school, it could be interesting to model the rooms to see the behavior of the room and its other systems. This could help in the design of the control for the window. Having this knowledge could assist in choosing if the heating system should start heating according to the room temperature or top cavity temperature, depending on the response time of the room.

7 References

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uRADMonitor » Metal Oxide VOC Sensors (2019). Available at: https://www.uradmonitor.com/metal-oxide-voc-sensors/ (Accessed: 8 January 2020).

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8 Appendix

8.1 Temperatures in the rooms after measurement period oct-nov 2019.

AAU_CIVIL_11 ▾ AAU_CIVIL_11 - TMV Kontor 1.351 ▾

Temperature °C - Week 50 (09.12 - 15.12)

December	9	10	11	12	13
Time:	Monday	Tuesday	Wednesday	Thursday	Friday
00:00 - 01:00	21.7 °C	21.7 °C	20.2 °C	21.0 °C	19.7 °C
01:00 - 02:00	21.8 °C	21.7 °C	20.3 °C	20.9 °C	19.4 °C
02:00 - 03:00	21.8 °C	21.7 °C	20.5 °C	20.9 °C	18.9 °C
03:00 - 04:00	21.7 °C	21.7 °C	20.6 °C	20.9 °C	18.7 °C
04:00 - 05:00	21.7 °C	21.7 °C	20.7 °C	20.8 °C	18.3 °C
05:00 - 06:00	21.6 °C	21.6 °C	20.9 °C	20.8 °C	18.1 °C
06:00 - 07:00	21.6 °C	21.4 °C	21.1 °C	20.9 °C	18.0 °C
07:00 - 08:00	21.8 °C	21.3 °C	21.3 °C	20.8 °C	18.1 °C
08:00 - 09:00	22.0 °C	21.6 °C	21.8 °C	21.0 °C	18.4 °C
09:00 - 10:00	22.3 °C	21.8 °C	22.0 °C	20.7 °C	19.3 °C
10:00 - 11:00	21.6 °C	22.1 °C	22.4 °C	20.4 °C	20.0 °C

AAU_CIVIL_18 ▾ AAU_CIVIL_18 ▾

Temperature °C - Week 50 (09.12 - 15.12)

December	9	10	11	12	13
Time:	Monday	Tuesday	Wednesday	Thursday	Friday
00:00 - 01:00	21.5 °C	20.9 °C	20.3 °C	21.0 °C	20.1 °C
01:00 - 02:00	21.5 °C	20.8 °C	20.3 °C	20.9 °C	19.9 °C
02:00 - 03:00	21.4 °C	20.8 °C	20.3 °C	20.9 °C	19.5 °C
03:00 - 04:00	21.3 °C	20.7 °C	20.4 °C	20.9 °C	19.4 °C
04:00 - 05:00	21.3 °C	20.7 °C	20.4 °C	20.8 °C	19.0 °C
05:00 - 06:00	21.3 °C	20.6 °C	20.6 °C	20.9 °C	18.8 °C
06:00 - 07:00	22.1 °C	20.6 °C	20.7 °C	21.1 °C	18.8 °C
07:00 - 08:00	21.7 °C	20.6 °C	20.7 °C	20.8 °C	19.0 °C
08:00 - 09:00	22.0 °C	22.0 °C	21.7 °C	21.1 °C	19.4 °C
09:00 - 10:00	22.4 °C	21.9 °C	22.0 °C	21.3 °C	19.7 °C
10:00 - 11:00	22.4 °C	22.2 °C	22.3 °C	21.7 °C	20.2 °C

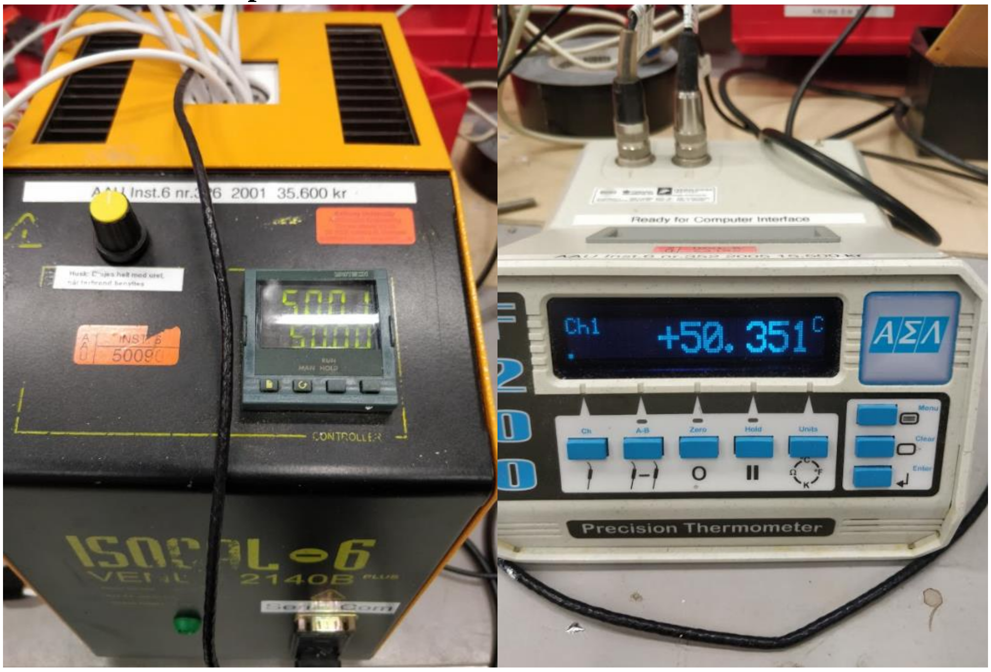
AAU_CIVIL_12 ▾ AAU_CIVIL_12 - TMV Kontor 1.243 ▾

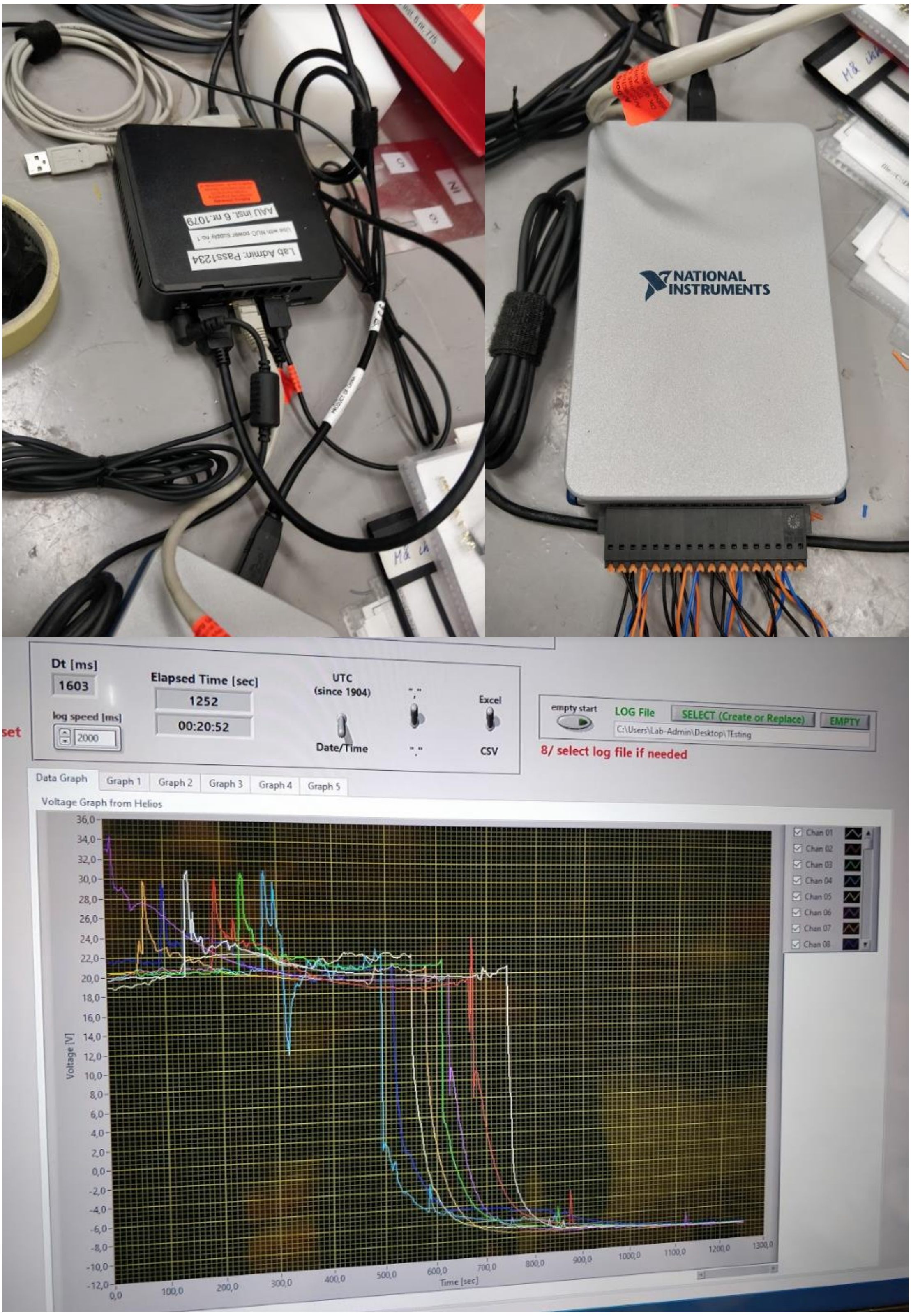
Temperature °C - Week 50 (09.12 - 15.12)

December	9	10	11	12	13
Time:	Monday	Tuesday	Wednesday	Thursday	Friday
00:00 - 01:00	6.8 °C	2.8 °C	4.2 °C	5.9 °C	2.2 °C
01:00 - 02:00	7.0 °C	2.5 °C	4.0 °C	5.8 °C	2.4 °C
02:00 - 03:00	6.8 °C	2.5 °C	4.0 °C	5.9 °C	2.8 °C
03:00 - 04:00	6.4 °C	2.0 °C	4.0 °C	5.9 °C	2.4 °C
04:00 - 05:00	6.2 °C	1.9 °C	4.4 °C	5.9 °C	2.4 °C
05:00 - 06:00	6.2 °C	1.7 °C	4.9 °C	5.9 °C	2.6 °C
06:00 - 07:00	6.2 °C	1.7 °C	5.9 °C	5.4 °C	2.3 °C
07:00 - 08:00	6.2 °C	1.6 °C	6.2 °C	5.0 °C	2.3 °C
08:00 - 09:00	6.4 °C	2.2 °C	6.5 °C	4.7 °C	2.5 °C
09:00 - 10:00	6.1 °C	4.4 °C	6.5 °C	5.0 °C	2.9 °C
10:00 - 11:00	6.9 °C	4.5 °C	6.6 °C	5.2 °C	3.4 °C
11:00 - 12:00	7.8 °C	6.5 °C	6.9 °C	5.5 °C	4.0 °C

8.2 Calibration of instruments

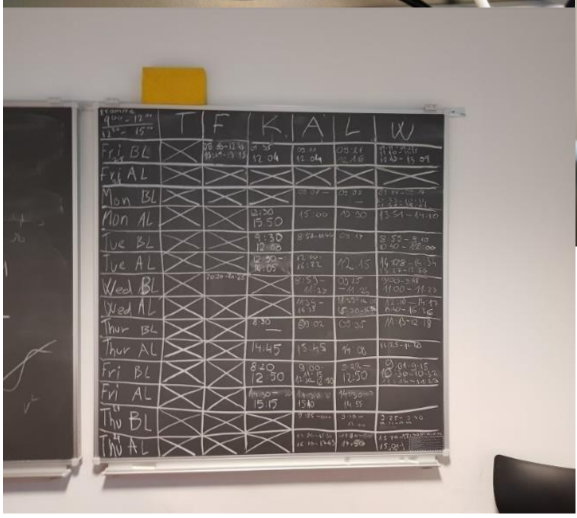
8.2.1 PT100 temperature sensors




AAU inst. 6 nr.1079
Lab Admin: Pass1234
NATIONAL INSTRUMENTS
Dt [ms]
1603
Elapsed Time [sec]
1252
00:20:52
UTC (since 1904)
Date/Time
Excel
CSV
log speed [ms]
2000
empty start
LOG File
SELECT (Create or Replace)
EMPTY
8/ select log file if needed
Data Graph
Graph 1
Graph 2
Graph 3
Graph 4
Graph 5
Voltage Graph from Helios
Voltage [V]
Time [sec]

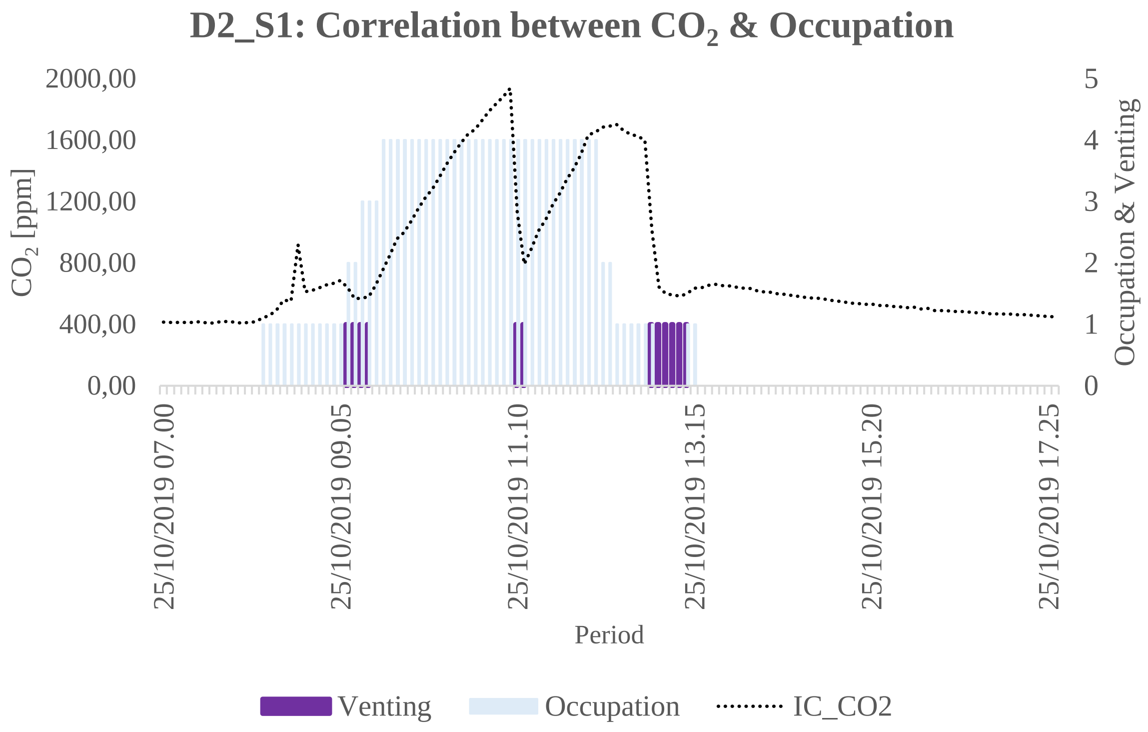
8.2.2 Lindab FTMU flowmeters

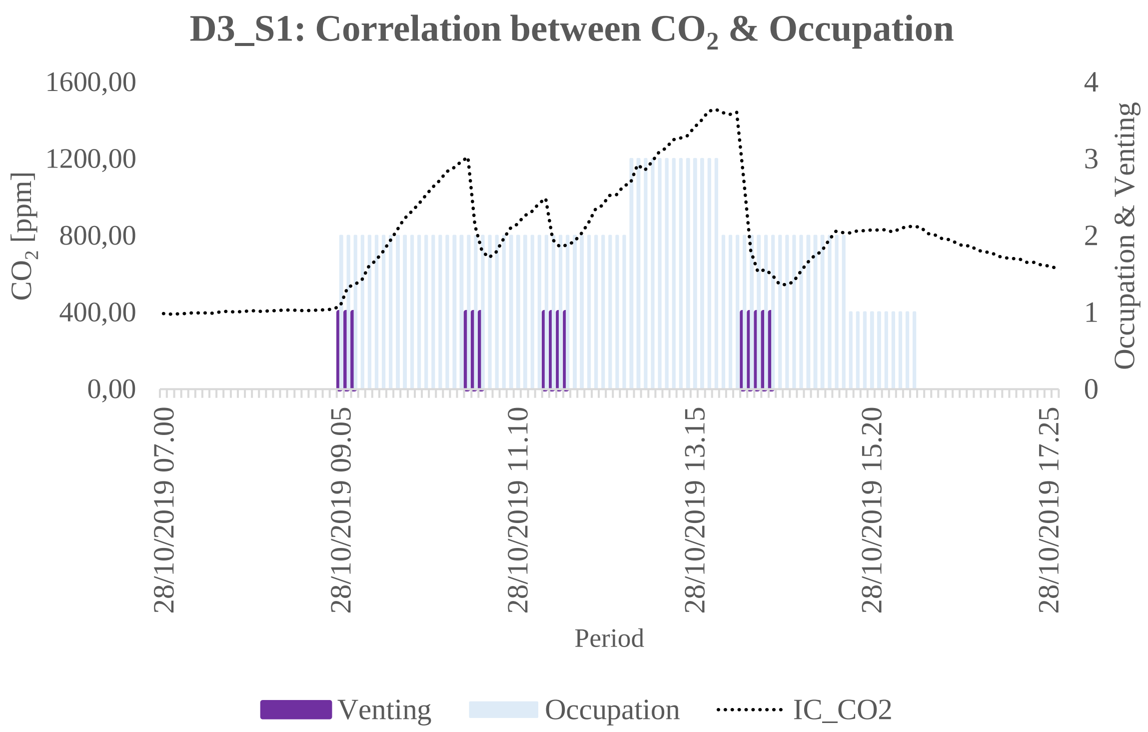
8.3 VOC sensor investigation

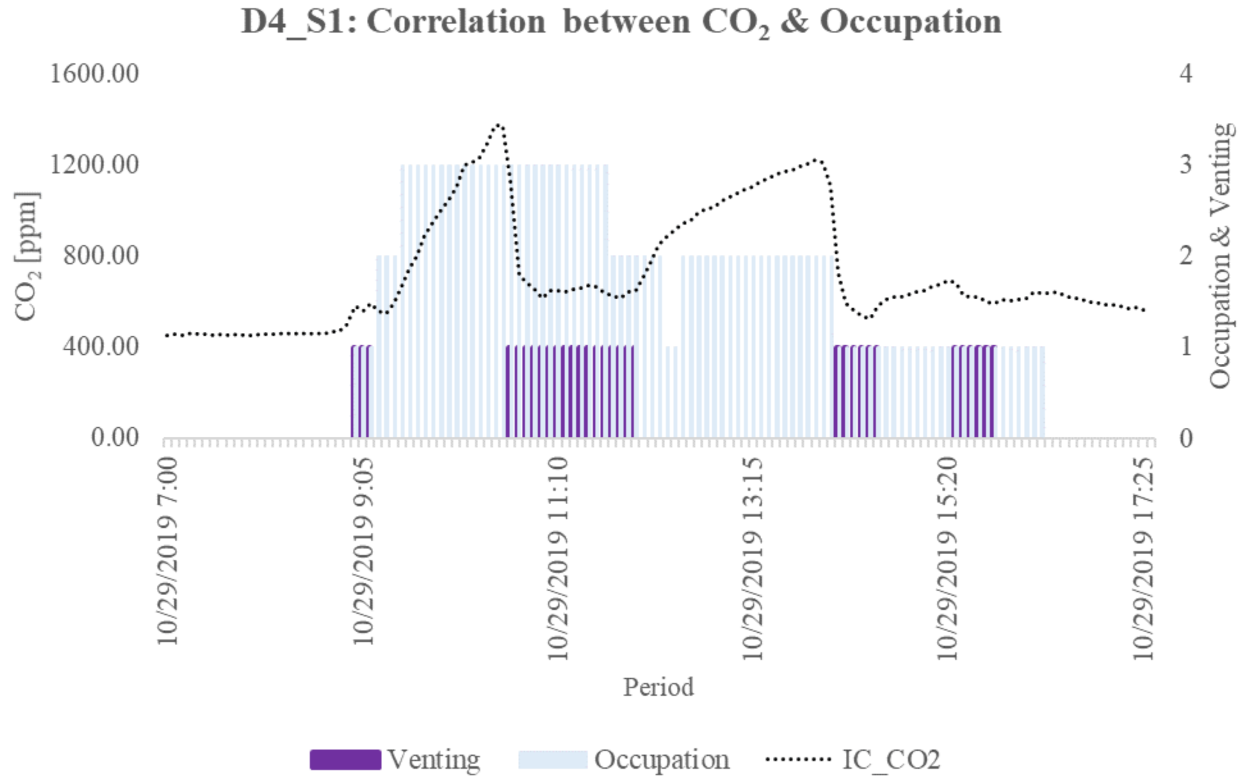


8.3.1 Correlation between the CO_2 & Occupancy during the 1st until the 5th day for all sensors

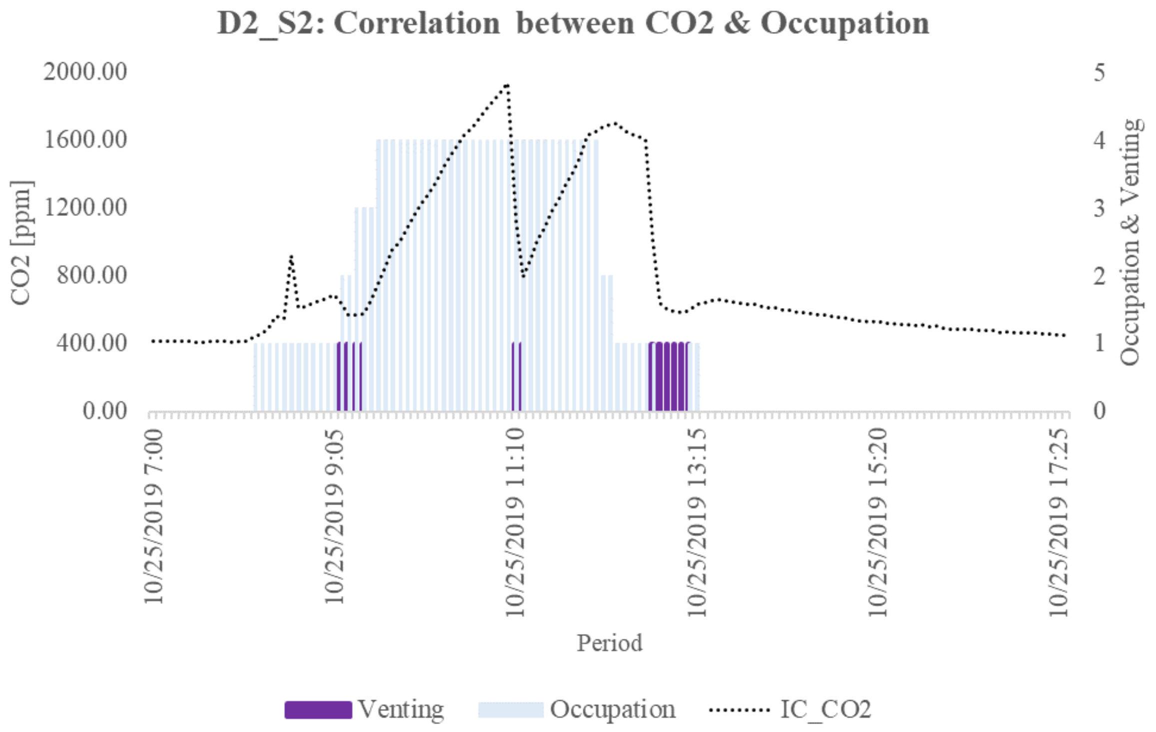
Sensor S1 presented only from the 2nd until the 4th day since it is referred in 5.6.1)

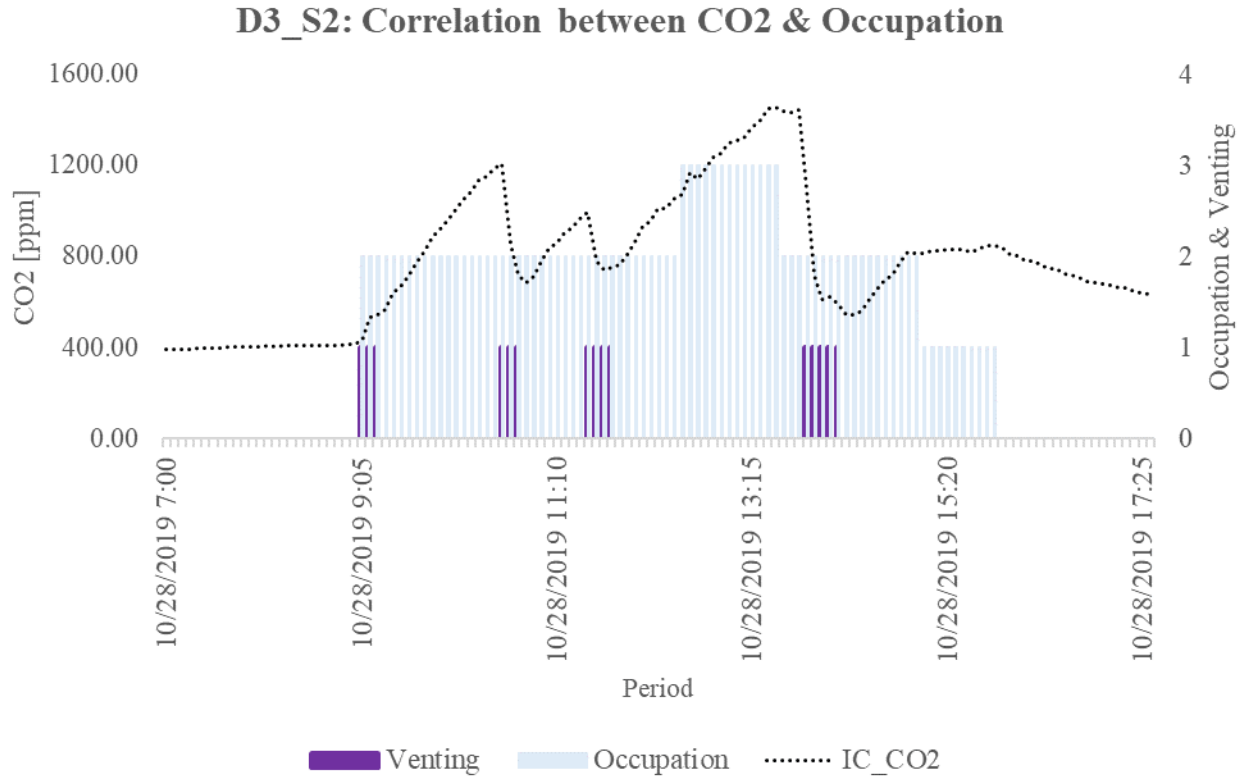


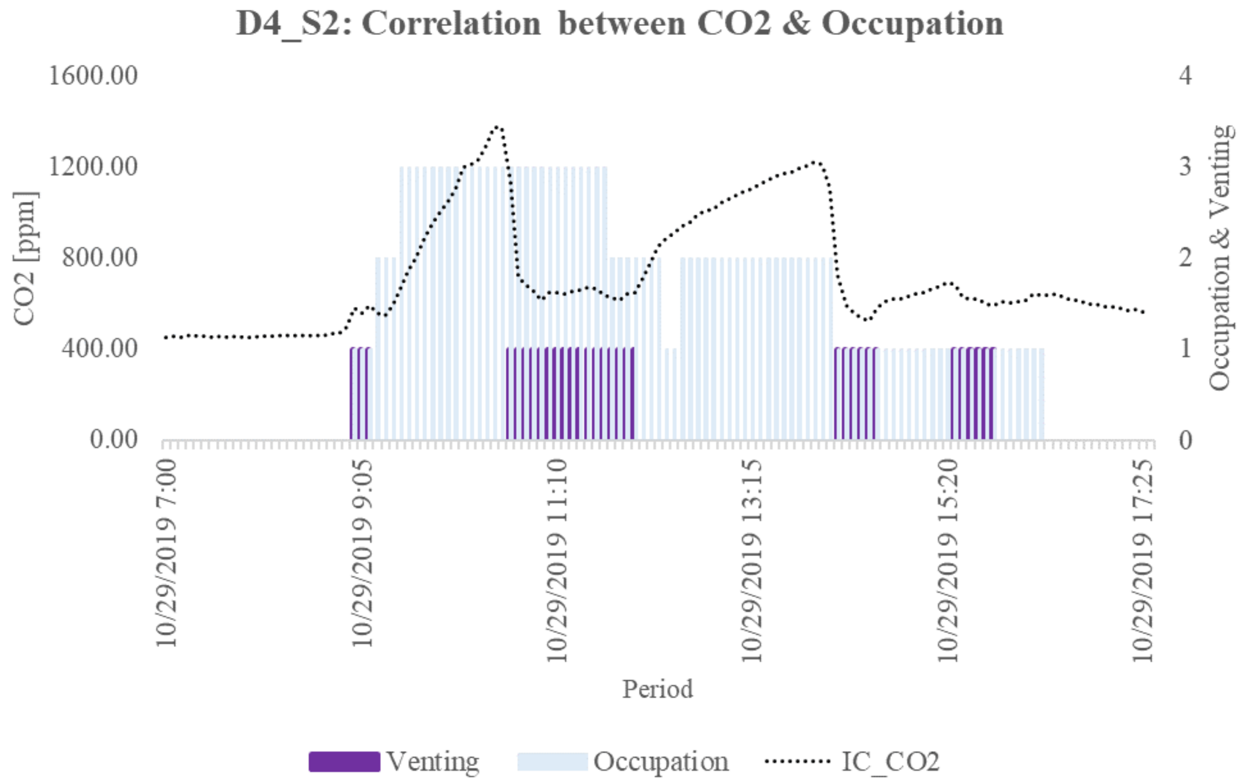



D4_S1: Correlation between CO2 & Occupation
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
4
3
2
1
0
Occupation & Venting
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
Venting
Occupation
IC_CO2

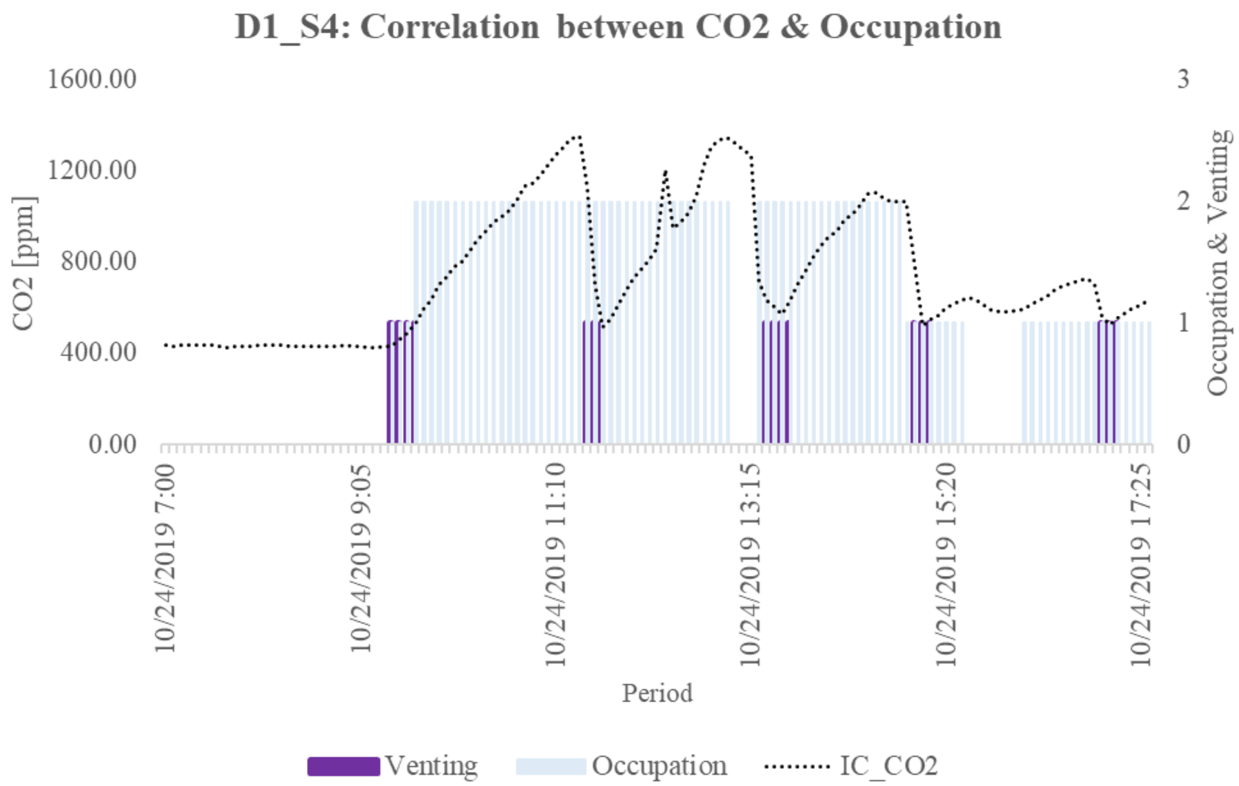
Sensor S2

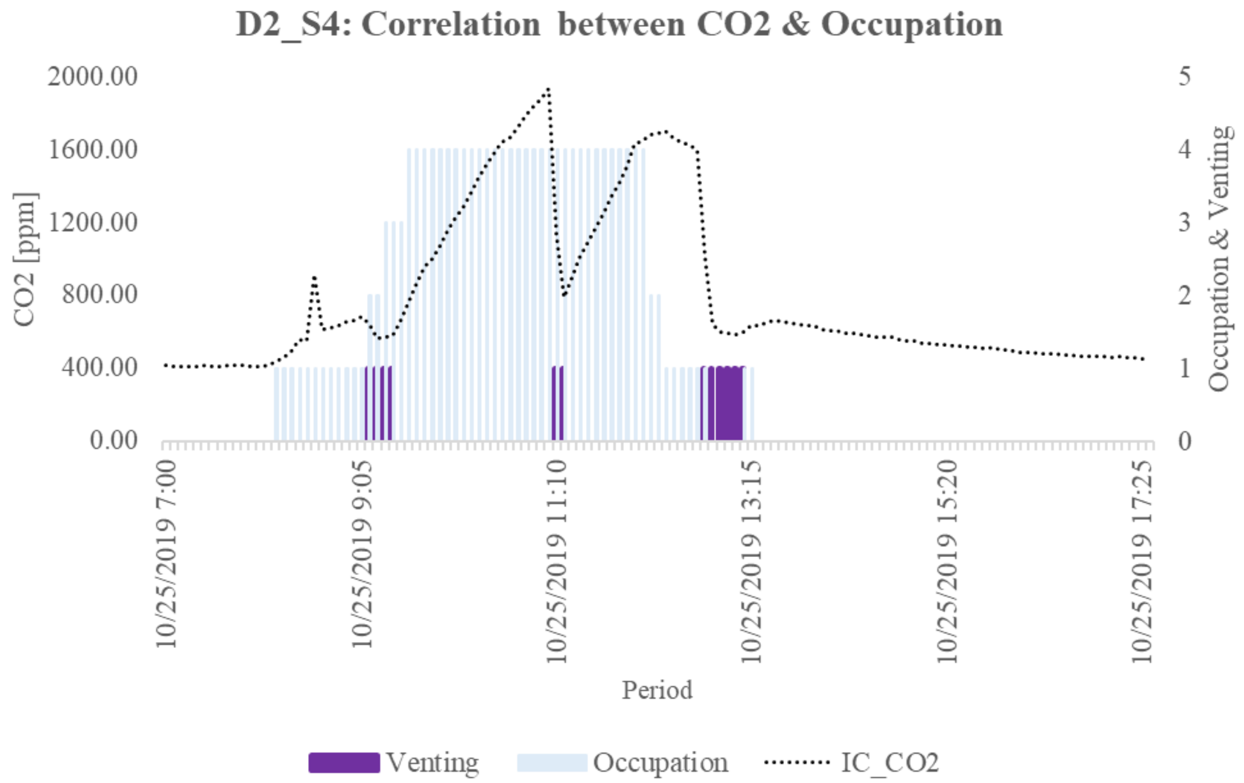

D2_S2: Correlation between CO2 & Occupation
2000.00
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
5
4
3
2
1
0
Occupation & Venting
10/25/2019 7:00
10/25/2019 9:05
10/25/2019 11:10
10/25/2019 13:15
10/25/2019 15:20
10/25/2019 17:25
Period
Venting
Occupation
IC_CO2

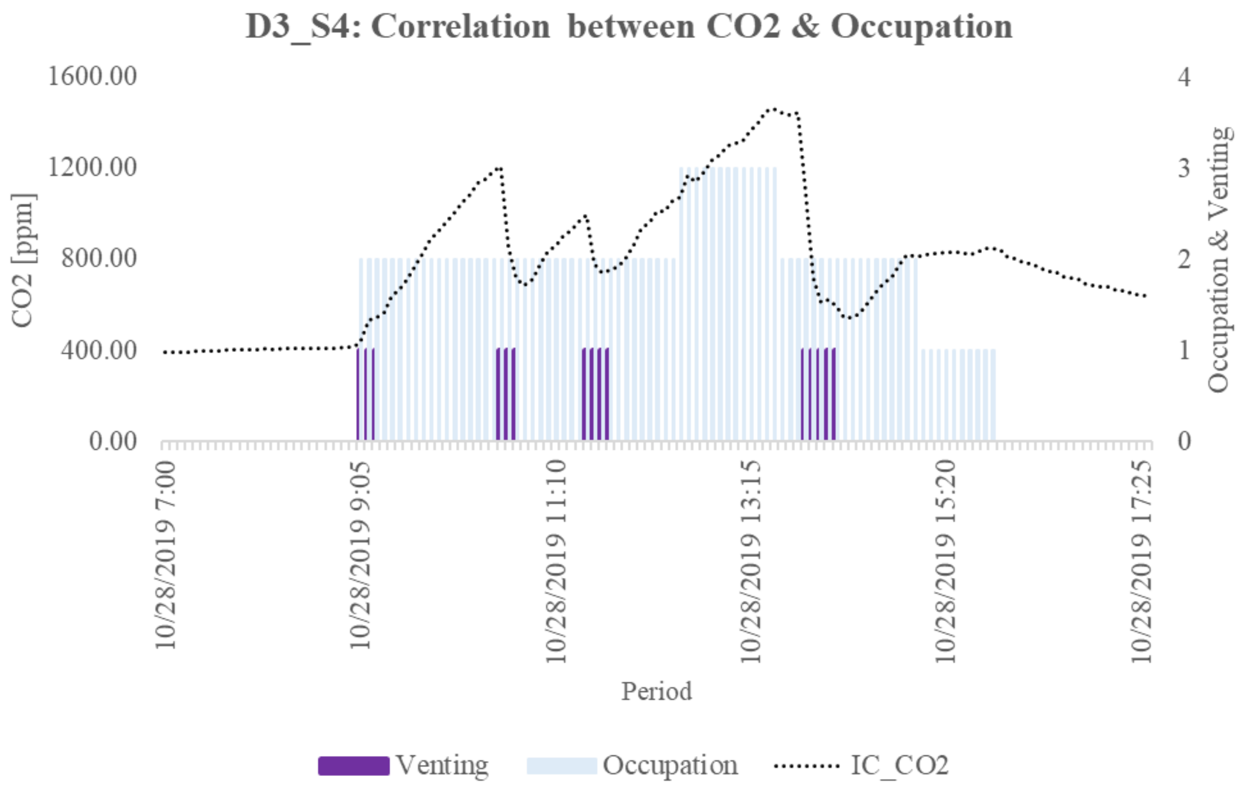

D3_S2: Correlation between CO2 & Occupation
CO2 [ppm]
1600.00
1200.00
800.00
400.00
0.00
Occupation & Venting
4
3
2
1
0
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
Venting
Occupation
IC_CO2

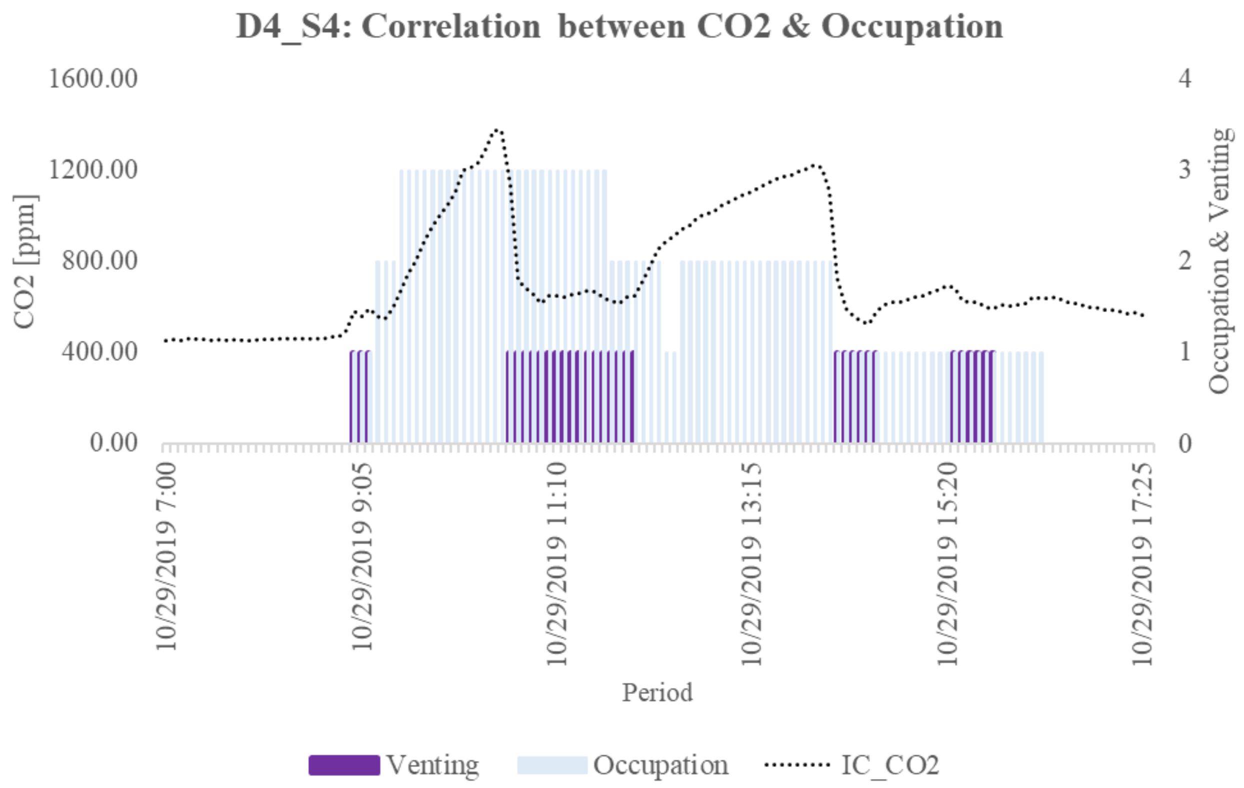

D4_S2: Correlation between CO2 & Occupation
CO2 [ppm]
1600.00
1200.00
800.00
400.00
0.00
Occupation & Venting
4
3
2
1
0
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
Venting
Occupation
IC_CO2

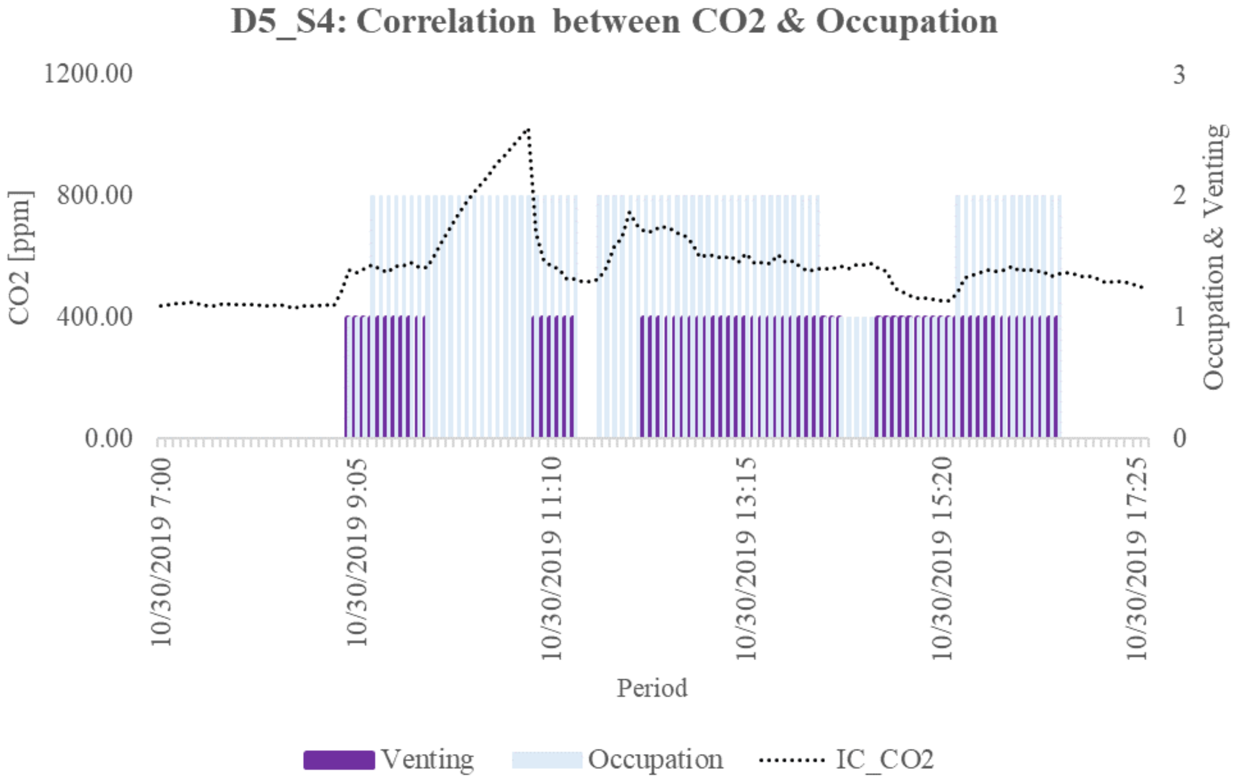
Sensor S4


D1_S4: Correlation between CO2 & Occupation
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
3
2
1
0
Occupation & Venting
10/24/2019 7:00
10/24/2019 9:05
10/24/2019 11:10
10/24/2019 13:15
10/24/2019 15:20
10/24/2019 17:25
Period
Venting
Occupation
IC_CO2


D2_S4: Correlation between CO2 & Occupation
2000.00
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
5
4
3
2
1
0
Occupation & Venting
10/25/2019 7:00
10/25/2019 9:05
10/25/2019 11:10
10/25/2019 13:15
10/25/2019 15:20
10/25/2019 17:25
Period
Venting
Occupation
IC_CO2

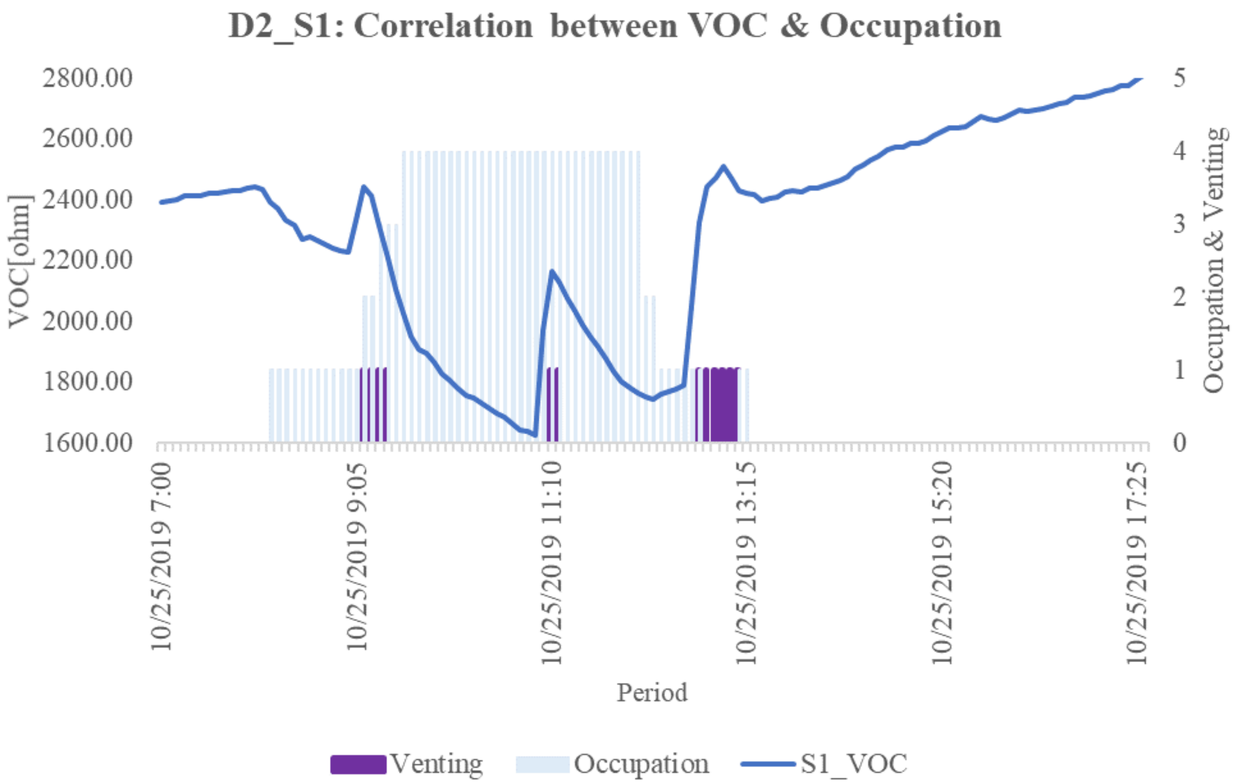

D3_S4: Correlation between CO2 & Occupation
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
4
3
2
1
0
Occupation & Venting
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
Venting
Occupation
IC_CO2

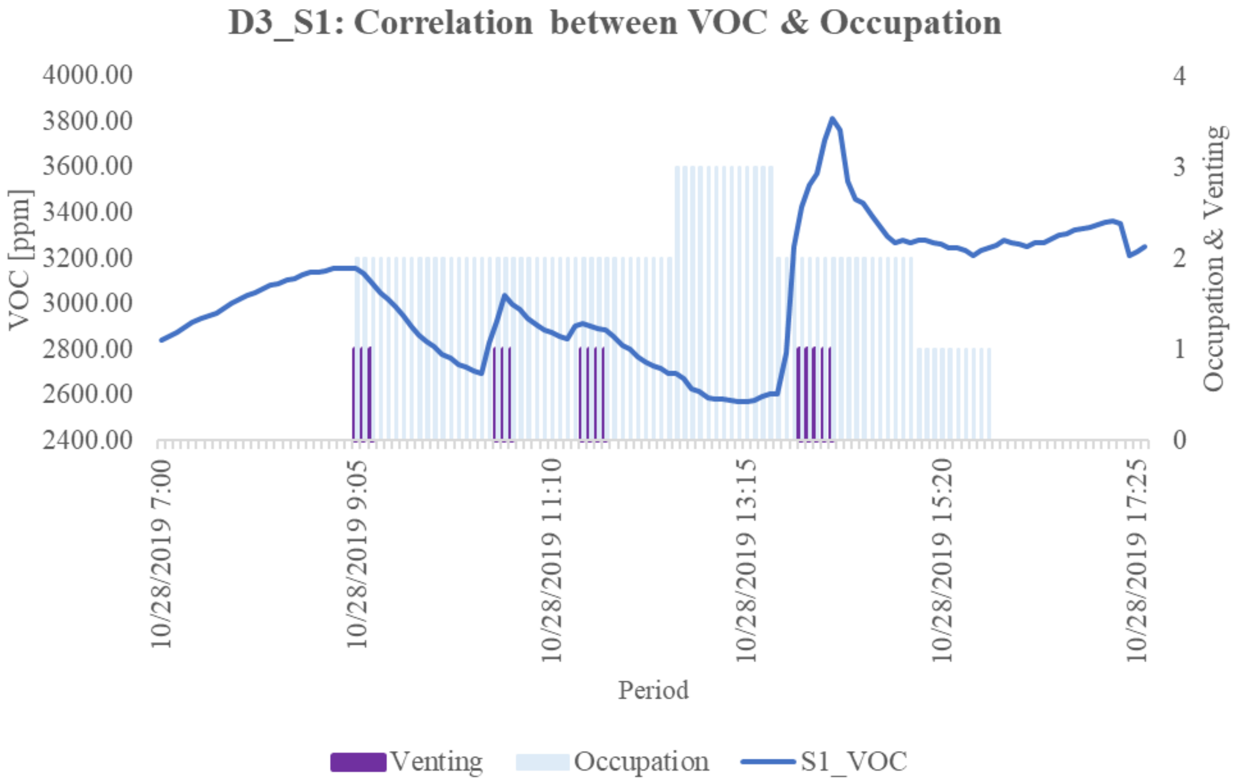

D4_S4: Correlation between CO2 & Occupation
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
4
3
2
1
0
Occupation & Venting
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
Venting
Occupation
IC_CO2

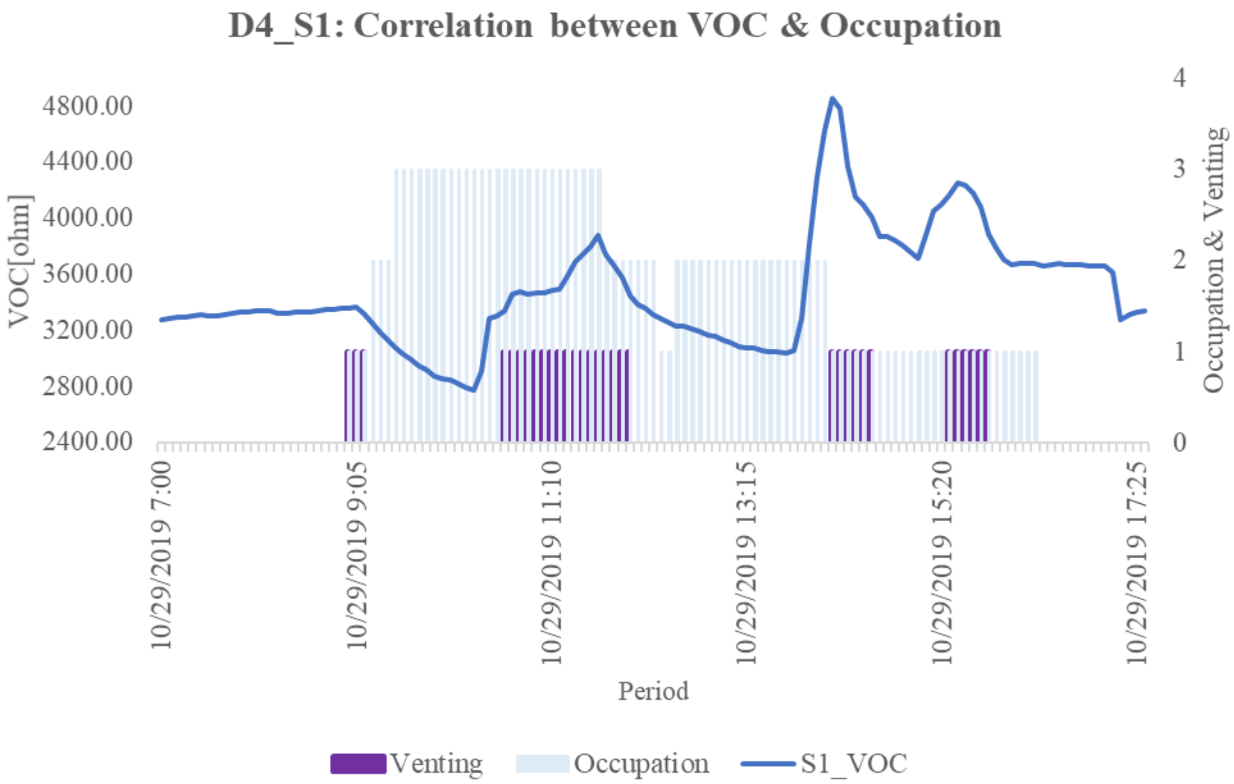


8.3.2 Correlation between the VOC & Occupancy during the 1st until the 4th day for all sensors

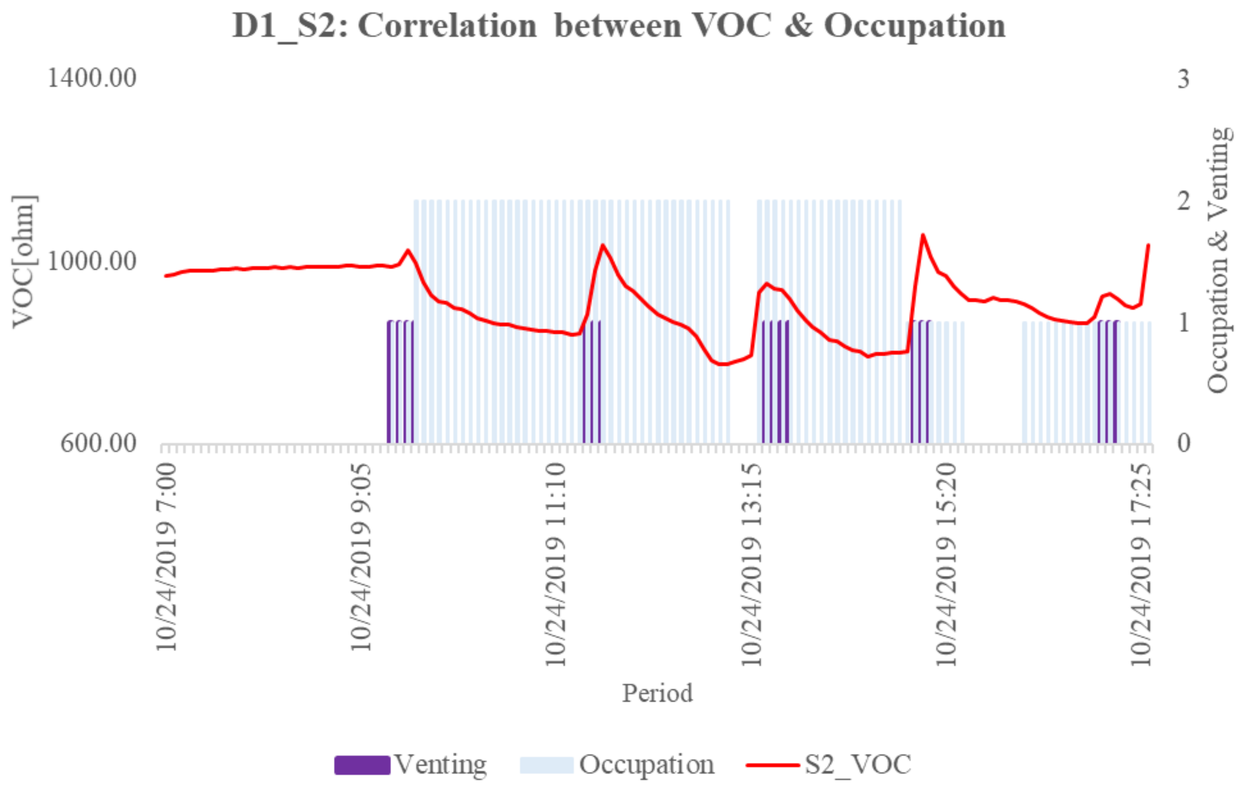
Sensor S1 presented only from the 2nd until the 4th day since it is referred in 5.6.2)

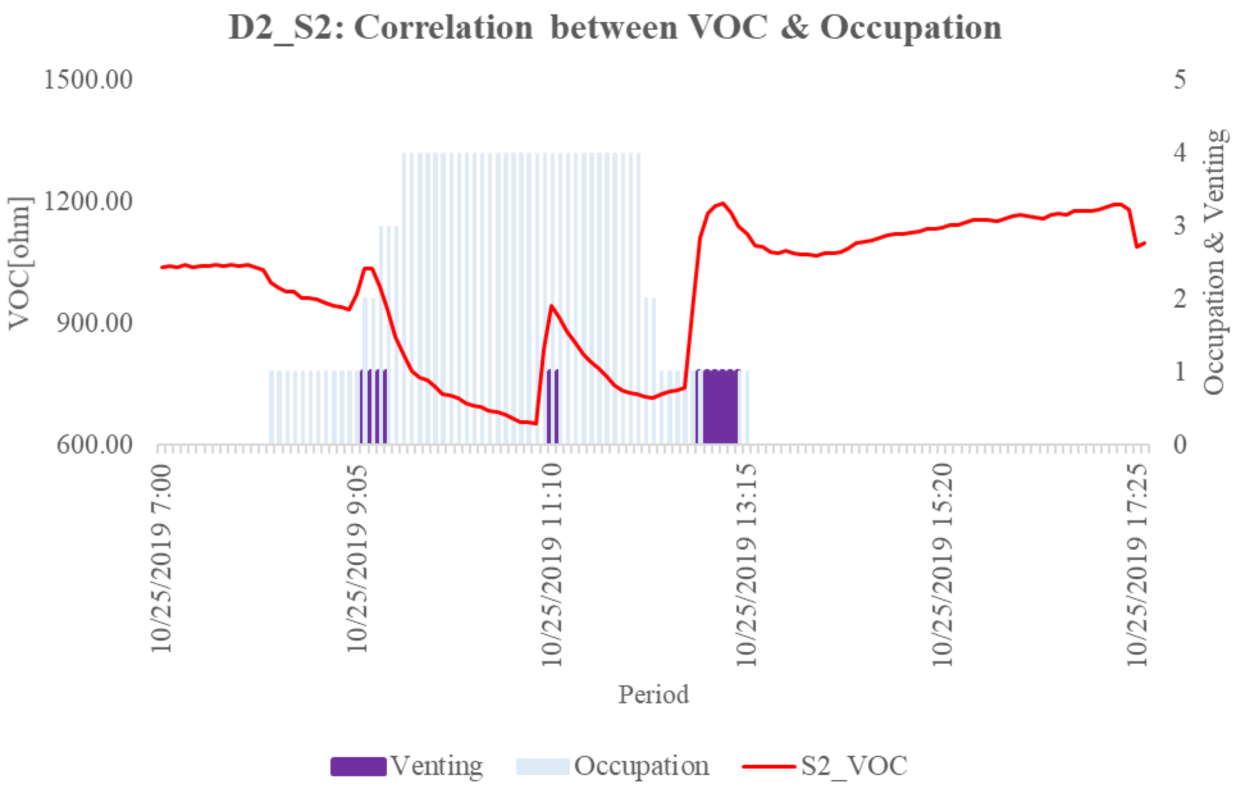


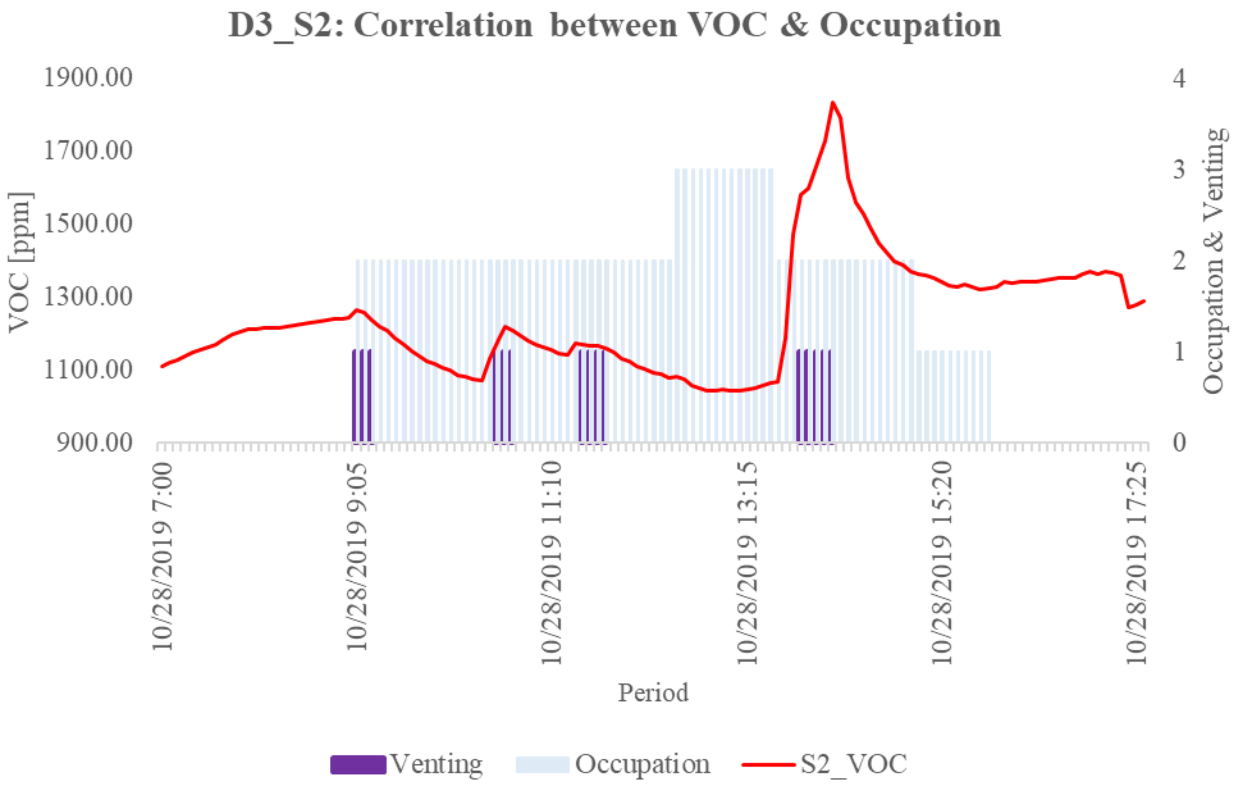

D3_S1: Correlation between VOC & Occupation
VOC [ppm]
4000.00
3800.00
3600.00
3400.00
3200.00
3000.00
2800.00
2600.00
2400.00
Occupation & Venting
4
3
2
1
0
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
Venting
Occupation
S1_VOC

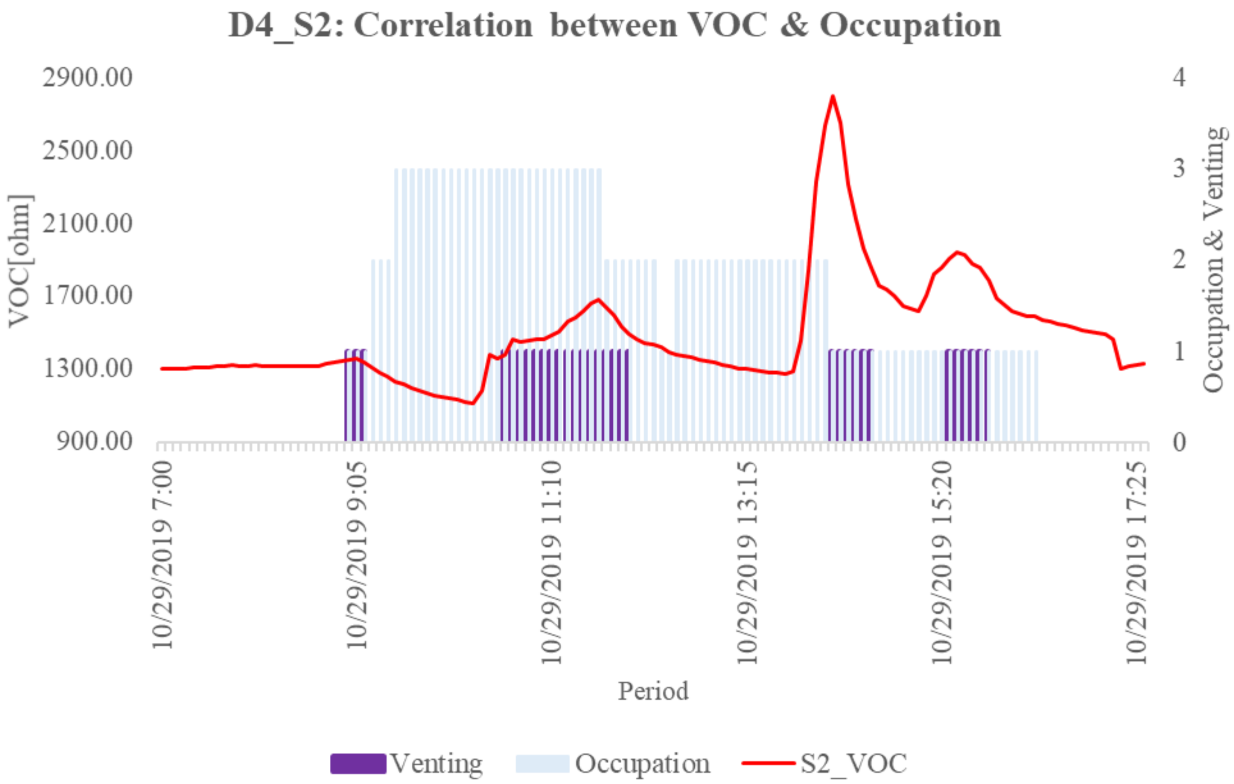

D4_S1: Correlation between VOC & Occupation
VOC[ohm]
4800.00
4400.00
4000.00
3600.00
3200.00
2800.00
2400.00
Occupation & Venting
4
3
2
1
0
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
Venting
Occupation
S1_VOC

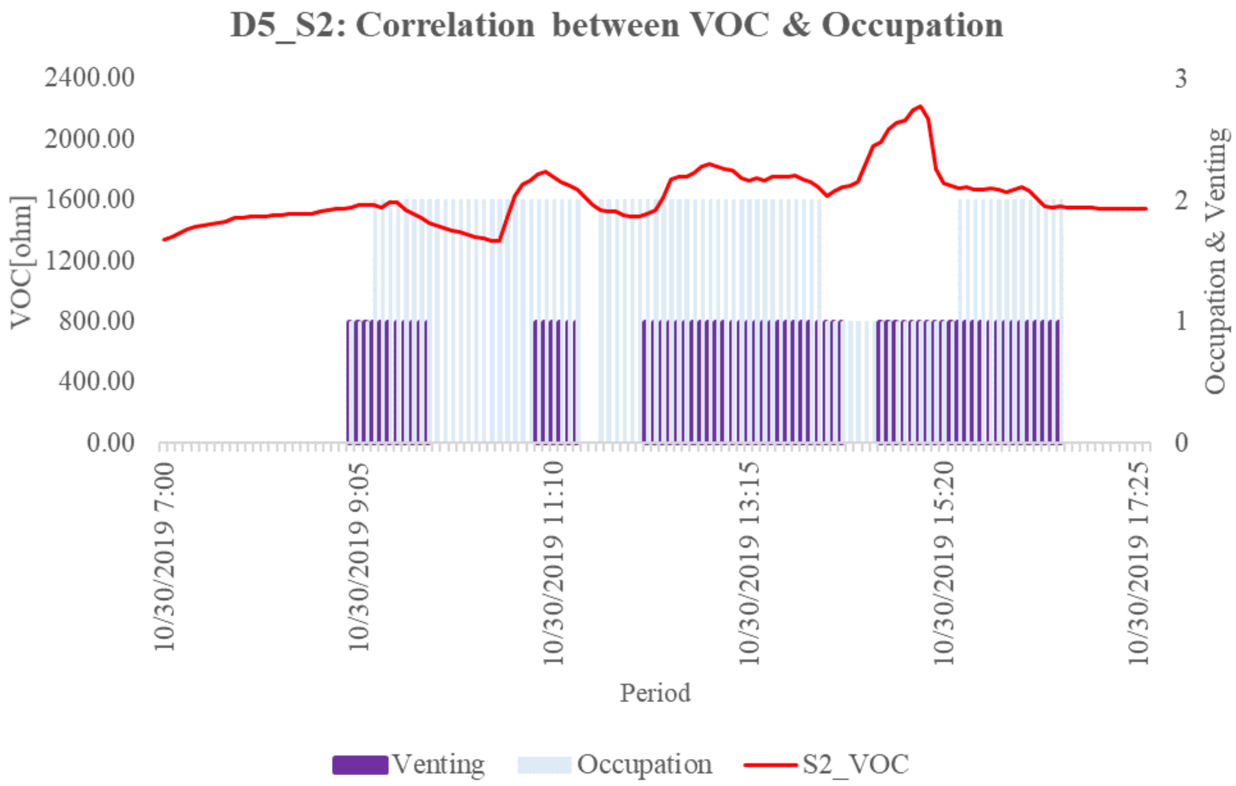
Sensor S2


D1_S2: Correlation between VOC & Occupation
1400.00
1000.00
600.00
VOC[ohm]
3
2
1
0
Occupation & Venting
10/24/2019 7:00
10/24/2019 9:05
10/24/2019 11:10
10/24/2019 13:15
10/24/2019 15:20
10/24/2019 17:25
Period
Venting
Occupation
S2_VOC

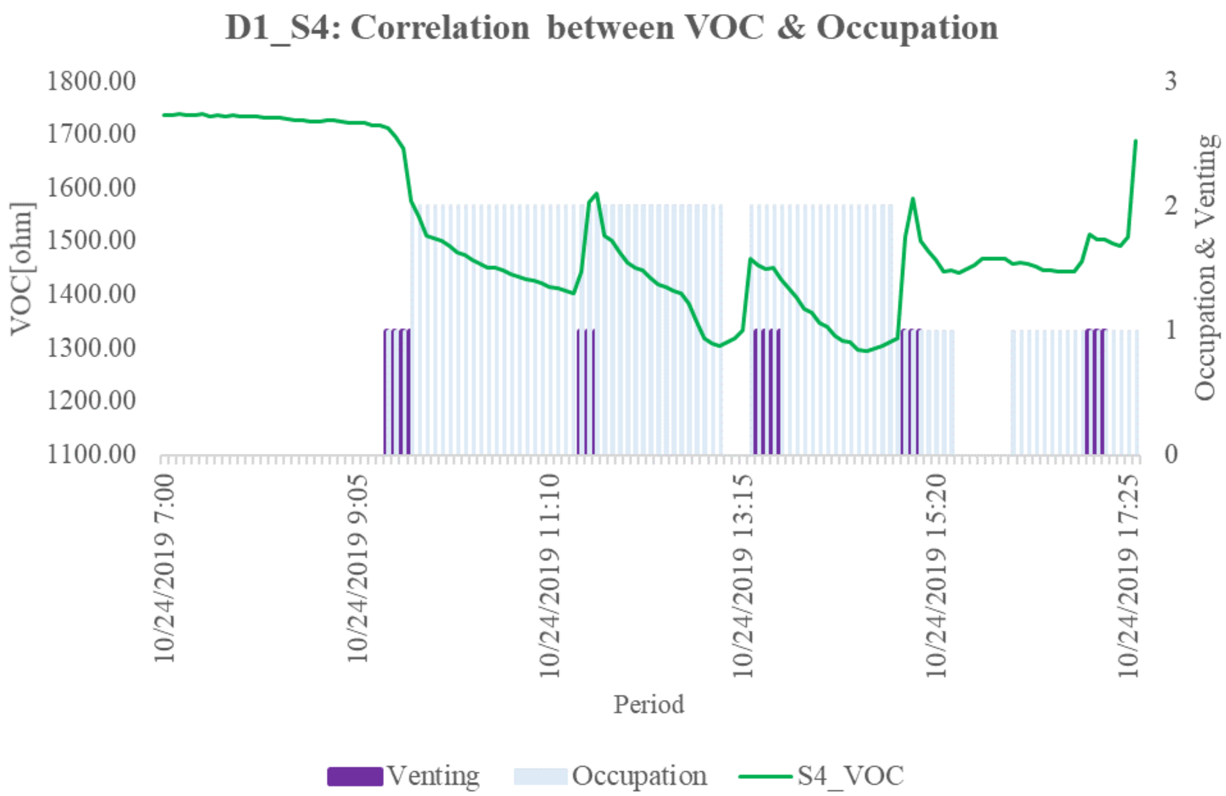

D2_S2: Correlation between VOC & Occupation
1500.00
1200.00
900.00
600.00
VOC[ohm]
5
4
3
2
1
0
Occupation & Venting
10/25/2019 7:00
10/25/2019 9:05
10/25/2019 11:10
10/25/2019 13:15
10/25/2019 15:20
10/25/2019 17:25
Period
Venting
Occupation
S2_VOC

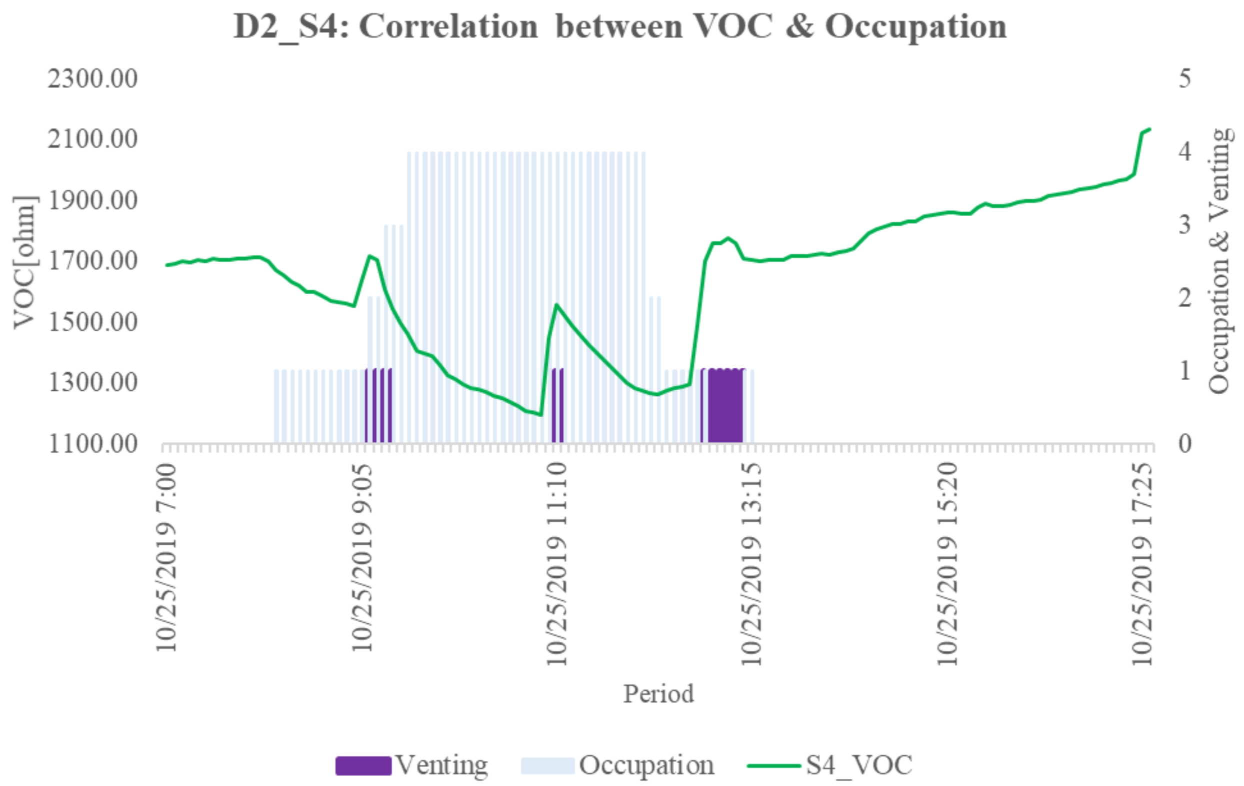

D3_S2: Correlation between VOC & Occupation
VOC [ppm]
1900.00
1700.00
1500.00
1300.00
1100.00
900.00
Occupation & Venting
4
3
2
1
0
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
Venting
Occupation
S2_VOC

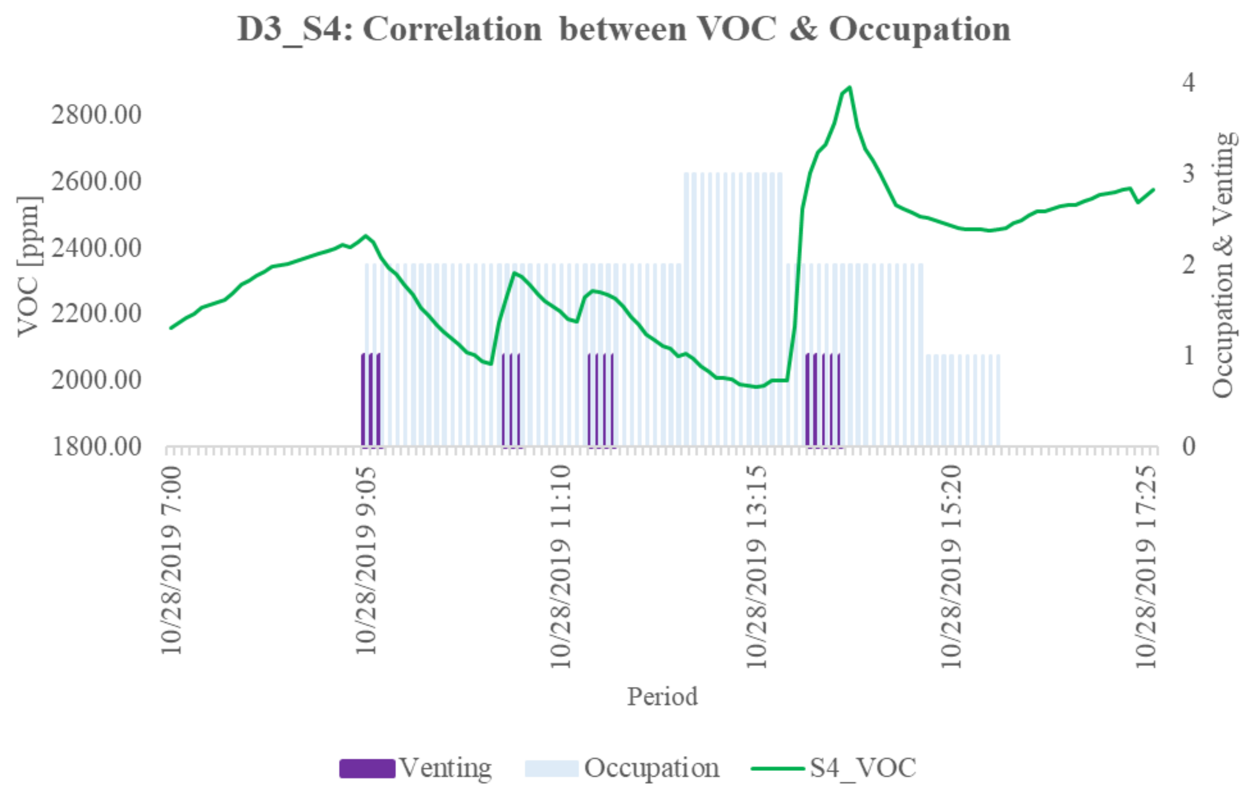

D4_S2: Correlation between VOC & Occupation
VOC[ohm]
2900.00
2500.00
2100.00
1700.00
1300.00
900.00
Occupation & Venting
4
3
2
1
0
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
Venting
Occupation
S2_VOC

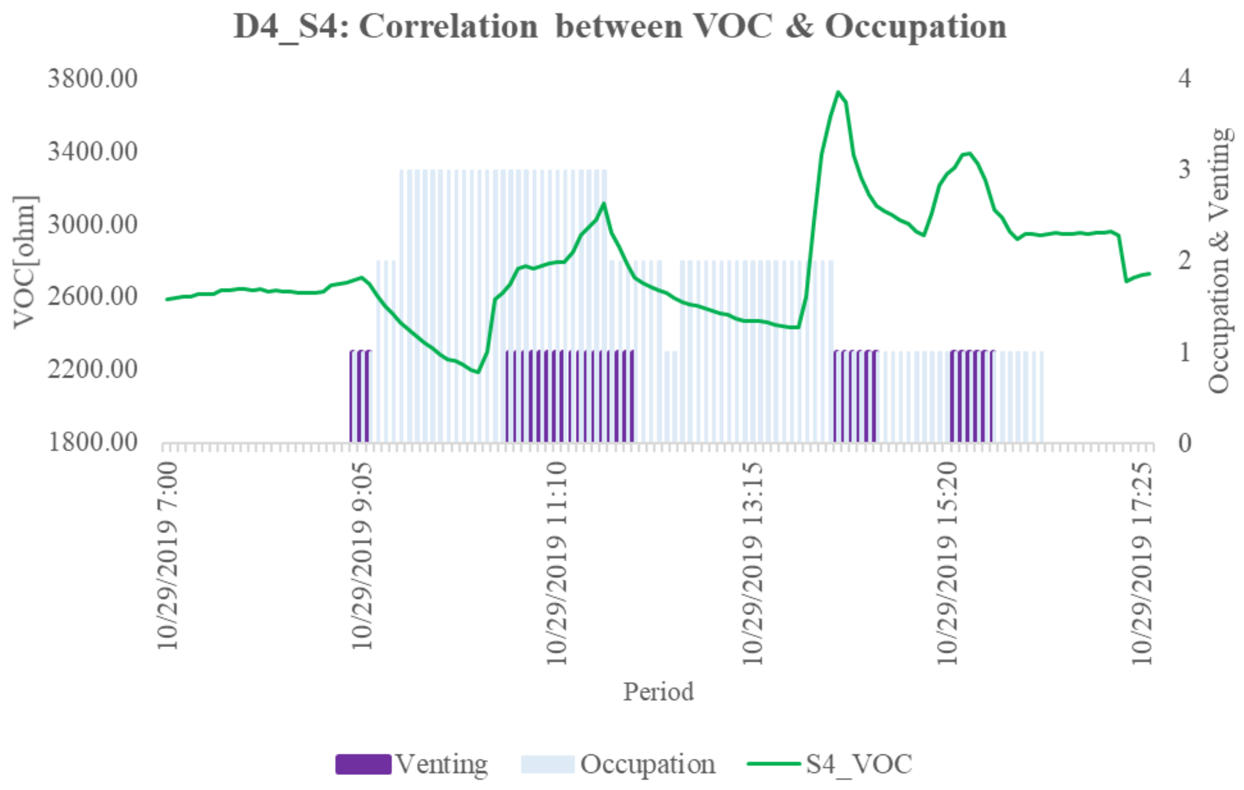

D5_S2: Correlation between VOC & Occupation
2400.00
2000.00
1600.00
1200.00
800.00
400.00
0.00
VOC[ohm]
3
2
1
0
Occupation & Venting
10/30/2019 7:00
10/30/2019 9:05
10/30/2019 11:10
10/30/2019 13:15
10/30/2019 15:20
10/30/2019 17:25
Period
Venting
Occupation
S2_VOC

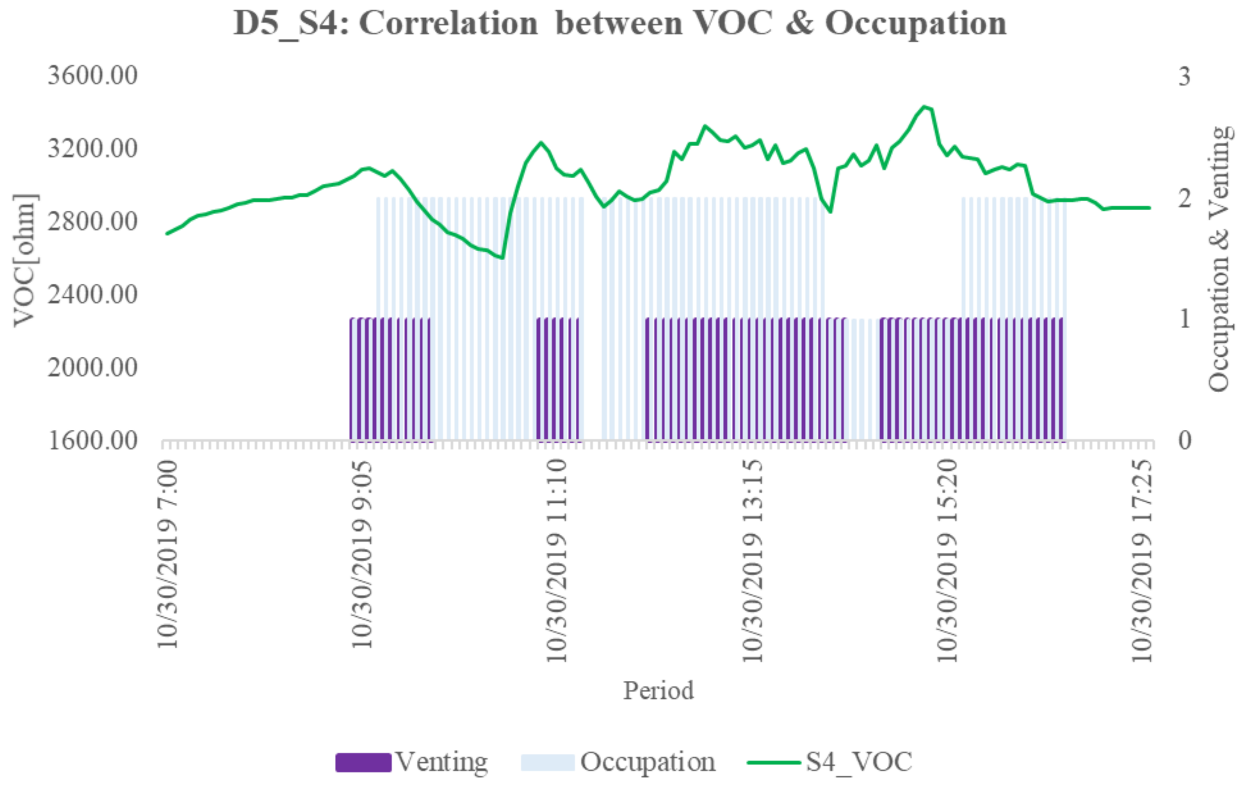
Sensor S4


D1_S4: Correlation between VOC & Occupation
1800.00
1700.00
1600.00
1500.00
1400.00
1300.00
1200.00
1100.00
VOC[ohm]
3
2
1
0
Occupation & Venting
10/24/2019 7:00
10/24/2019 9:05
10/24/2019 11:10
10/24/2019 13:15
10/24/2019 15:20
10/24/2019 17:25
Period
Venting
Occupation
S4_VOC


D2_S4: Correlation between VOC & Occupation
2300.00
2100.00
1900.00
1700.00
1500.00
1300.00
1100.00
VOC[ohm]
5
4
3
2
1
0
Occupation & Venting
10/25/2019 7:00
10/25/2019 9:05
10/25/2019 11:10
10/25/2019 13:15
10/25/2019 15:20
10/25/2019 17:25
Period
Venting
Occupation
S4_VOC

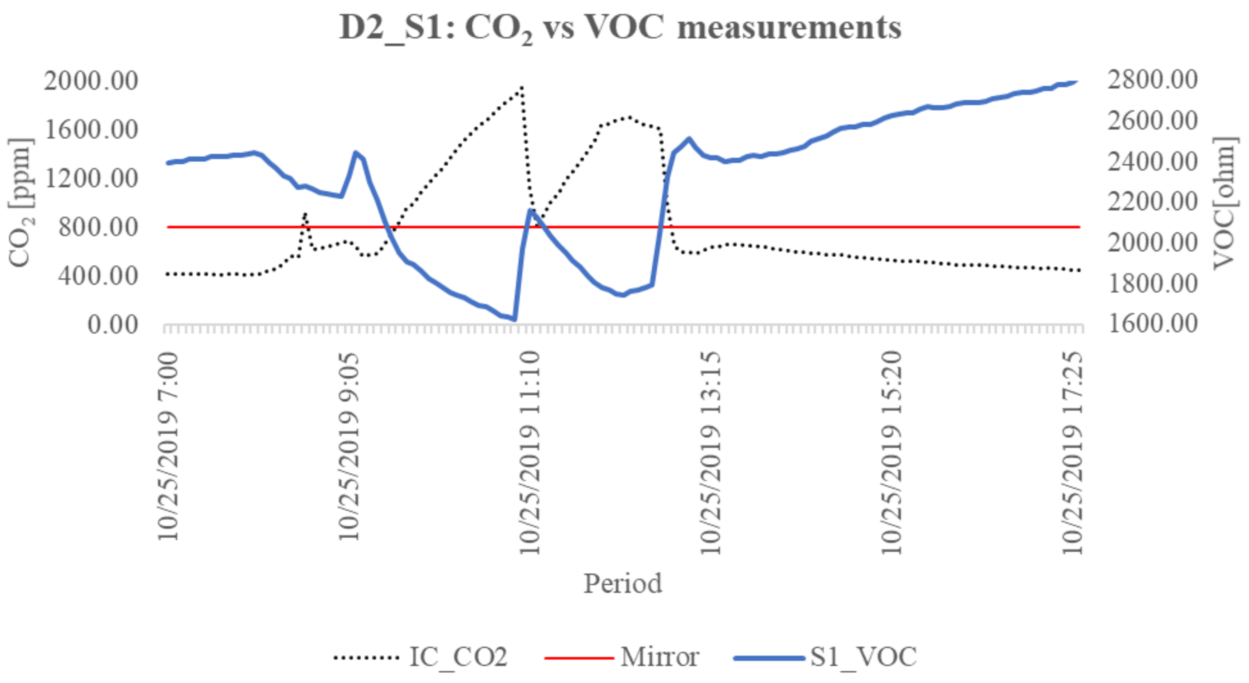

D3_S4: Correlation between VOC & Occupation
2800.00
2600.00
2400.00
2200.00
2000.00
1800.00
VOC [ppm]
4
3
2
1
0
Occupation & Venting
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
Venting
Occupation
S4_VOC

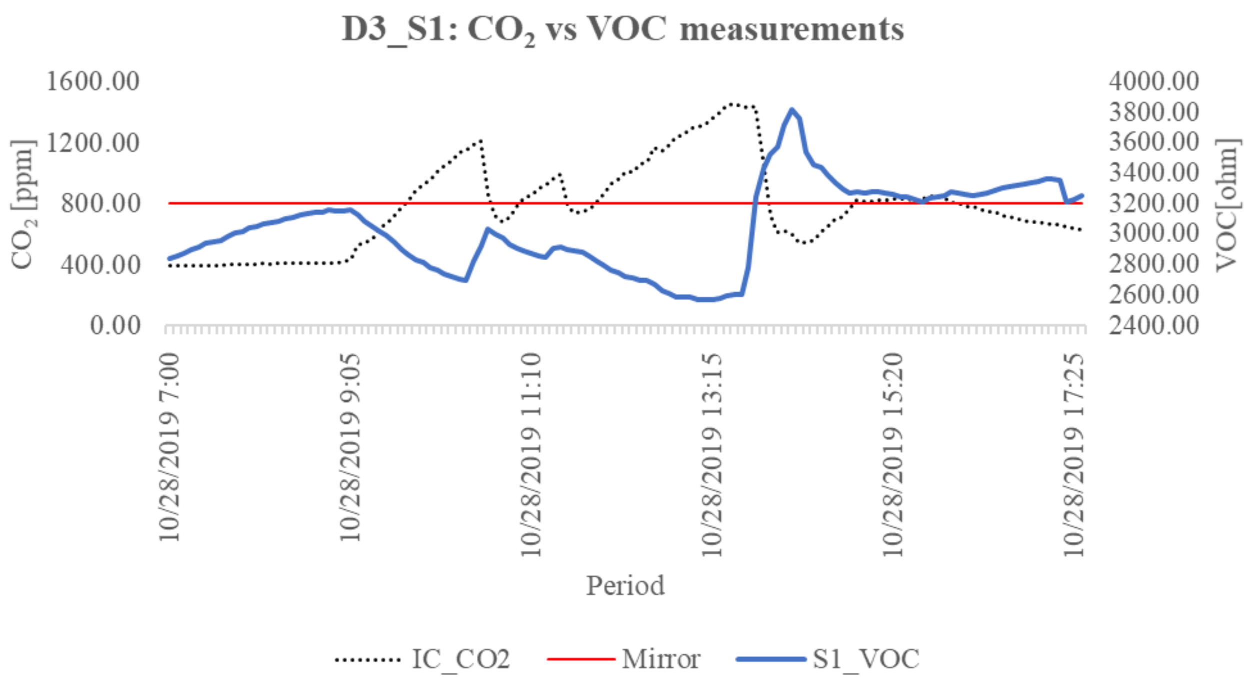

D4_S4: Correlation between VOC & Occupation
3800.00
3400.00
3000.00
2600.00
2200.00
1800.00
VOC[ohm]
4
3
2
1
0
Occupation & Venting
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
Venting
Occupation
S4_VOC

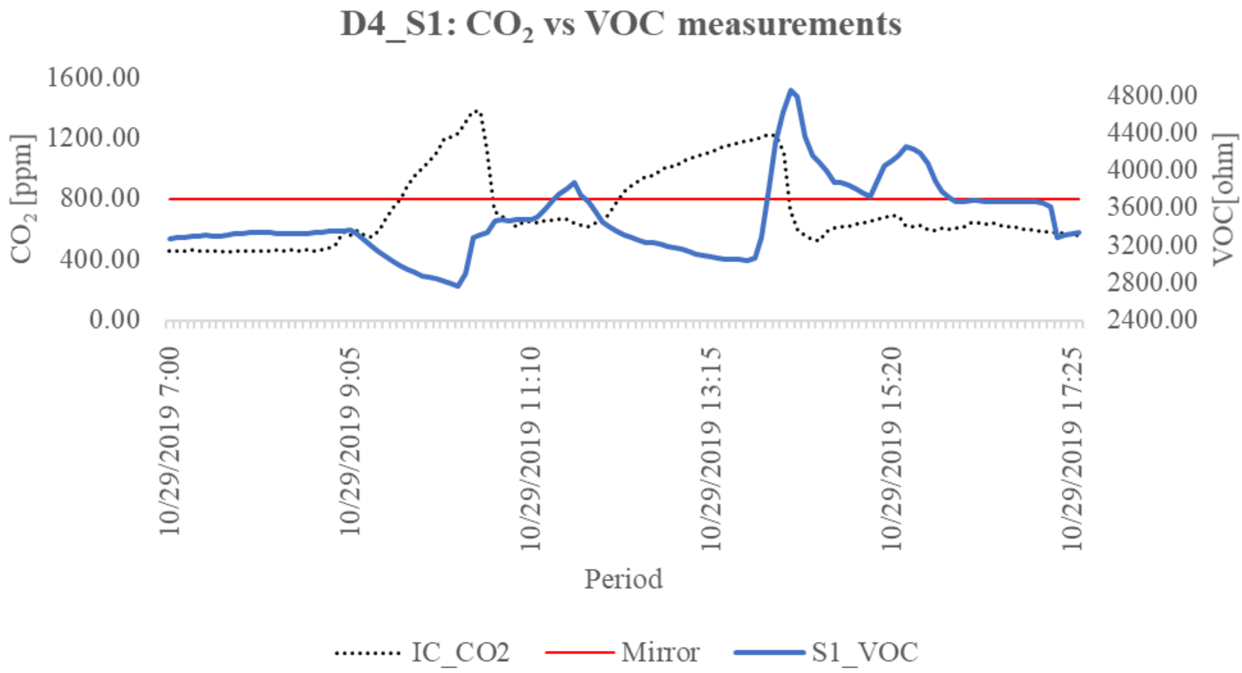

D5_S4: Correlation between VOC & Occupation
3600.00
3200.00
2800.00
2400.00
2000.00
1600.00
VOC[ohm]
3
2
1
0
Occupation & Venting
10/30/2019 7:00
10/30/2019 9:05
10/30/2019 11:10
10/30/2019 13:15
10/30/2019 15:20
10/30/2019 17:25
Period
Venting
Occupation
S4_VOC

8.3.3 Correlation between the CO_2 & VOC during the 1st until the 5th day for all sensors

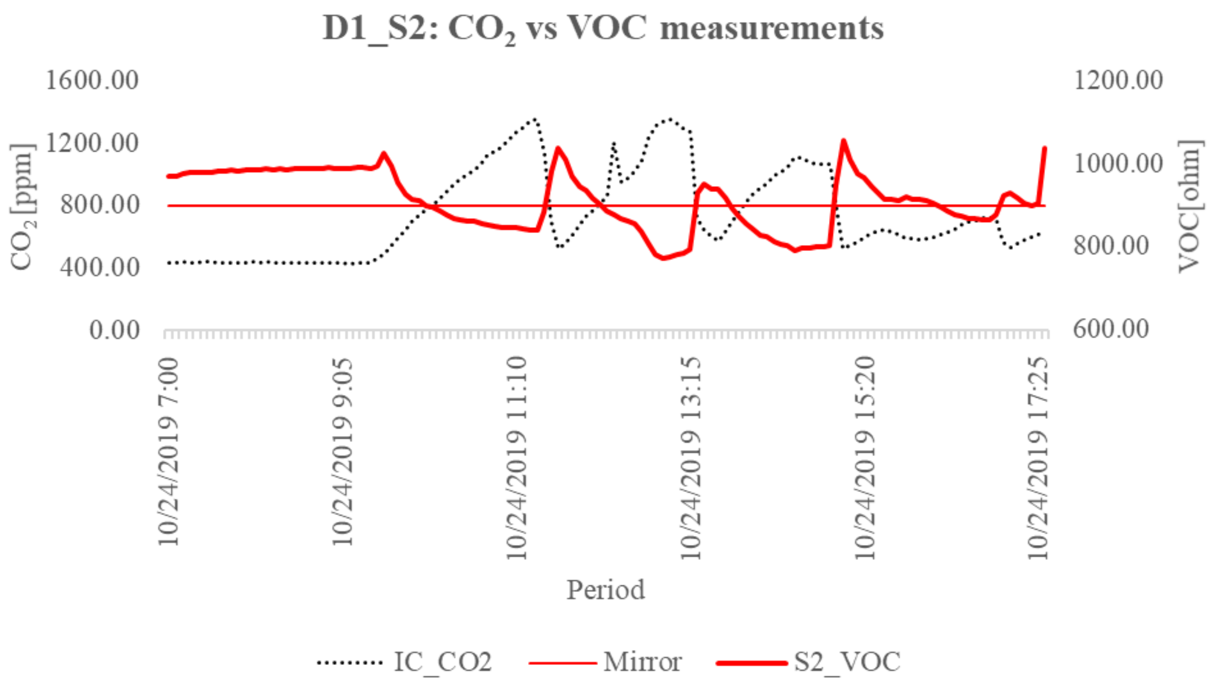
Sensor S1 presented only from the 2nd until the 4th day since it is referred in 5.6.3)

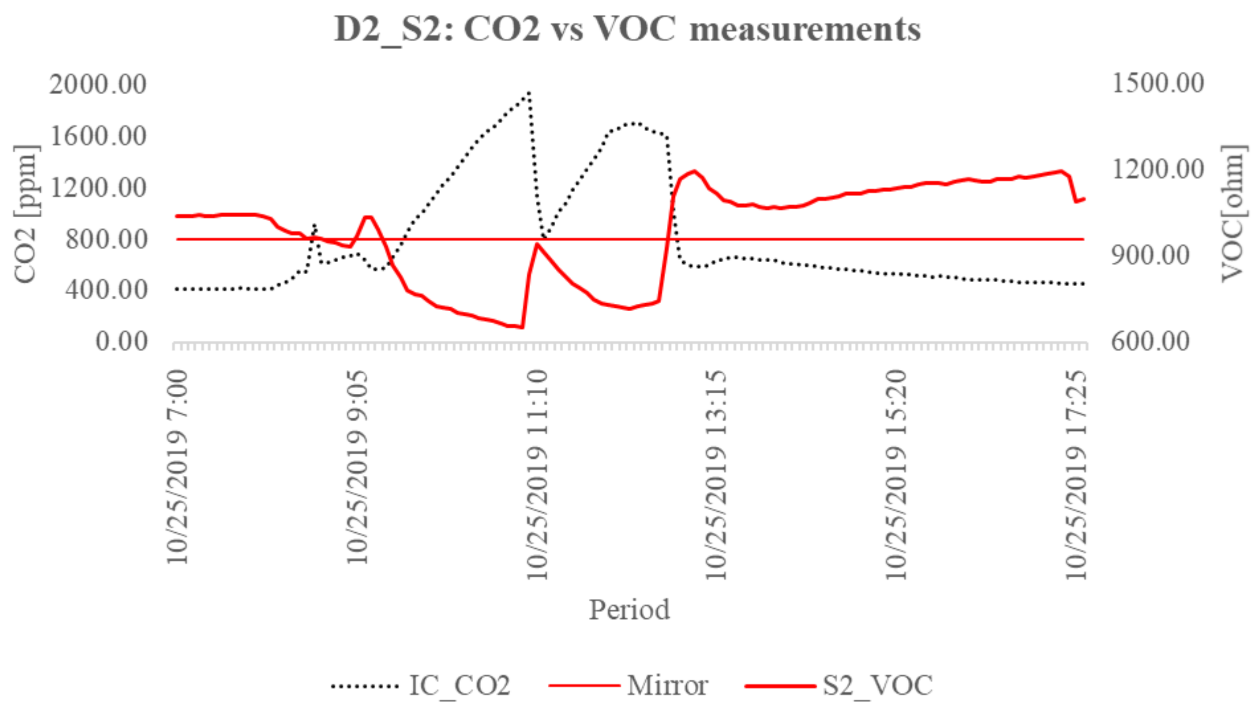


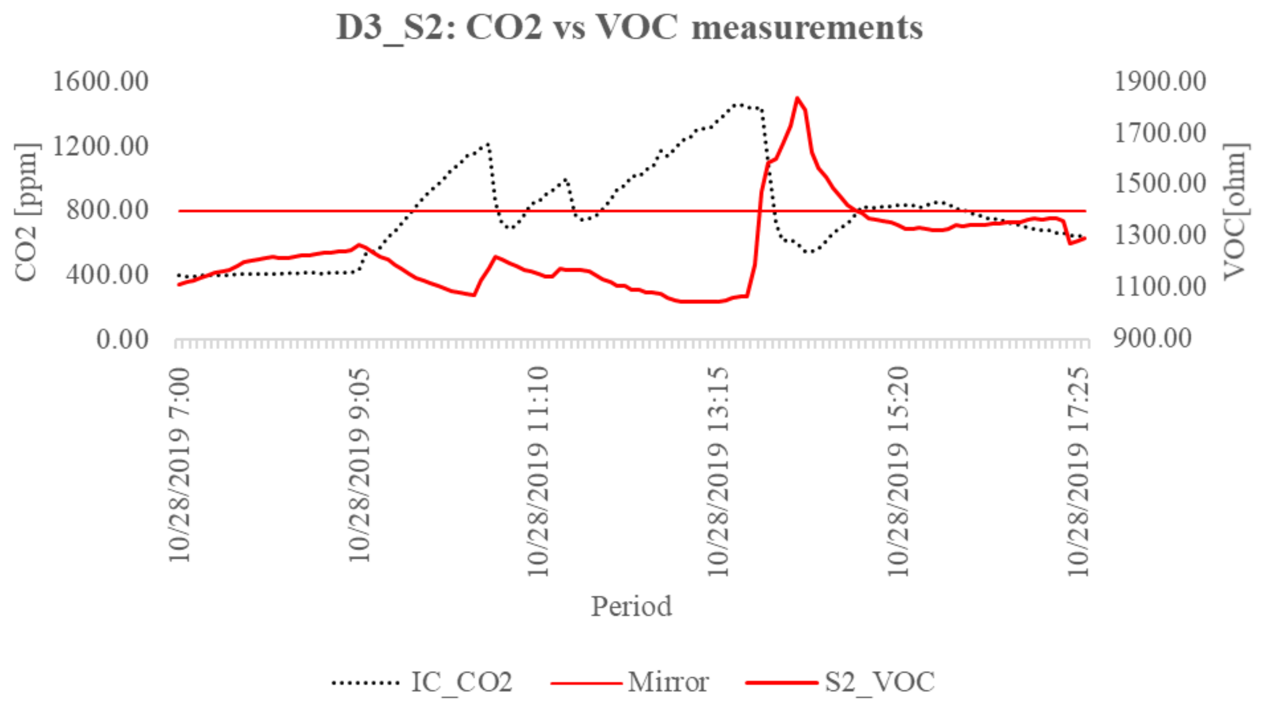


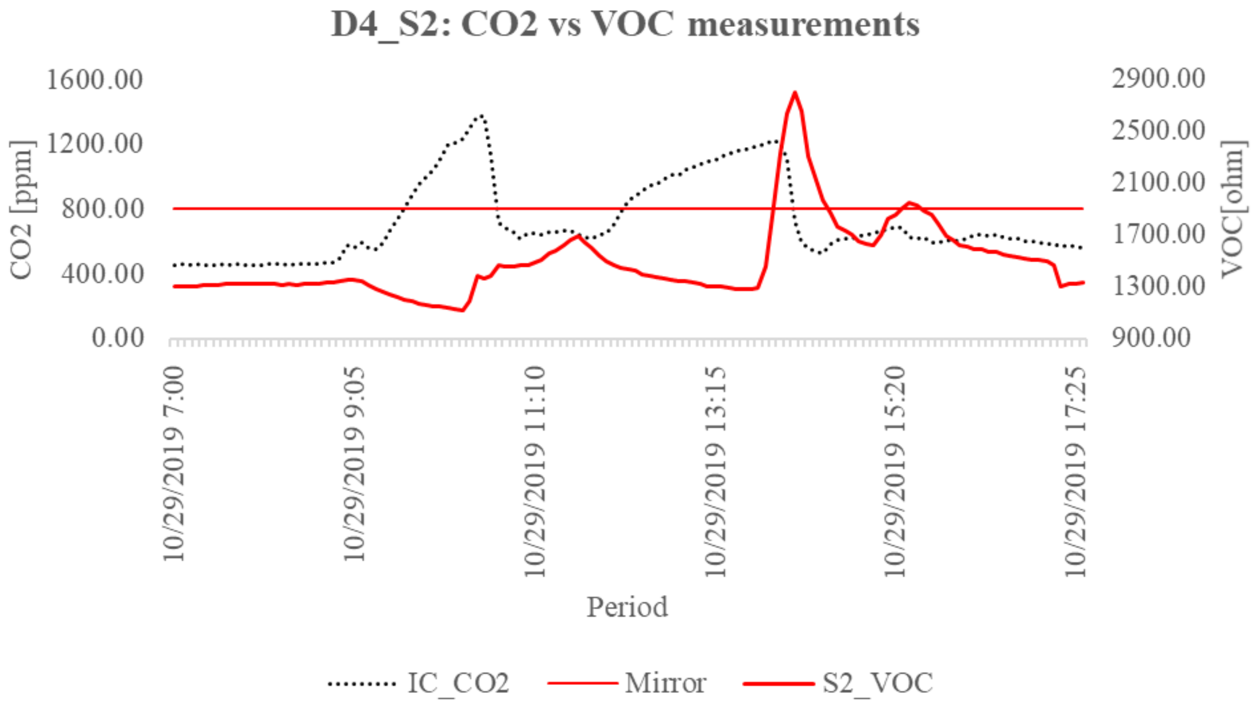

D4_S1: CO_2 vs VOC measurements
1600.00
1200.00
800.00
400.00
0.00
CO_2 [ppm]
4800.00
4400.00
4000.00
3600.00
3200.00
2800.00
2400.00
VOC[ohm]
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
IC_CO2
Mirror
S1_VOC

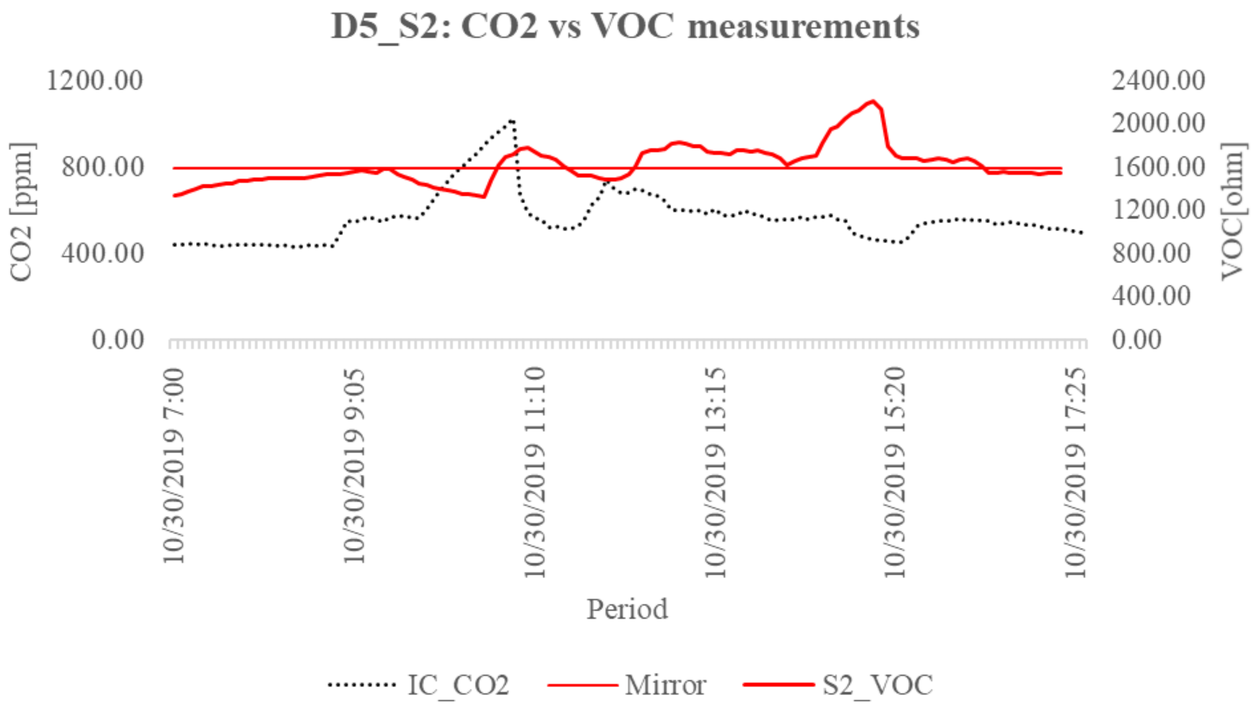
Sensor S2


D1_S2: CO_2 vs VOC measurements
1600.00
1200.00
800.00
400.00
0.00
CO_2 [ppm]
1200.00
1000.00
800.00
600.00
VOC[ohm]
10/24/2019 7:00
10/24/2019 9:05
10/24/2019 11:10
10/24/2019 13:15
10/24/2019 15:20
10/24/2019 17:25
Period
IC_CO2
Mirror
S2_VOC

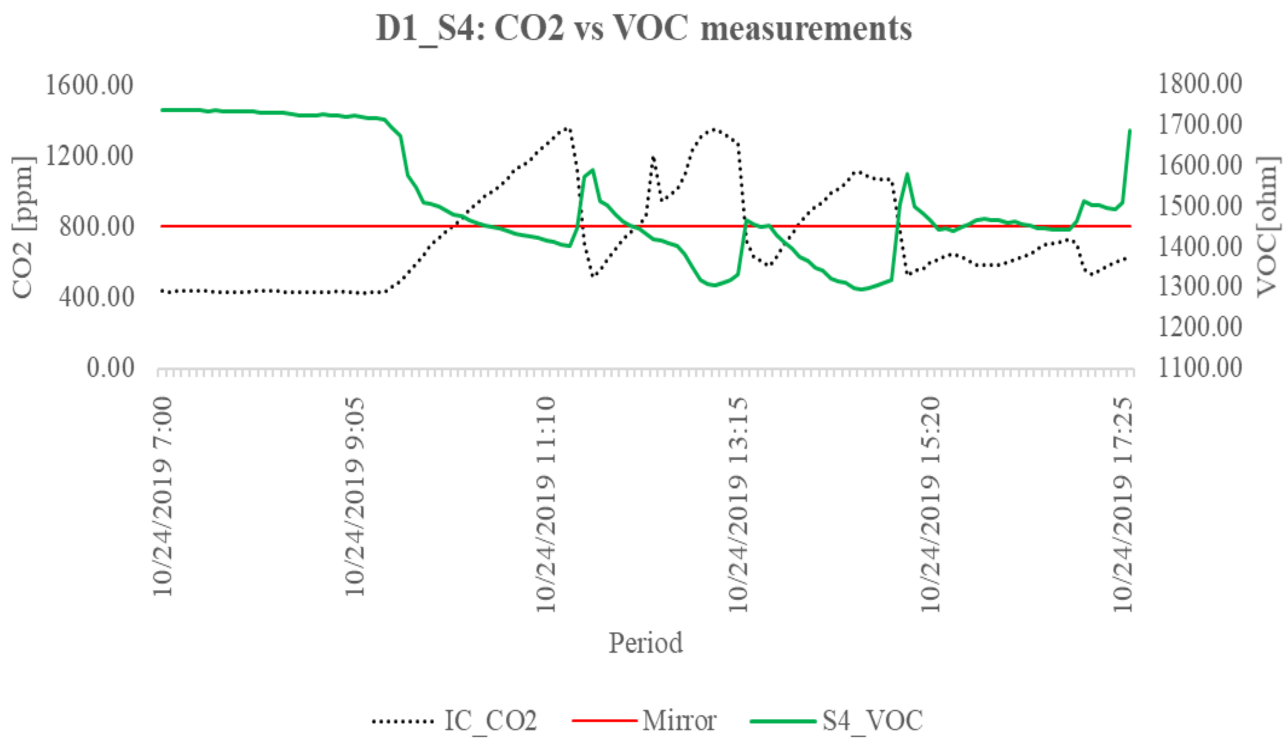

D2_S2: CO2 vs VOC measurements
CO2 [ppm]
VOC[ohm]
2000.00
1600.00
1200.00
800.00
400.00
0.00
1500.00
1200.00
900.00
600.00
10/25/2019 7:00
10/25/2019 9:05
10/25/2019 11:10
10/25/2019 13:15
10/25/2019 15:20
10/25/2019 17:25
Period
IC_CO2
Mirror
S2_VOC

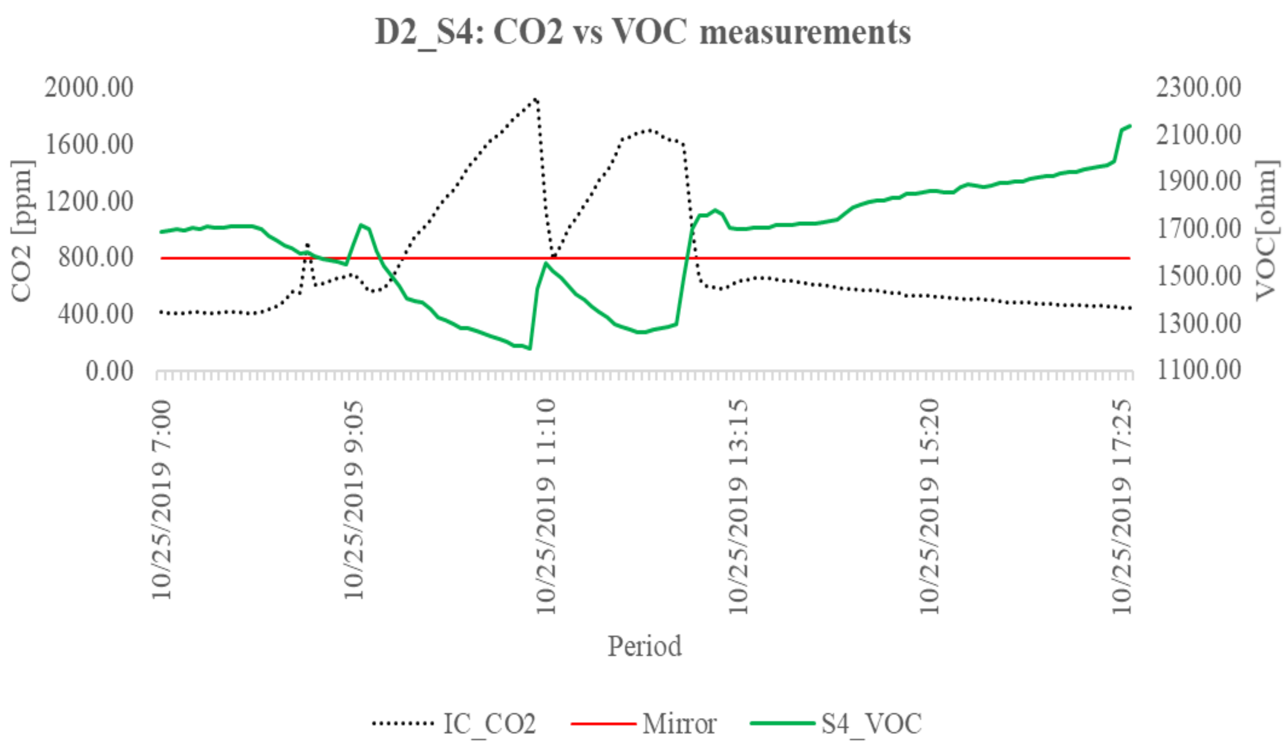

D3_S2: CO2 vs VOC measurements
CO2 [ppm]
VOC[ohm]
1600.00
1200.00
800.00
400.00
0.00
1900.00
1700.00
1500.00
1300.00
1100.00
900.00
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
IC_CO2
Mirror
S2_VOC

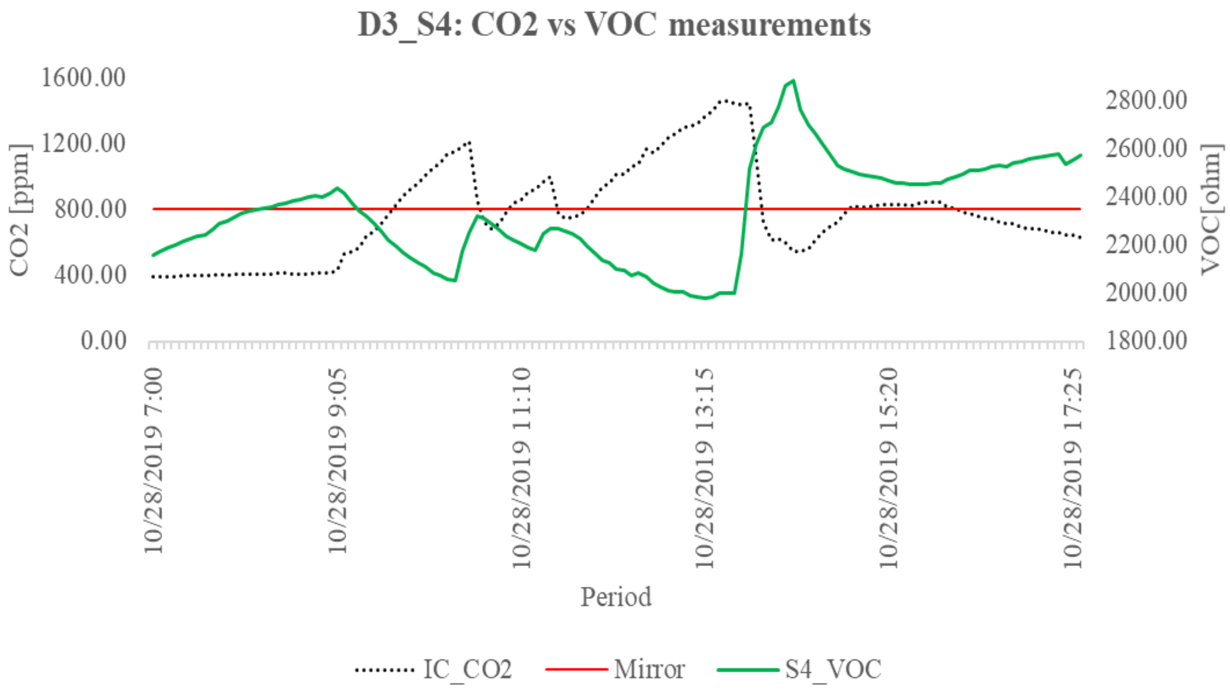

D4_S2: CO2 vs VOC measurements
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
2900.00
2500.00
2100.00
1700.00
1300.00
900.00
VOC[ohm]
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
IC_CO2
Mirror
S2_VOC

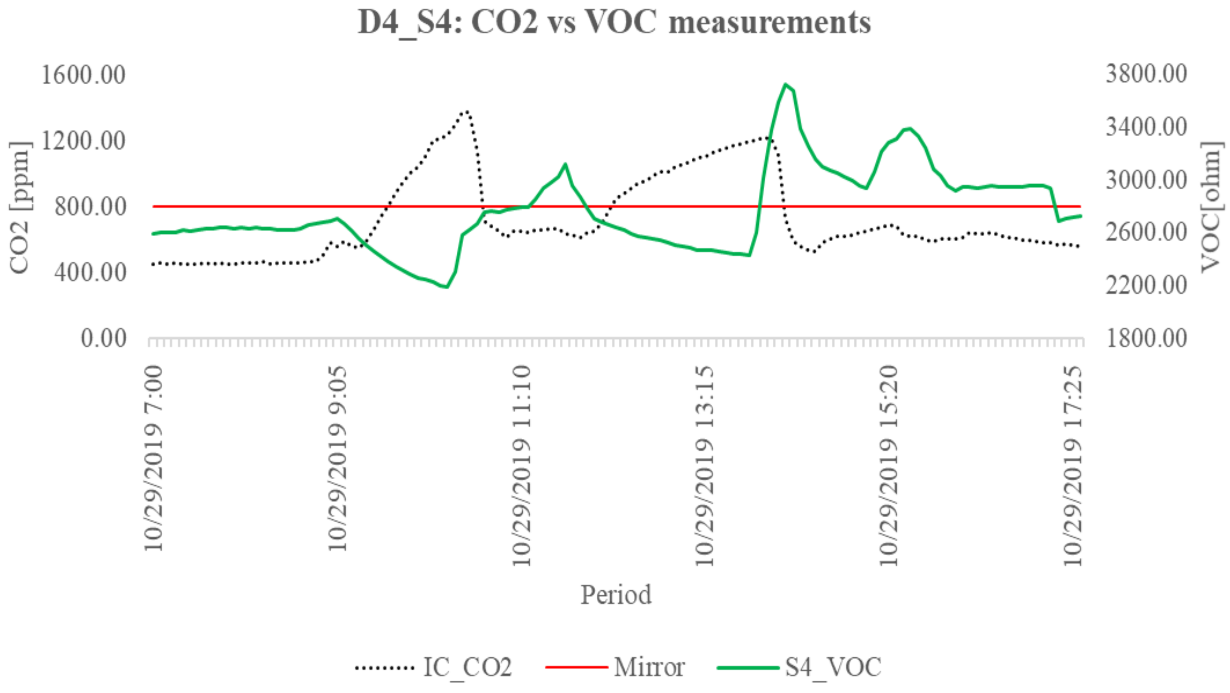

D5_S2: CO2 vs VOC measurements
1200.00
800.00
400.00
0.00
CO2 [ppm]
2400.00
2000.00
1600.00
1200.00
800.00
400.00
0.00
VOC[ohm]
10/30/2019 7:00
10/30/2019 9:05
10/30/2019 11:10
10/30/2019 13:15
10/30/2019 15:20
10/30/2019 17:25
Period
IC_CO2
Mirror
S2_VOC

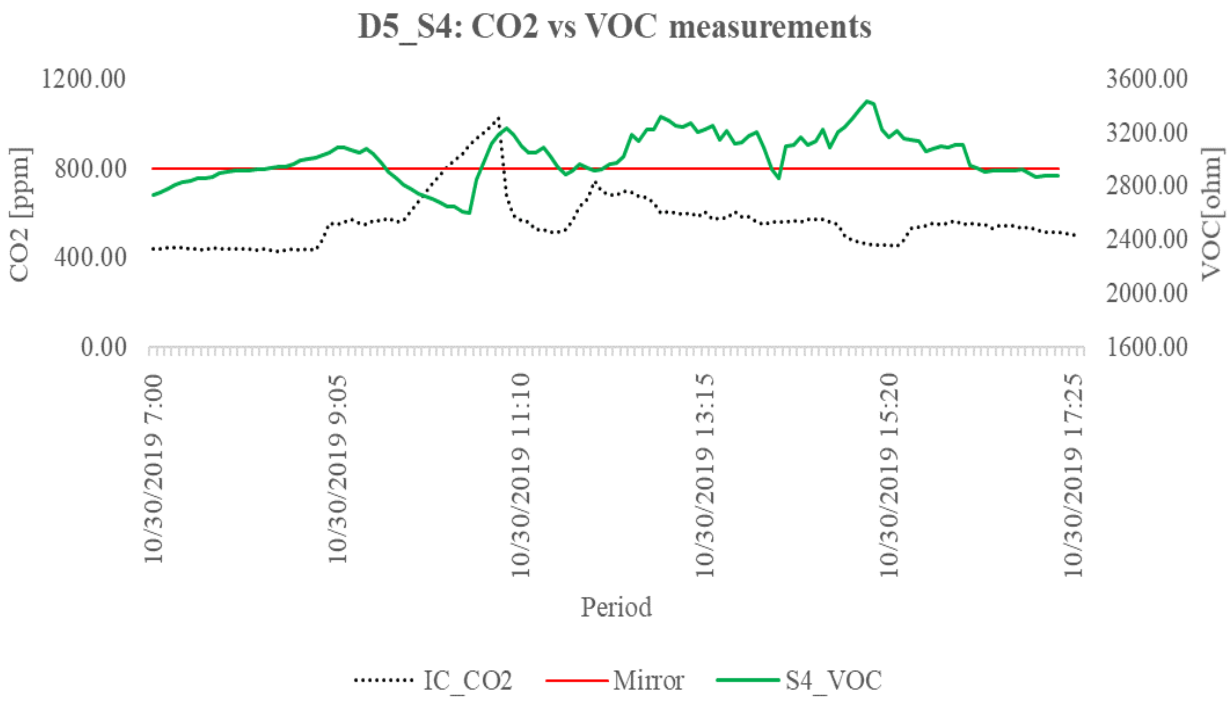
Sensor S4


D1_S4: CO2 vs VOC measurements
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
1800.00
1700.00
1600.00
1500.00
1400.00
1300.00
1200.00
1100.00
VOC[ohm]
10/24/2019 7:00
10/24/2019 9:05
10/24/2019 11:10
10/24/2019 13:15
10/24/2019 15:20
10/24/2019 17:25
Period
IC_CO2
Mirror
S4_VOC


D2_S4: CO2 vs VOC measurements
2000.00
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
2300.00
2100.00
1900.00
1700.00
1500.00
1300.00
1100.00
VOC[ohm]
10/25/2019 7:00
10/25/2019 9:05
10/25/2019 11:10
10/25/2019 13:15
10/25/2019 15:20
10/25/2019 17:25
Period
IC_CO2
Mirror
S4_VOC

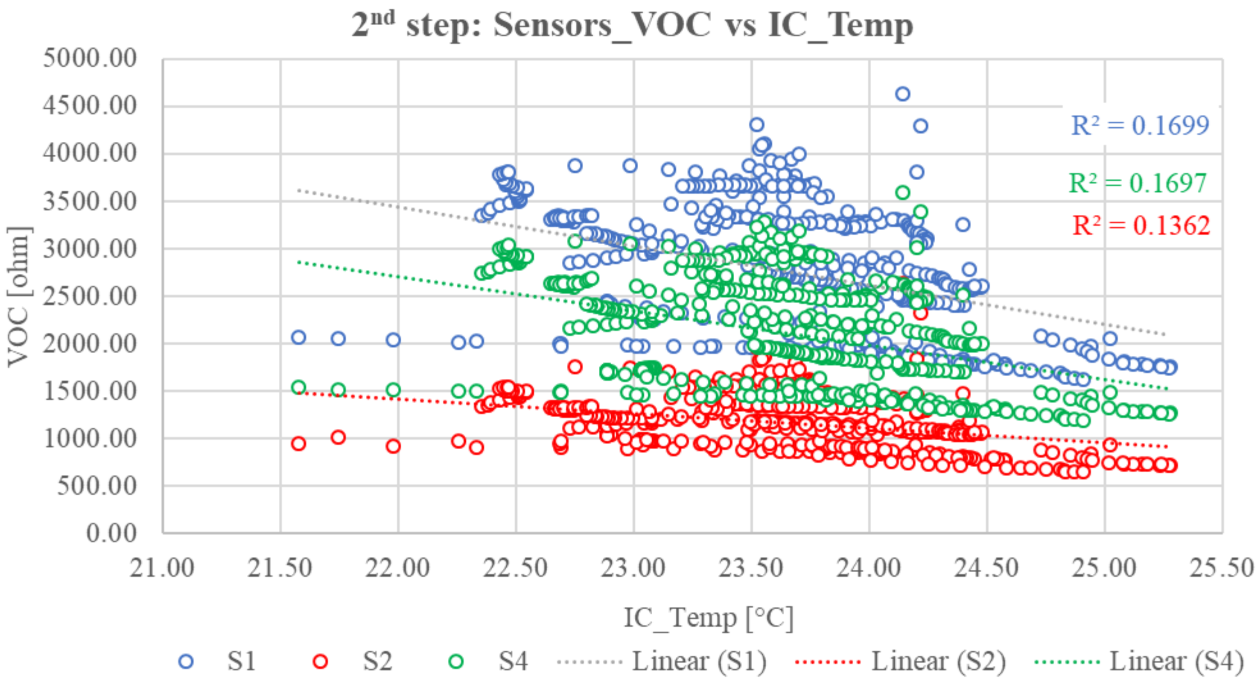

D3_S4: CO2 vs VOC measurements
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
2800.00
2600.00
2400.00
2200.00
2000.00
1800.00
VOC[ohm]
10/28/2019 7:00
10/28/2019 9:05
10/28/2019 11:10
10/28/2019 13:15
10/28/2019 15:20
10/28/2019 17:25
Period
IC_CO2
Mirror
S4_VOC

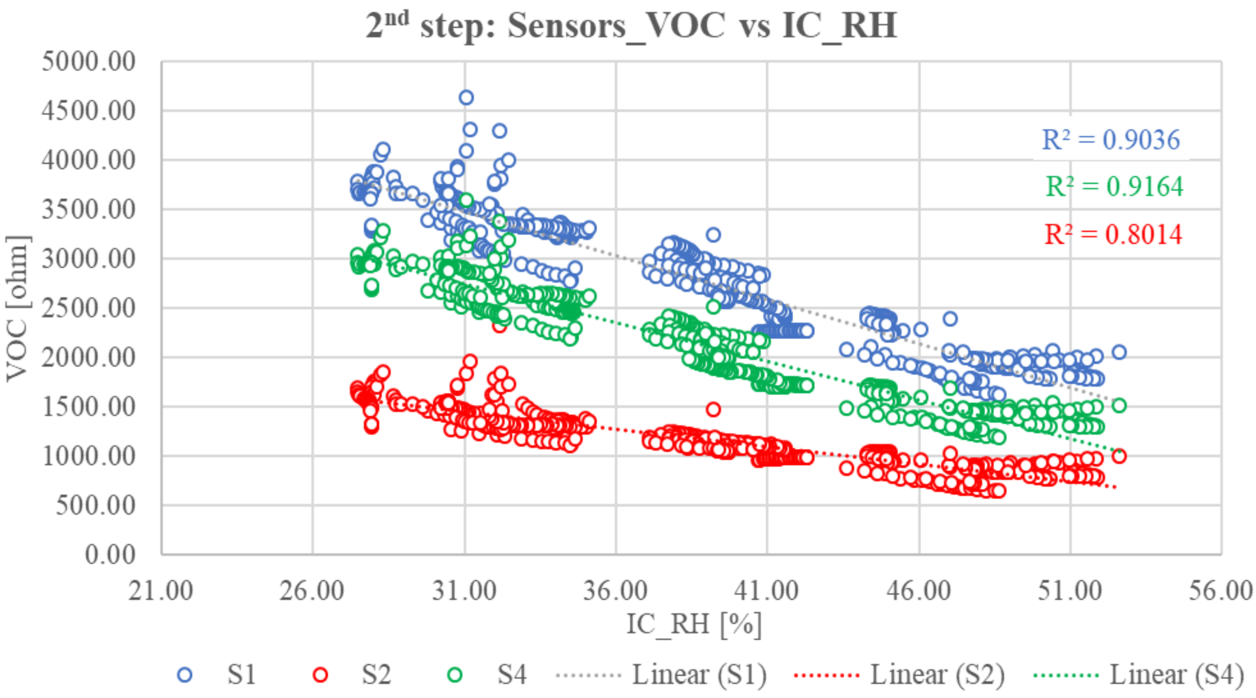

D4_S4: CO2 vs VOC measurements
1600.00
1200.00
800.00
400.00
0.00
CO2 [ppm]
3800.00
3400.00
3000.00
2600.00
2200.00
1800.00
VOC[ohm]
10/29/2019 7:00
10/29/2019 9:05
10/29/2019 11:10
10/29/2019 13:15
10/29/2019 15:20
10/29/2019 17:25
Period
IC_CO2
Mirror
S4_VOC

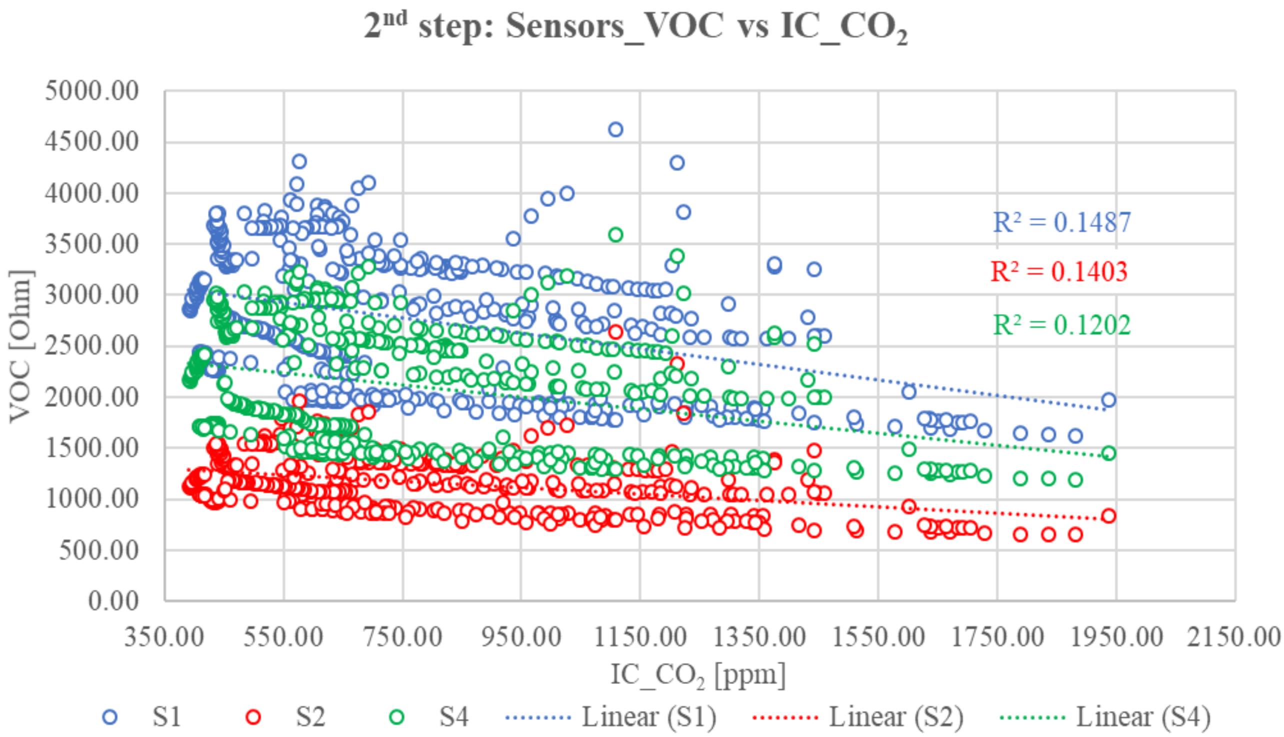


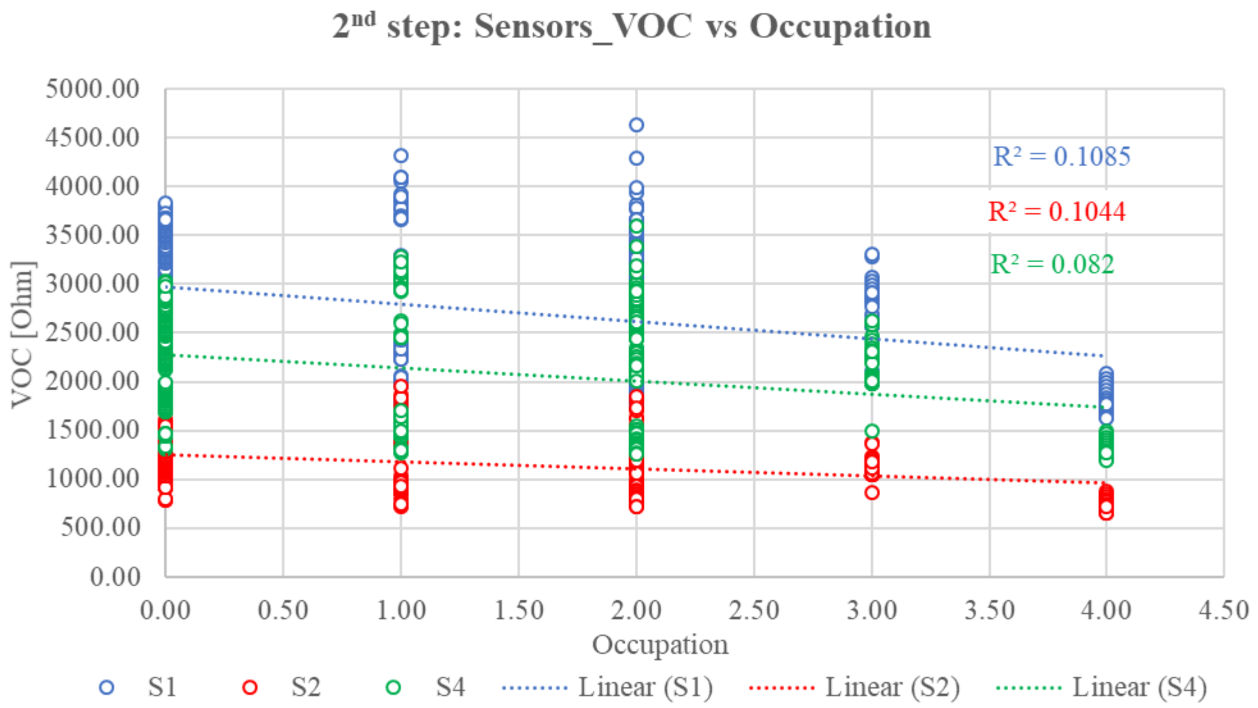
8.3.4 Further investigation of the correlation between VOC readings, temperature, relative humidity, CO_2 and occupation

Step 2: Data filtered based when venting was off

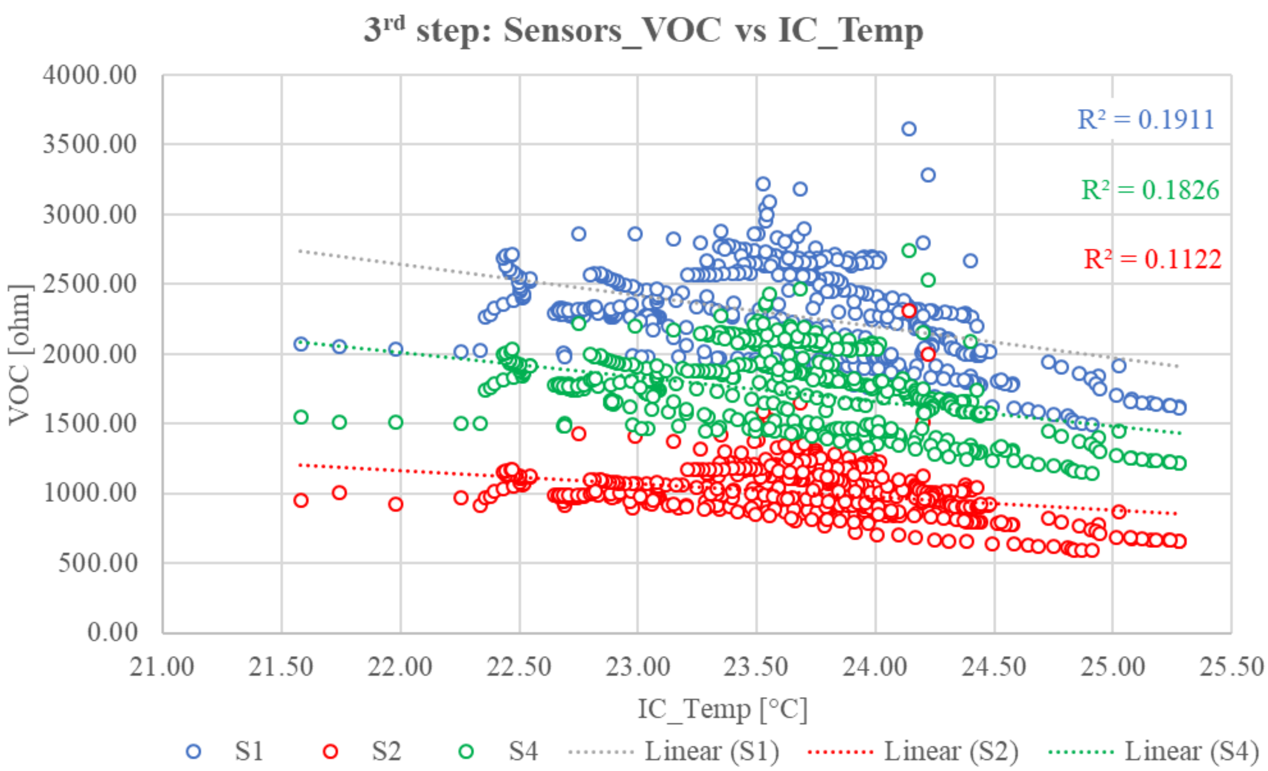


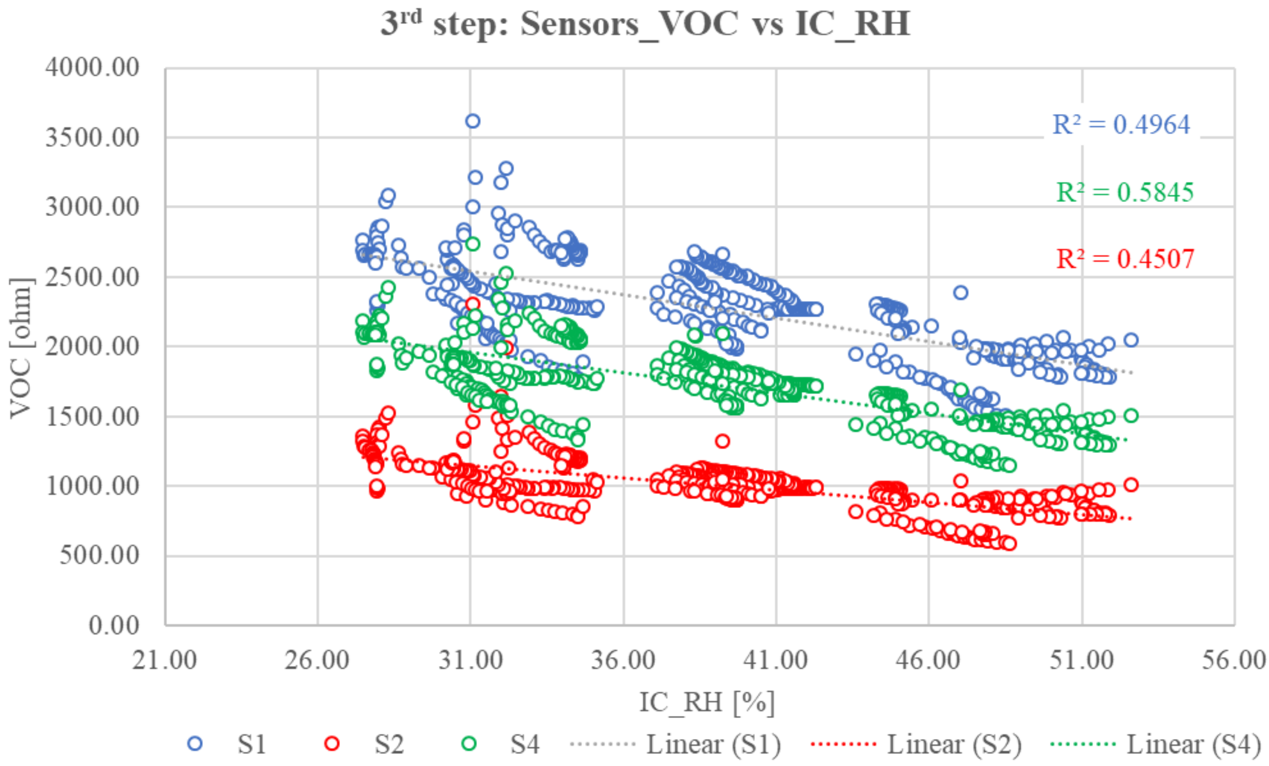

2nd step: Sensors_VOC vs IC_RH
VOC [ohm]
IC_RH [%]
5000.00
4500.00
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
21.00
26.00
31.00
36.00
41.00
46.00
51.00
56.00
R² = 0.9036
R² = 0.9164
R² = 0.8014
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

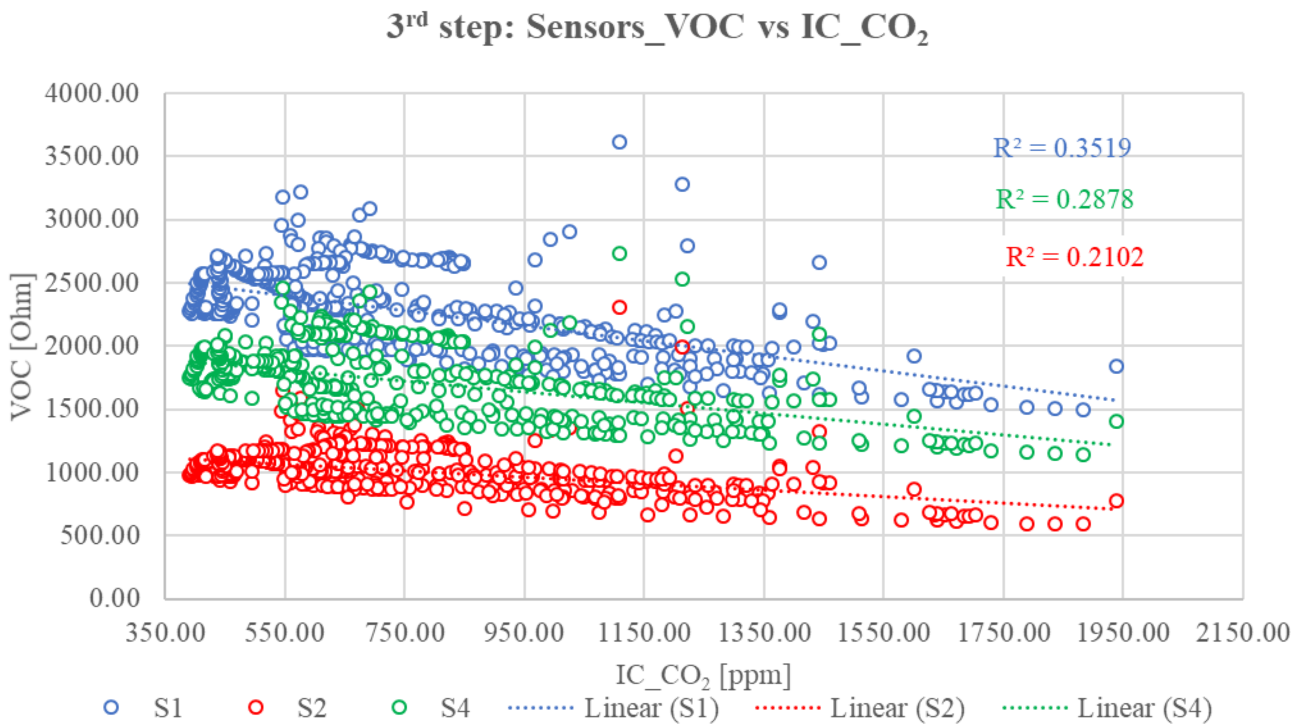

2nd step: Sensors_VOC vs IC_CO2
VOC [Ohm]
IC_CO2 [ppm]
5000.00
4500.00
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
350.00
550.00
750.00
950.00
1150.00
1350.00
1550.00
1750.00
1950.00
2150.00
R² = 0.1487
R² = 0.1403
R² = 0.1202
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

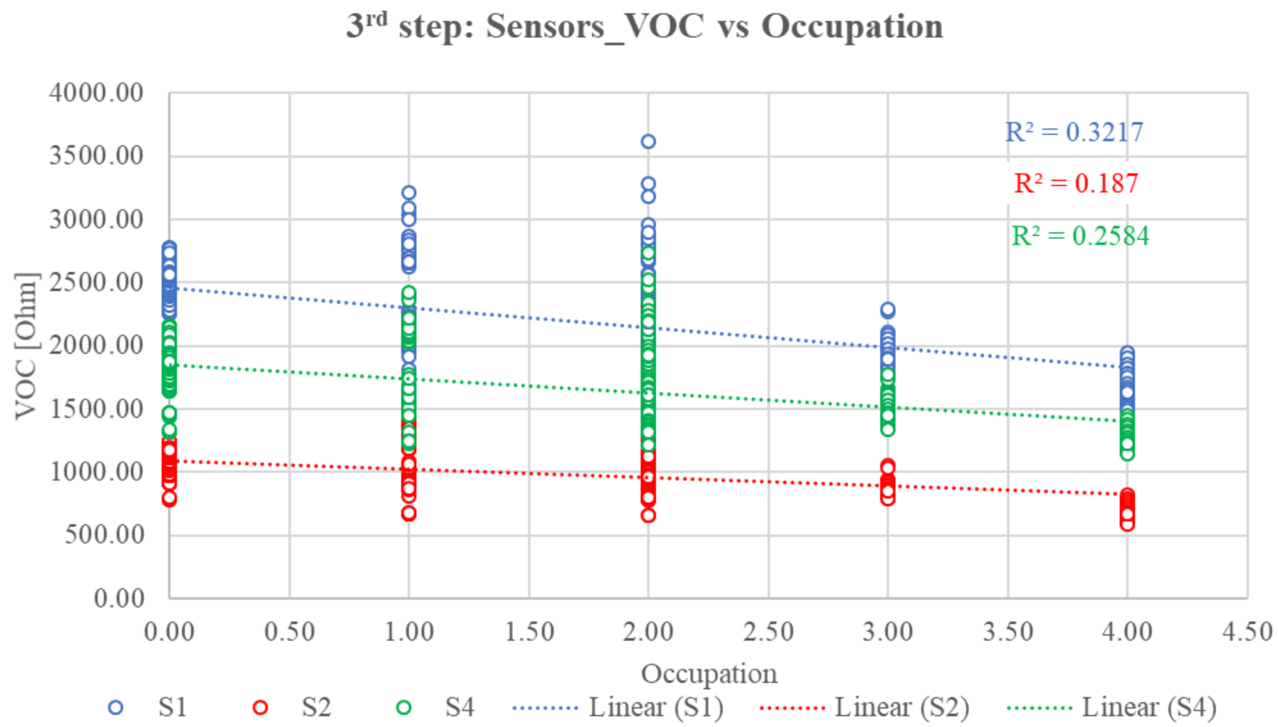


Step 3: Normalization of the data



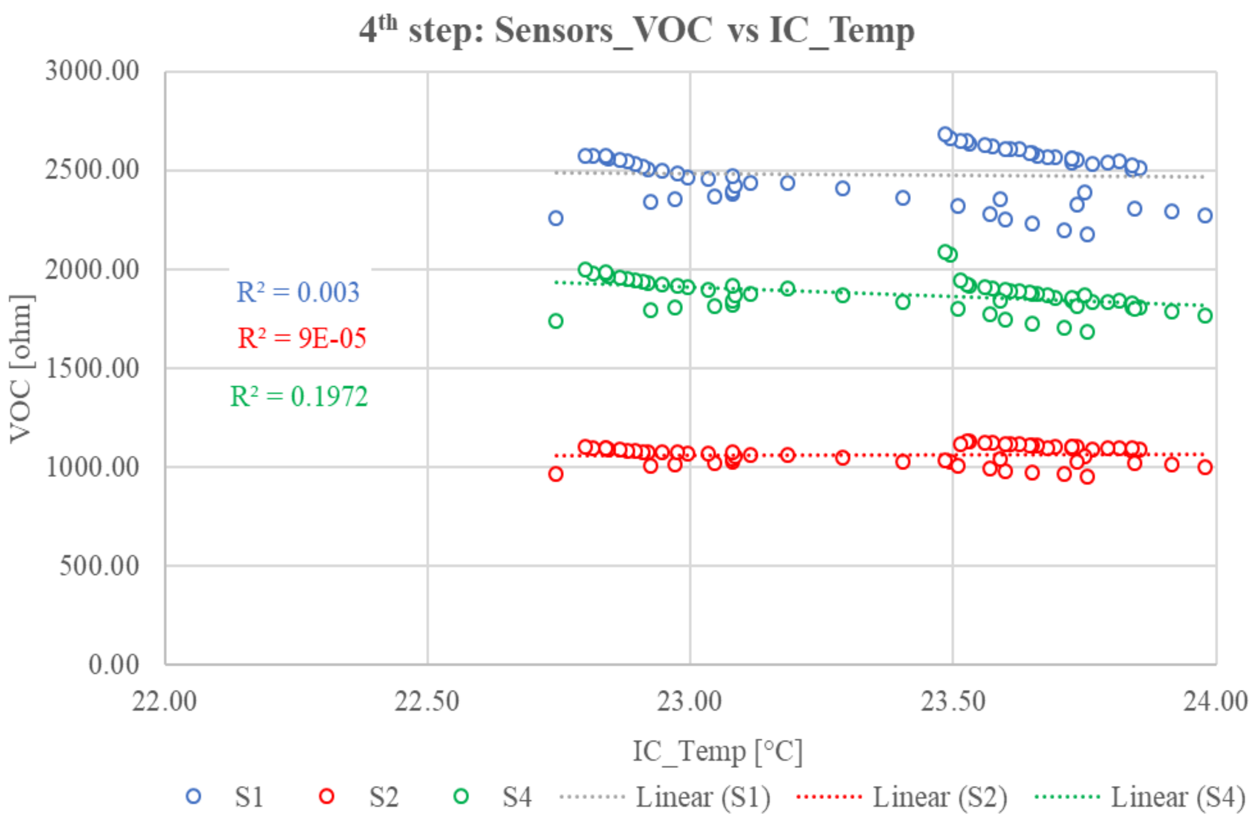

3rd step: Sensors_VOC vs IC_RH
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [ohm]
21.00
26.00
31.00
36.00
41.00
46.00
51.00
56.00
IC_RH [%]
R² = 0.4964
R² = 0.5845
R² = 0.4507
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

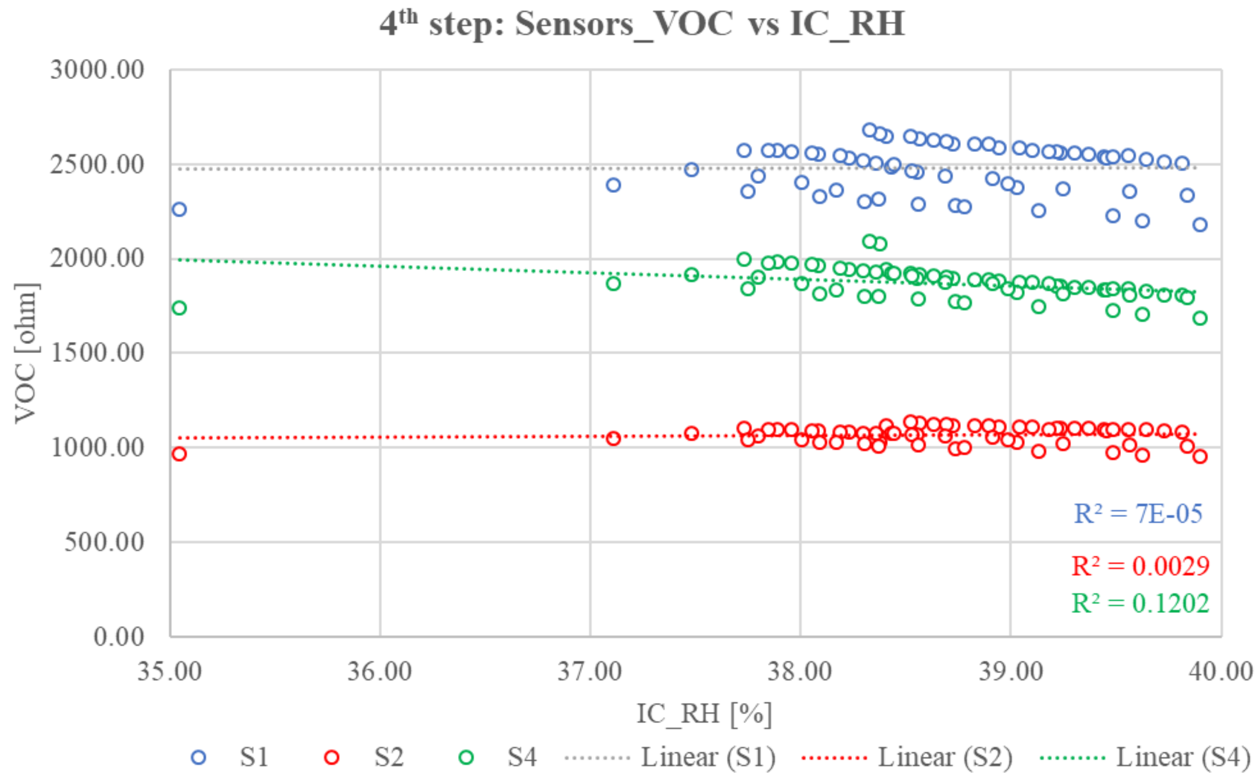

3rd step: Sensors_VOC vs IC_CO2
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [Ohm]
350.00
550.00
750.00
950.00
1150.00
1350.00
1550.00
1750.00
1950.00
2150.00
IC_CO2 [ppm]
R² = 0.3519
R² = 0.2878
R² = 0.2102
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

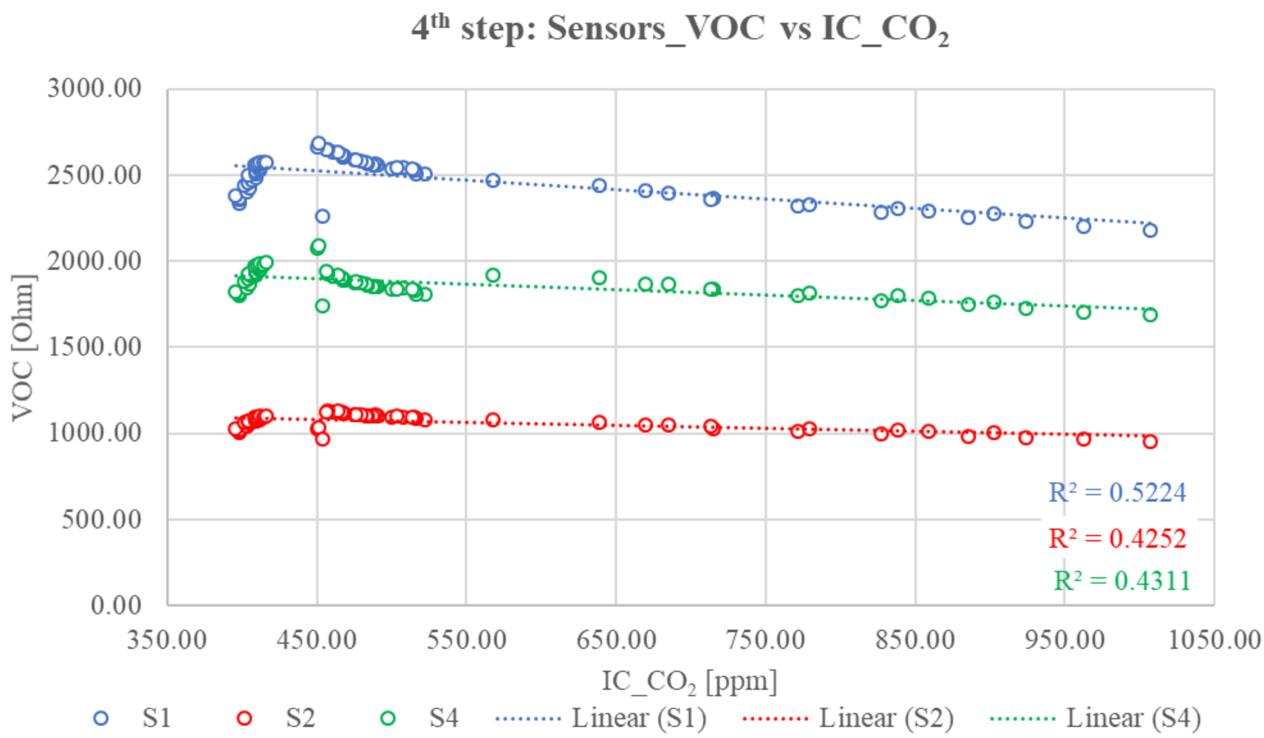


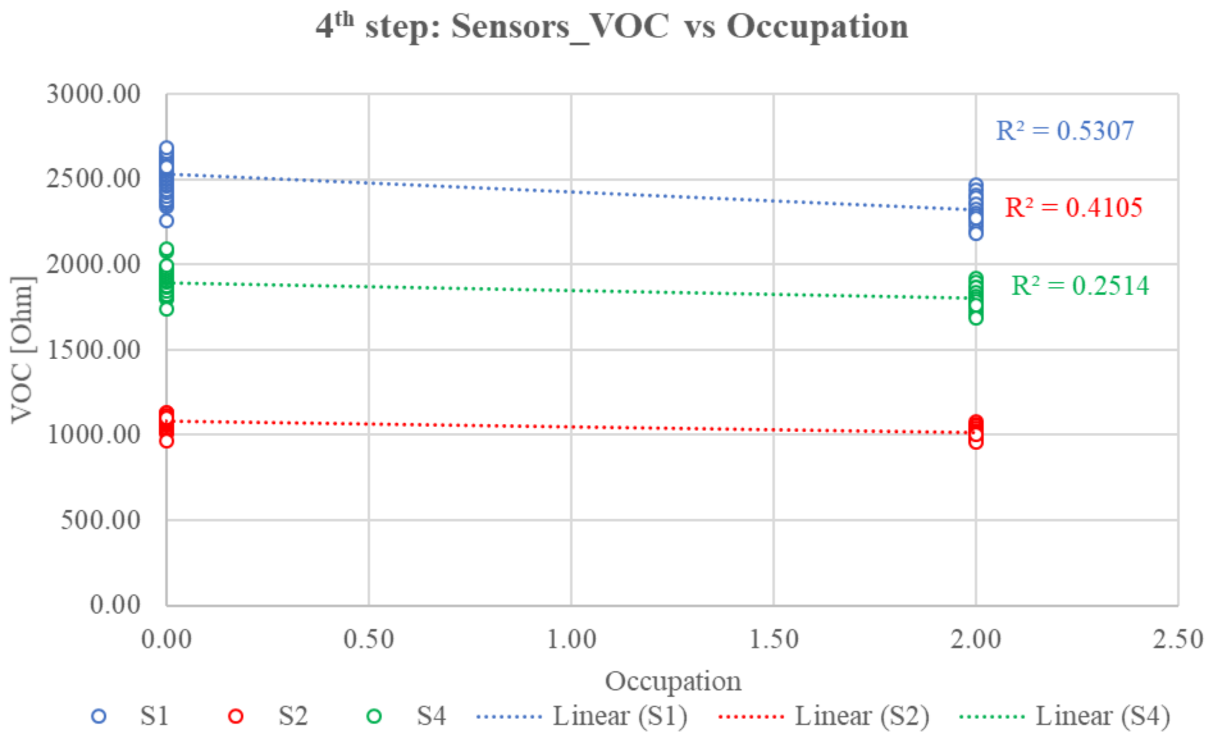
Step 4:

A - Sensors with VOC normalized data and filtered based T:22-24 °C and RH:35-40 %

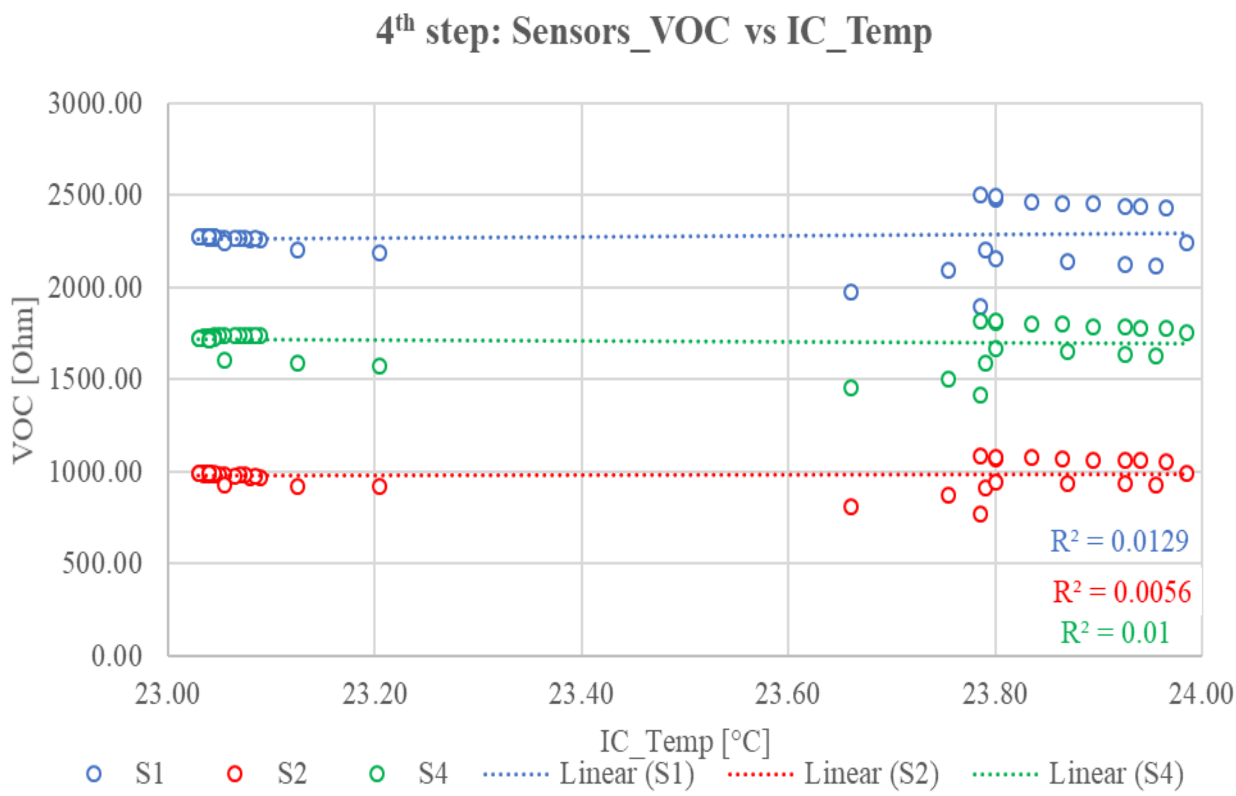


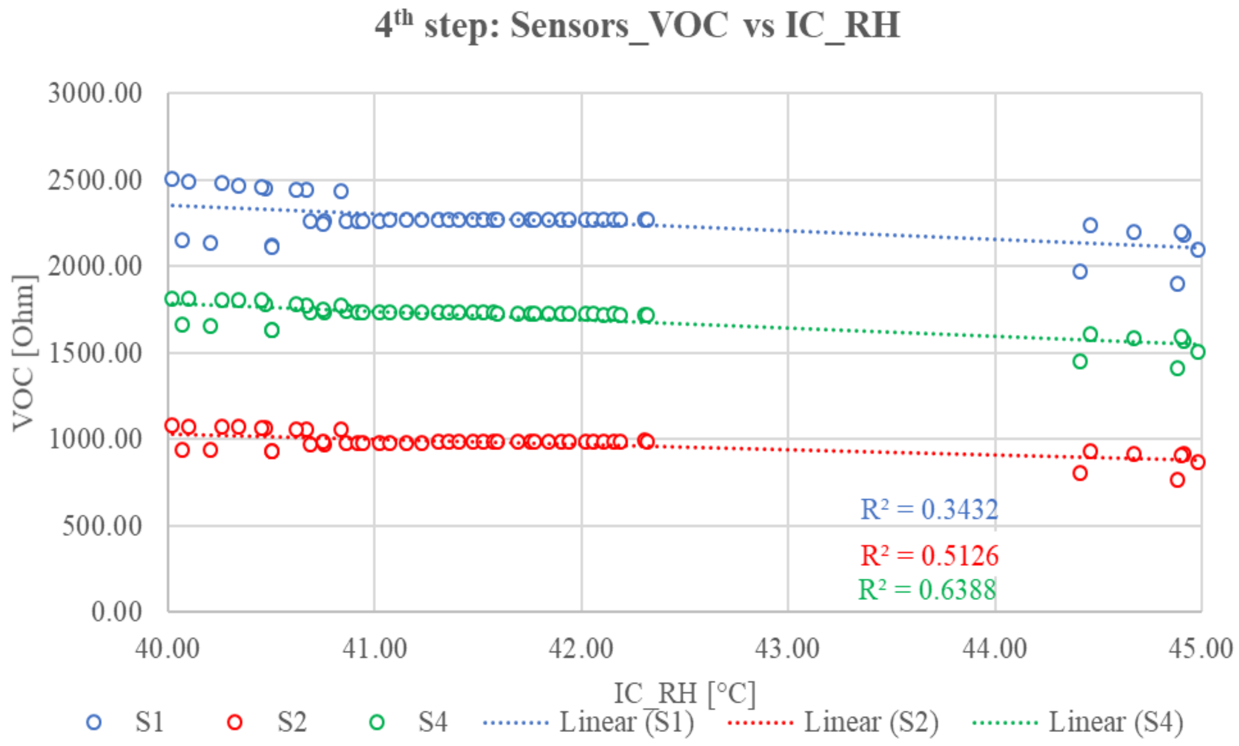

4th step: Sensors_VOC vs IC_RH
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [ohm]
35.00
36.00
37.00
38.00
39.00
40.00
IC_RH [%]
R² = 7E-05
R² = 0.0029
R² = 0.1202
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

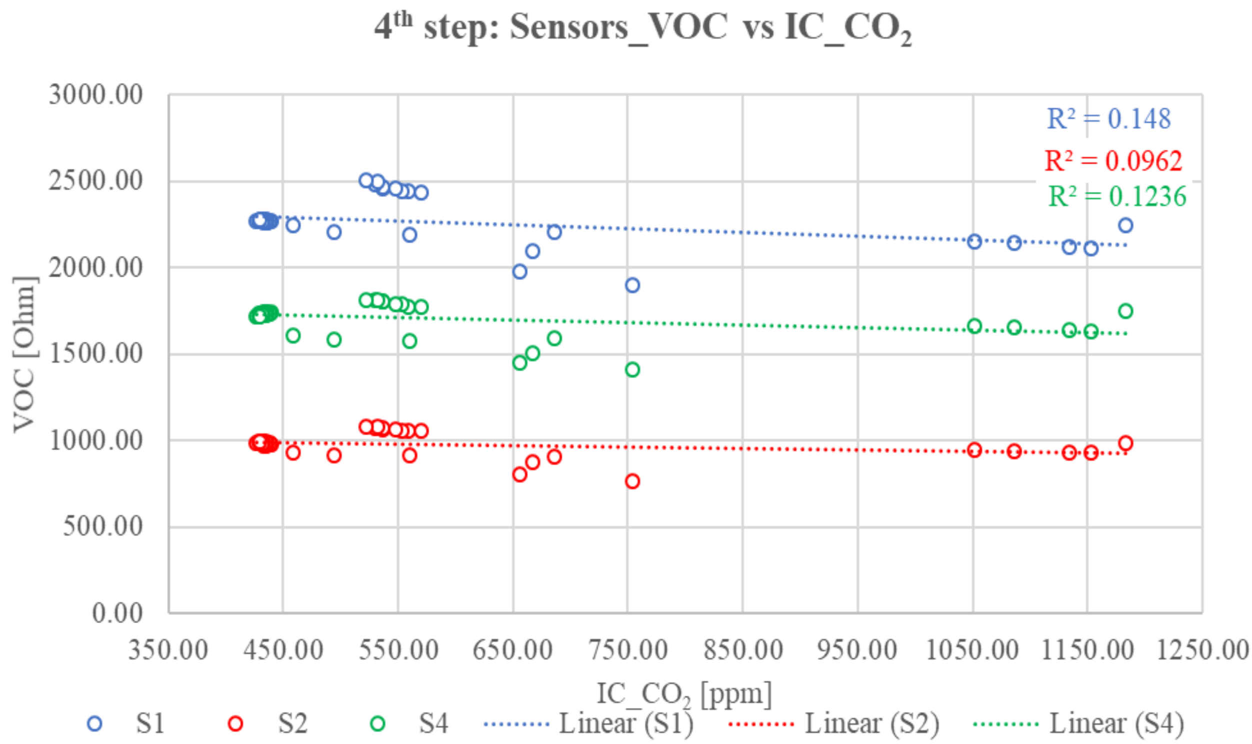

4th step: Sensors_VOC vs IC_CO2
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [Ohm]
350.00
450.00
550.00
650.00
750.00
850.00
950.00
1050.00
IC_CO2 [ppm]
R² = 0.5224
R² = 0.4252
R² = 0.4311
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

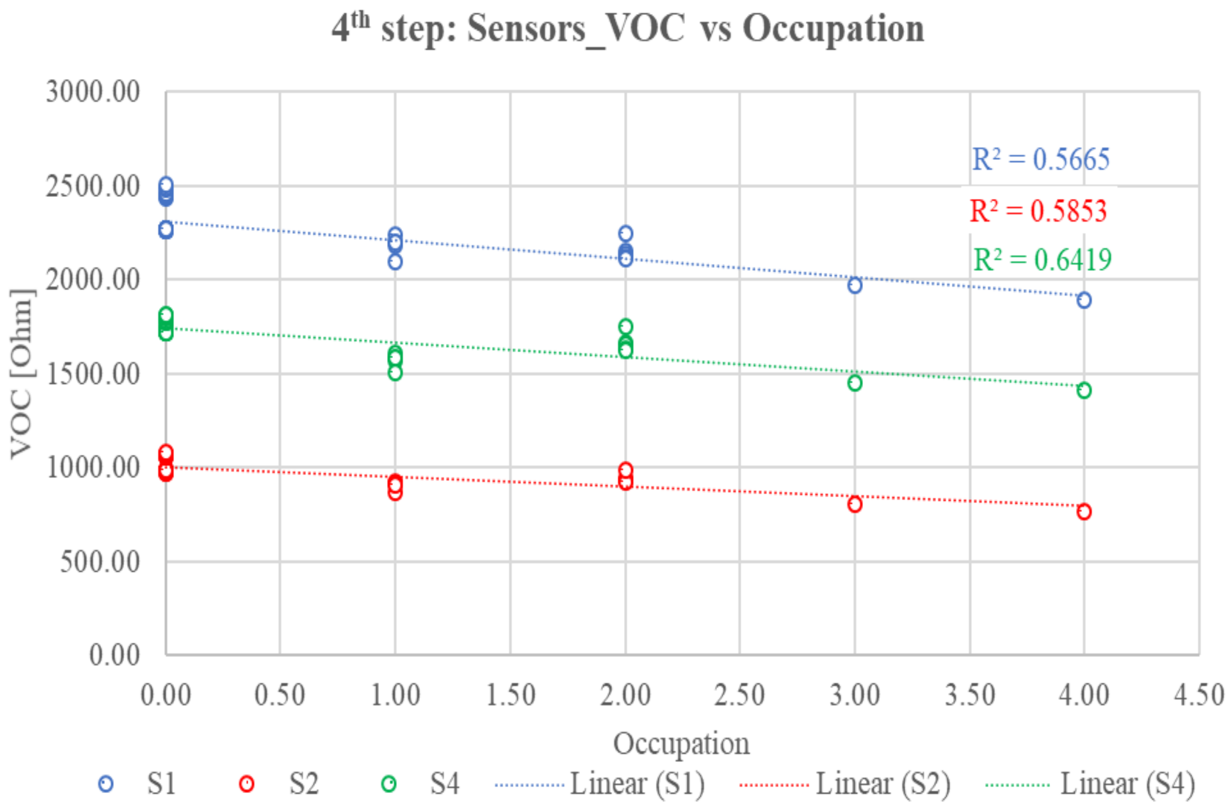


B - Sensors with VOC normalized data and filtered based T:23-24 °C and RH:40-45 %



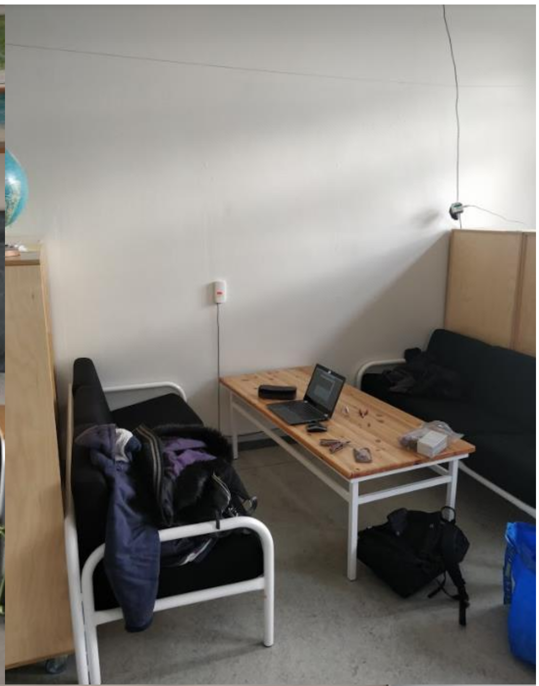

4th step: Sensors_VOC vs IC_RH
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [Ohm]
40.00
41.00
42.00
43.00
44.00
45.00
IC_RH [°C]
R² = 0.3432
R² = 0.5126
R² = 0.6388
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

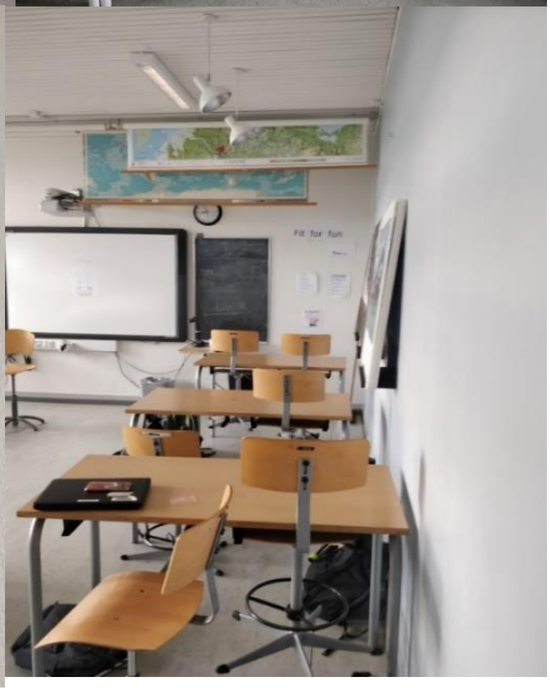

4th step: Sensors_VOC vs IC_CO2
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [Ohm]
350.00
450.00
550.00
650.00
750.00
850.00
950.00
1050.00
1150.00
1250.00
IC_CO2 [ppm]
R² = 0.148
R² = 0.0962
R² = 0.1236
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

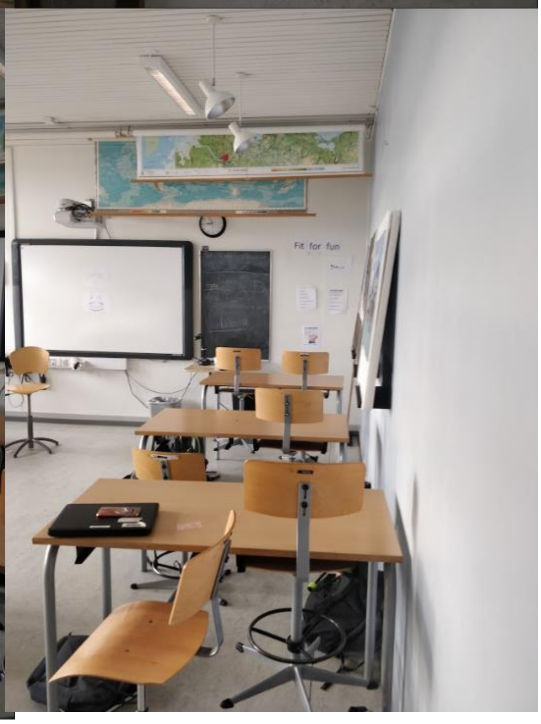

4th step: Sensors_VOC vs Occupation
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
VOC [Ohm]
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
Occupation
R² = 0.5665
R² = 0.5853
R² = 0.6419
S1
S2
S4
Linear (S1)
Linear (S2)
Linear (S4)

8.4 Setup at the school Ødis

8.4.1 Room 1


Fit for fun


Fit for fun

8.4.2 Room 2




KLETT-PERTHES
Lav side 34
opg 13

KLETT-PERTHES
Lav side 34
opg 13

8.4.3 School facade

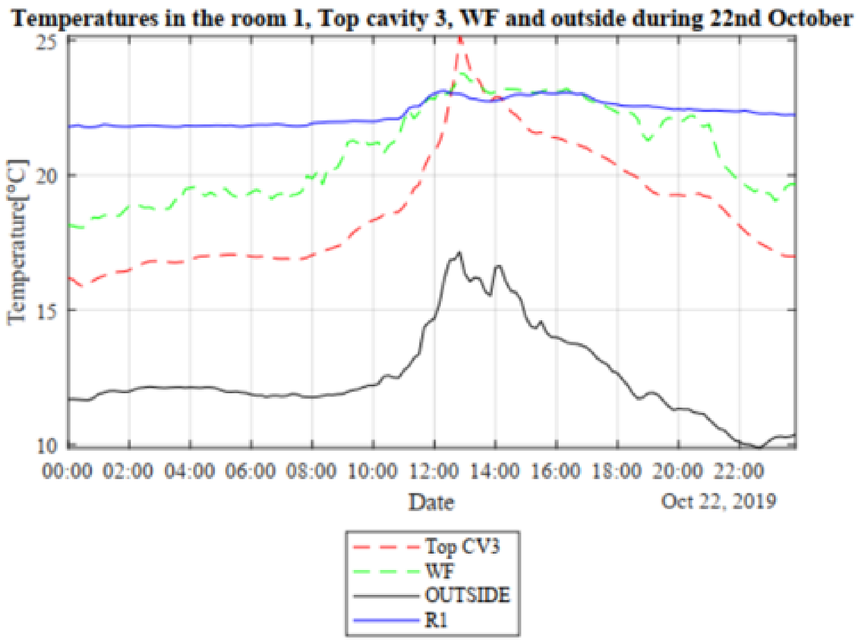
8.4.4 Equipment used in the school measurements

List of Equipment used at Ødis school in Kolding:

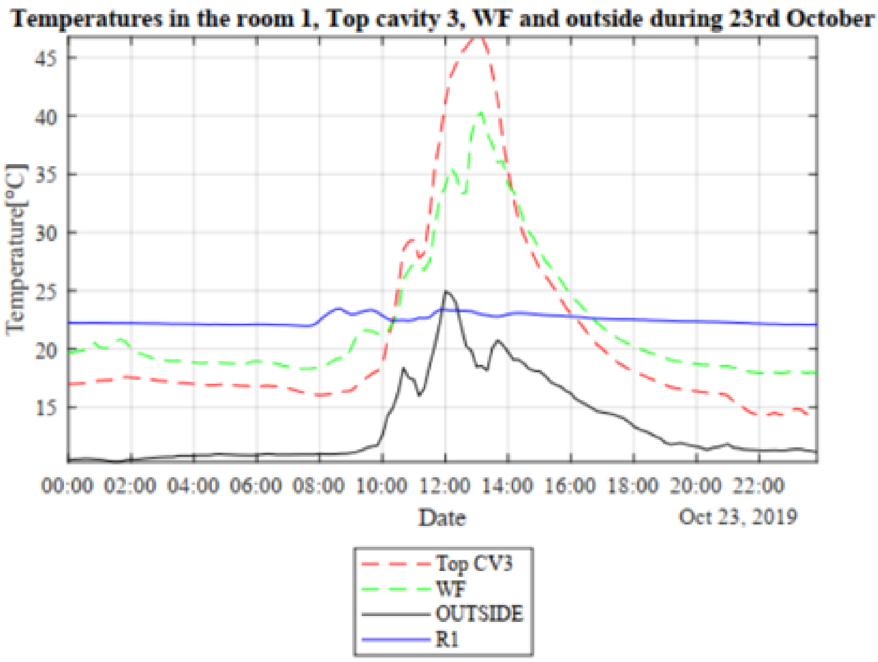
10 - IC Meters
2 - NUC Computers (nr.1079 and 1080)
1 - flat screen HP
2 - cDAQ NI 9216
2 - Lindab FTMU differential pressure sensors 160 mm
1 - Keyboard
1 - mouse
1 - Huawei AAU mobil wifi router
1 - Toolbox number 3
1 - gaffa tape
4 - double plugs extension
2 - 3 plugs extension
1 - eight plugs extension

8.5 PT100 investigation

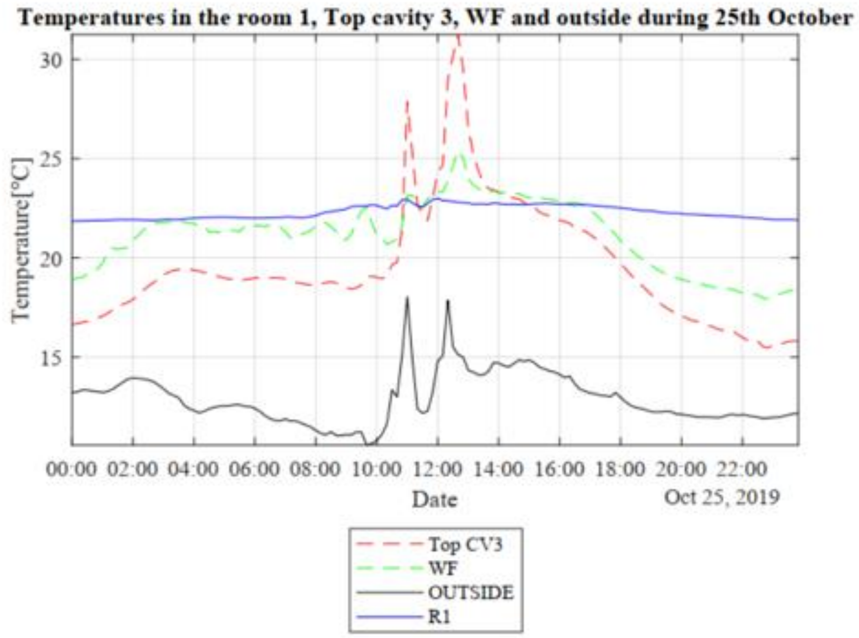
8.5.1 At the top cavity 3 of WT2 in room 1



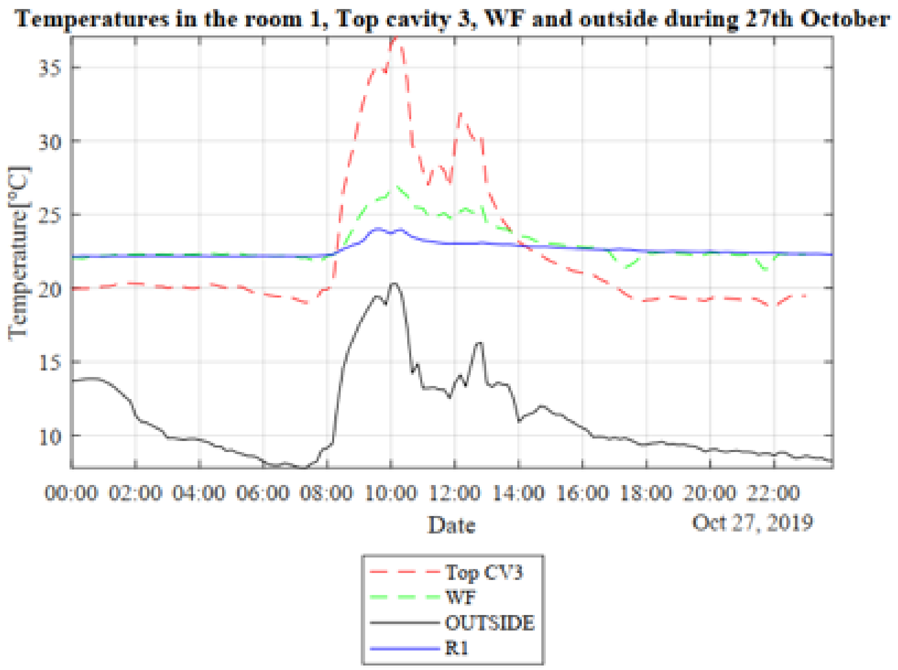
Temperatures [°C] measured in room 1					
Period	Outside	Top cavity 3	Window frame	R1	Slope
22/10/19 at 12:34	16.86	23.20	23.20	23.05	↗
22/10/19 at 12:50	**18.47**	**25.16**	**23.78**	**23.03**	$\Delta T_{Top\ CV3\ -\ WF}$
22/10/19 at 13:35	15.96	23.23	23.23	22.77	↘



23/10/19 at 10:17	14.80	22.03	22.03	22.44	↗
23/10/19 at 13:00	**18.47**	**46.76**	**39.98**	**23.07**	$\Delta T_{Top\ CV3\ -\ WF}$
23/10/19 at 14:07	19.27	33.69	33.69	23.03	↘

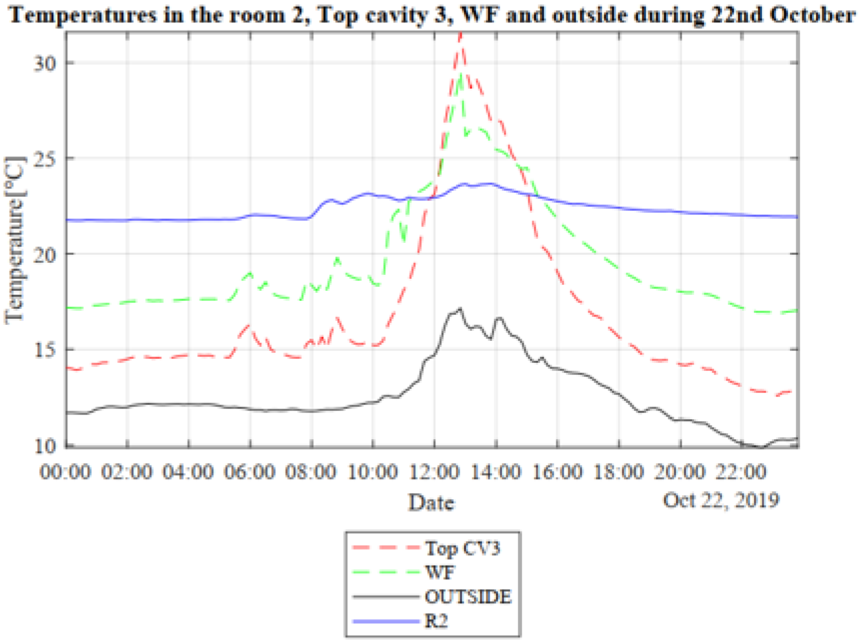


25/10/19 at 10:50	15.17	21.67	21.67	22.93	↗
25/10/19 at 11:20	12.39	22.65	22.65	22.61	↘
25/10/19 at 11:52	13.55	23.30	23.30	22.95	↗
25/10/19 at 12:40	**15.12**	**31.26**	**25.40**	**22.80**	**$\Delta T_{Top\ CV3 - WF}$**
25/10/19 at 14:04	14.64	23.28	23.28	22.78	↘

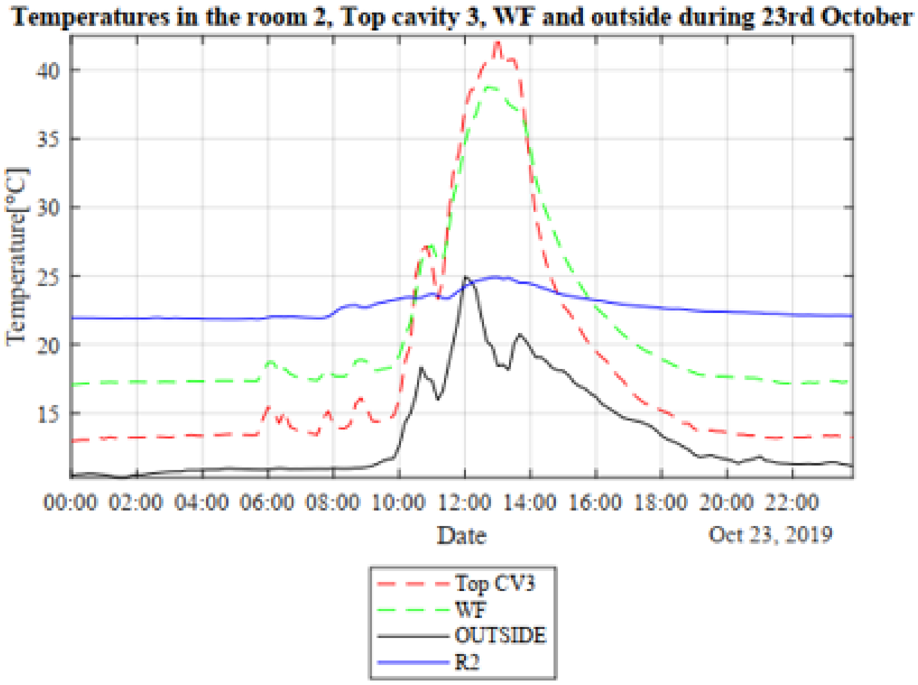


27/10/19 at 08:17	11.53	22.41	22.41	22.41	↗
27/10/19 at 10:10	**20.30**	**37.08**	**26.97**	**23.92**	**$\Delta T_{Top\ CV3 - WF}$**
27/10/19 at 13:47	12.71	23.75	23.75	22.95	↘

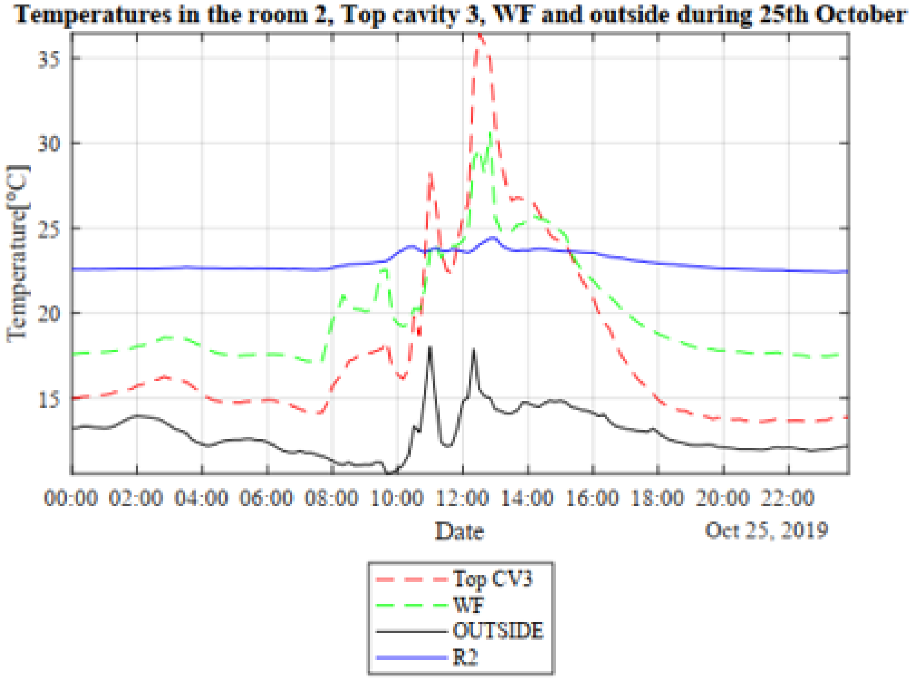
8.5.2 At the top cavity 3 of WT2 in room 2



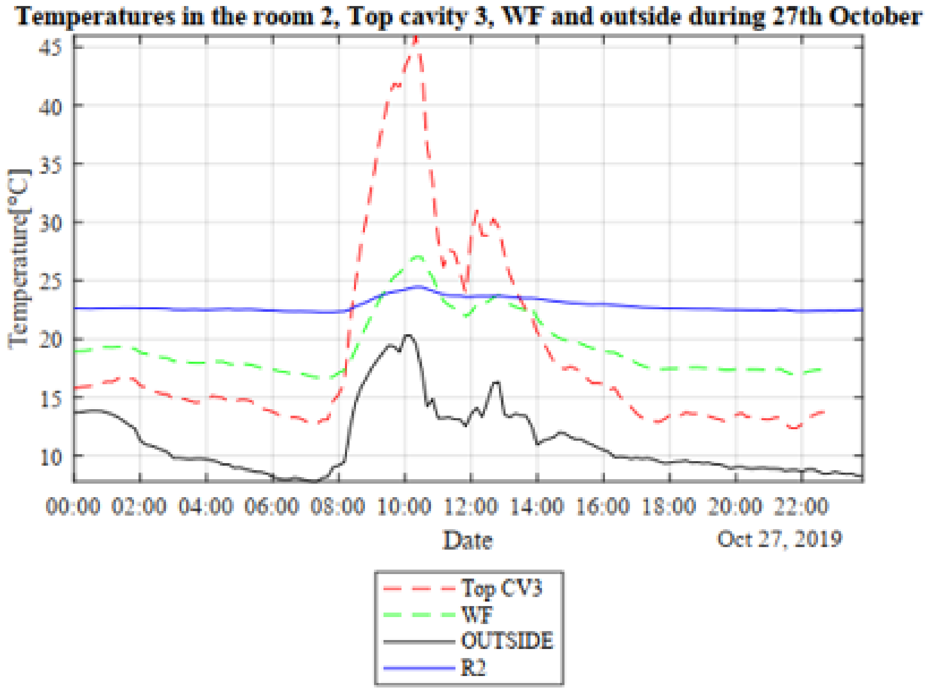
Temperatures [°C] measured in room 2					
Period	Outside	Top cavity 3	Window frame	R2	Slope
22/10/19 at 12:10	15.24	24.17	24.17	23.01	↗
22/10/19 at 12:50	**17.16**	**31.61**	**29.55**	**23.61**	$\Delta T_{Top\ CV3 - WF}$
22/10/19 at 14:50	15.38	24.43	24.43	23.16	↘



23/10/19 at 10:25	15.69	22.86	22.86	23.40	↗
23/10/19 at 10:50	17.52	26.99	26.99	23.58	↘
23/10/19 at 11:25	17.64	27.33	27.33	23.36	↗
23/10/19 at 13:00	**18.47**	**42.48**	**38.58**	**24.92**	$\Delta T_{Top\ CV3 - WF}$
23/10/19 at 13:51	20.31	35.84	35.84	24.50	↘



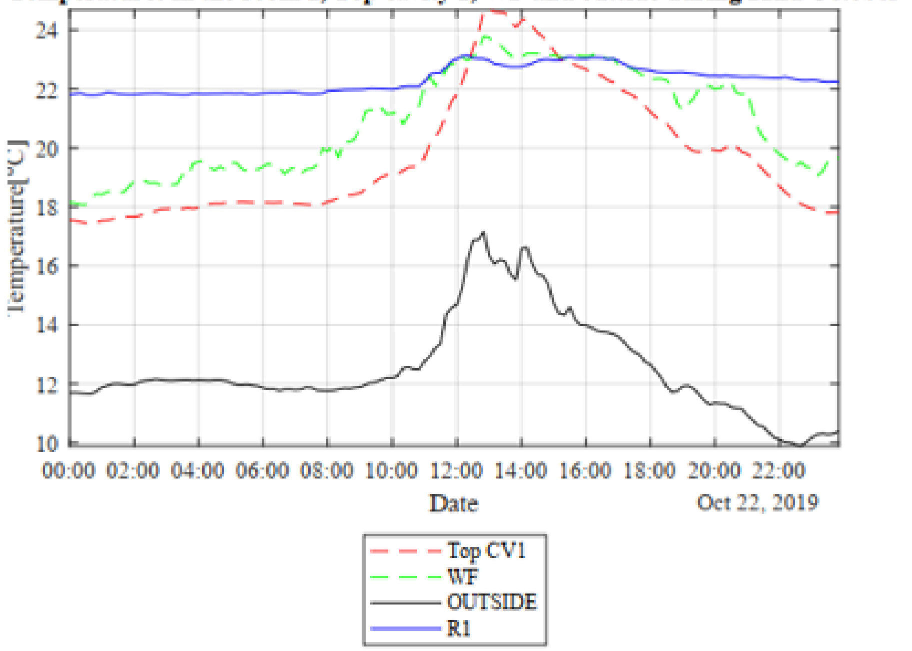
25/10/19 at 10:45	14.07	20.80	20.80	23.64	↗
25/10/19 at 11:22	12.39	23.30	23.30	23.68	↘
25/10/19 at 11:50	13.22	24.20	24.20	23.72	↗
25/10/19 at 12:30	**15.52**	**36.45**	**29.67**	**24.03**	$\Delta T_{Top\ CV3\ -\ WF}$
25/10/19 at 14:27	14.62	25.52	25.52	23.78	↘



27/10/19 at 08:10	9.45	17.34	17.34	22.37	↗
27/10/19 at 10:20	**19.57**	**45.99**	**27.06**	**24.46**	$\Delta T_{Top\ CV3\ -\ WF}$
27/10/19 at 13:40	13.41	22.47	22.47	23.47	↘

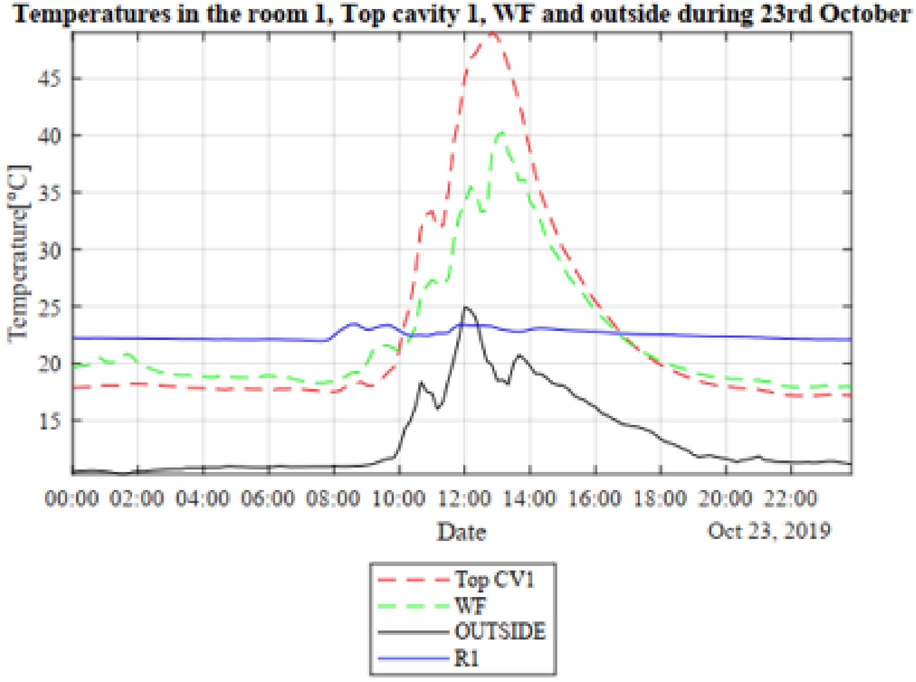
8.5.3 At the top cavity 1 of WT2 in room 1

Temperatures in the room 1, Top cavity 1, WF and outside during 22nd October



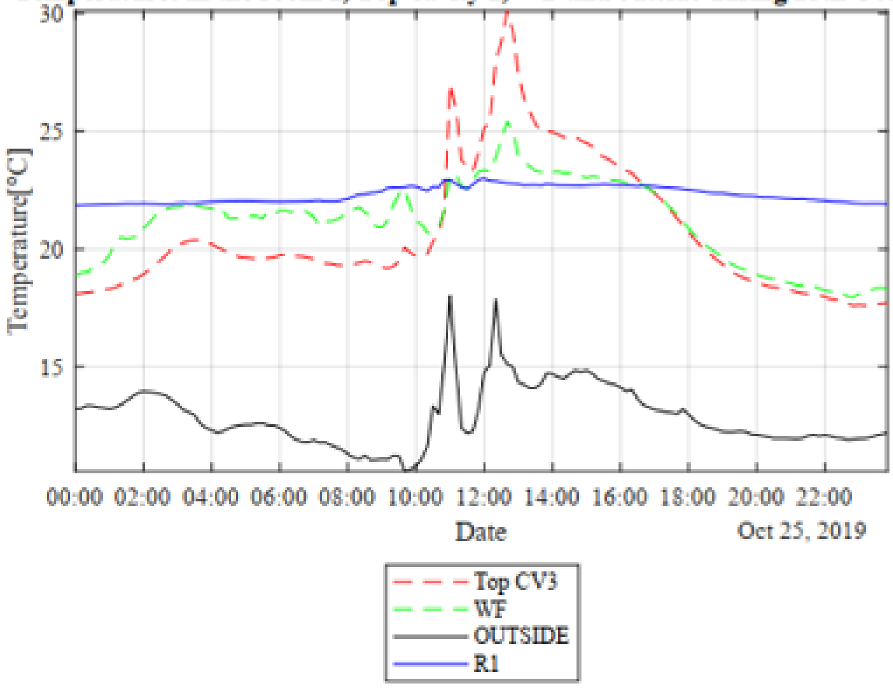
Temperatures [°C] measured in room 1					
Period	Outside	Top cavity 1	Window frame	R1	Slope
22/10/19 at 12:24	16.47	23.02	23.02	23.10	↗
22/10/19 at 13:00	**16.34**	**24.69**	**23.74**	**22.96**	**$\Delta T_{Top\ CV1\ -\ WF}$**
22/10/19 at 15:08	14.43	23.10	23.10	22.98	↘

Temperatures in the room 1, Top cavity 1, WF and outside during 23rd October



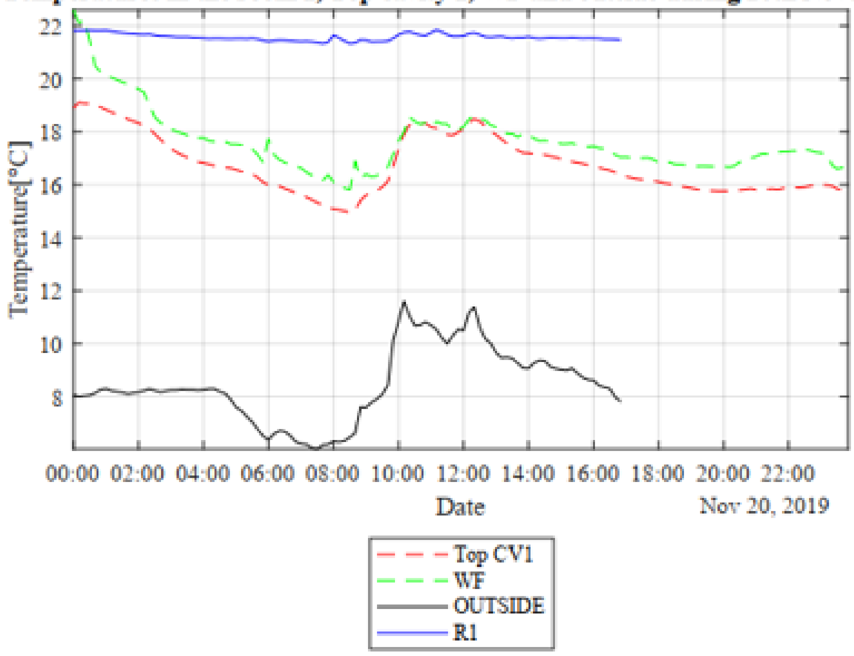
23/10/19 at 10:00	12.61	21.14	21.14	22.86	↗
23/10/19 at 12:50	**19.86**	**49.01**	**38.37**	**23.23**	**$\Delta T_{Top\ CV1\ -\ WF}$**
23/10/19 at 17:20	14.40	21.21	21.21	22.55	↘

Temperatures in the room 1, Top cavity 1, WF and outside during 25th October

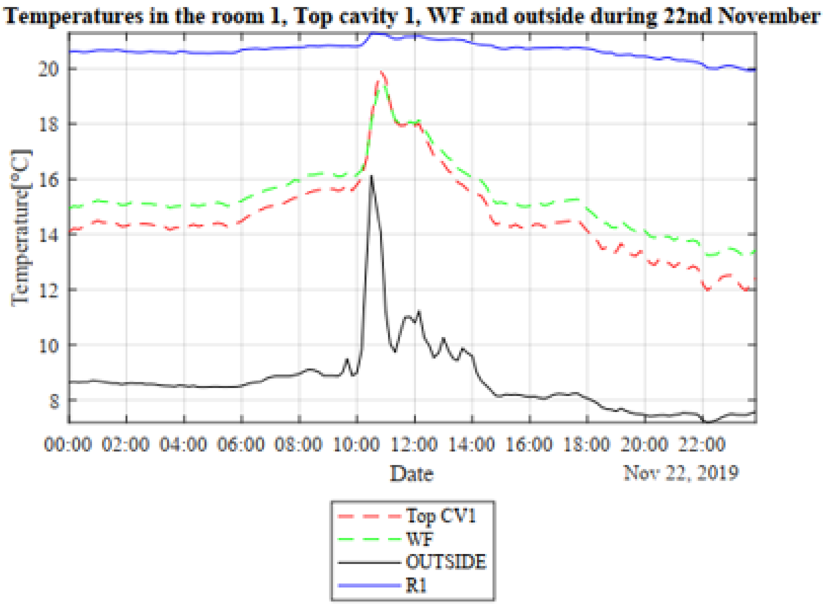


25/10/19 at 10:50	15.17	21.62	21.62	22.93	↗
25/10/19 at 12:40	**15.12**	**30.11**	**25.40**	**22.80**	**$\Delta T_{Top\ CV1 - WF}$**
25/10/19 at 16:53	13.25	22.50	22.50	22.67	↘

Temperatures in the room 1, Top cavity 1, WF and outside during 20th November

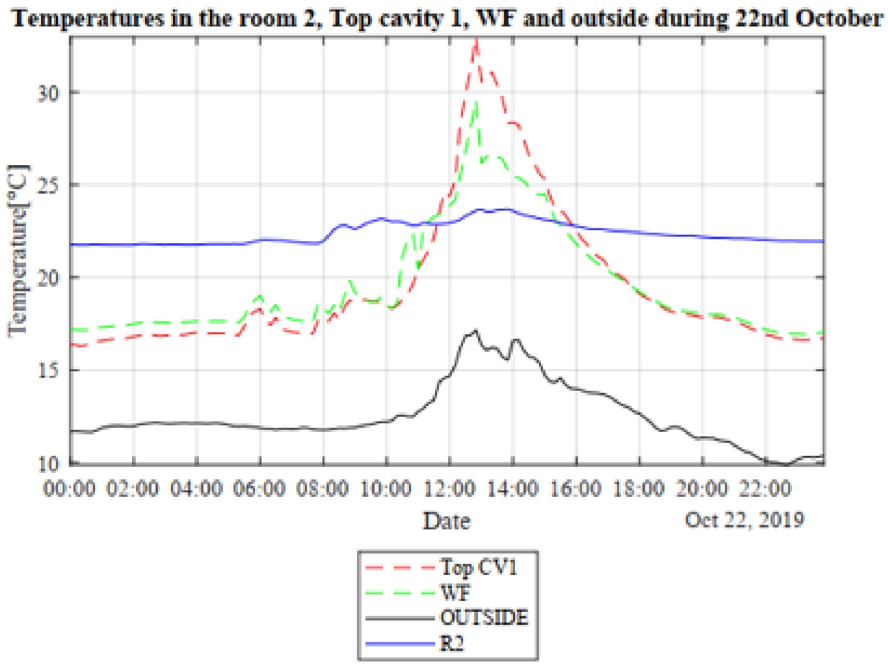


20/11/19 at 10:37	10.70	18.32	18.32	21.66	↗
20/11/19 at 10:43	10.74	18.31	18.31	21.65	↘

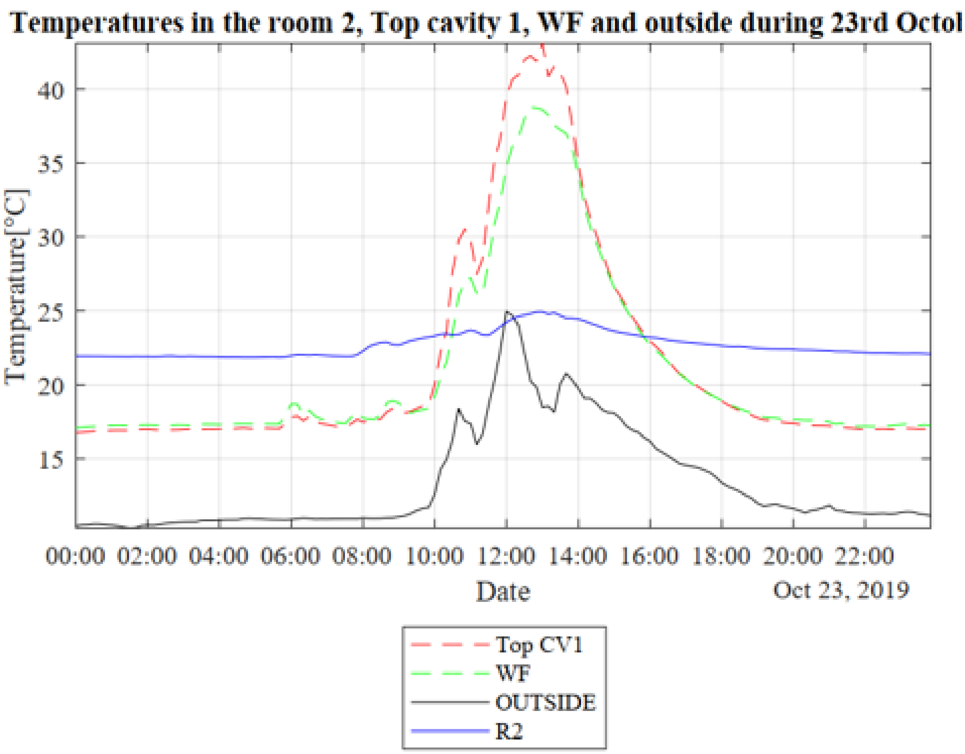


22/11/19 at 10:25	14.66	17.50	17.50	21.16	↗
22/11/19 at 10:50	**14.09**	**19.90**	**19.44**	**21.25**	$\Delta T_{Top\ CV1-WF}$
22/11/19 at 11:15	9.88	18.36	18.36	21.11	↗
22/11/19 at 11:43	11.00	18	18	21.16	↘

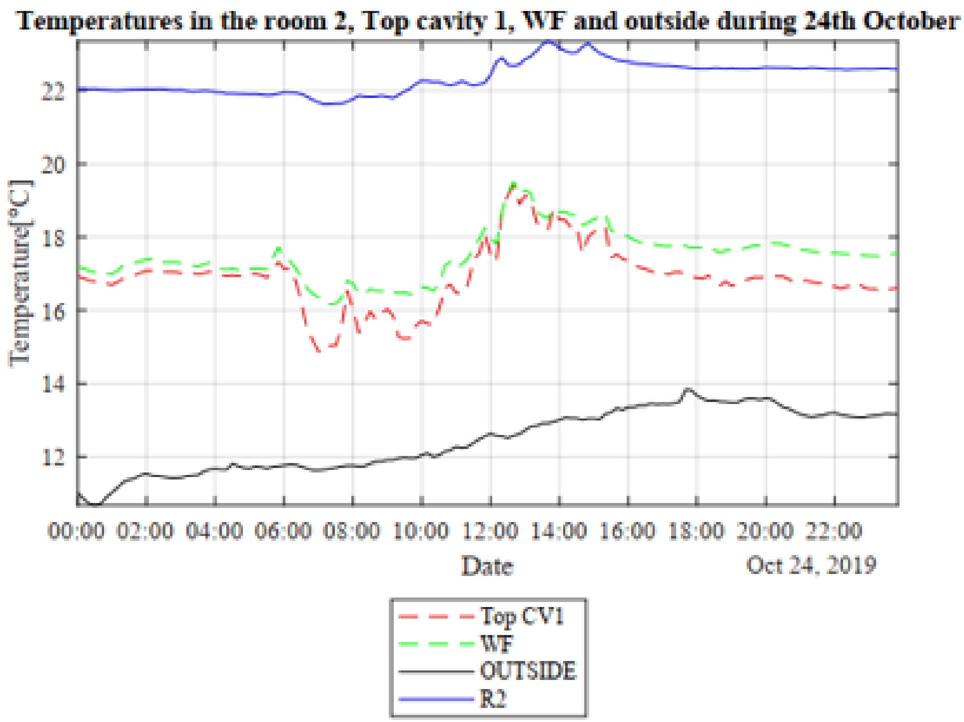
8.5.4 At the top cavity 1 of WT2 in room 2



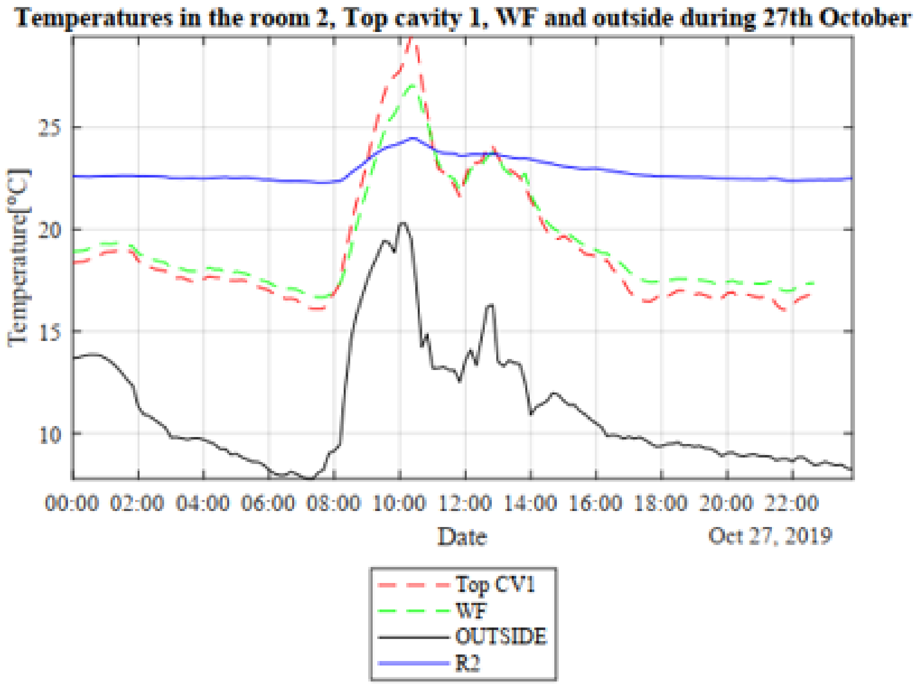
Temperatures [°C] measured in room 2					
Period	Outside	Top cavity 1	Window frame	R2	Slope
22/10/19 at 09:18	12.02	18.79	18.79	22.87	↗
22/10/19 at 09:40	12.14	18.70	18.70	23.09	↘
22/10/19 at 10:59	12.74	20.49	20.49	22.87	↗
22/10/19 at 11:00	12.77	20.53	20.53	22.87	↘
22/10/19 at 11:39	14.29	23.38	23.38	22.87	↗
22/10/19 at 12:50	**17.16**	**32.99**	**29.55**	**23.61**	$\Delta T_{Top\ CV1-WF}$
22/10/19 at 17:45	12.85	19.51	19.51	22.44	↘



23/10/19 at 09:14	11.22	22.86	22.86	23.40	↗
23/10/19 at 12:58	**18.74**	**42.94**	**38.60**	**24.92**	ΔT Top CV1 - WF
23/10/19 at 17:47	13.84	19.20	19.20	22.70	↘



24/10/19 at 12:19	12.56	18.66	18.66	22.89	↗
24/10/19 at 12:24	12.53	18.91	18.91	22,81	↘



27/10/19 at 08:10	9.45	17.35	17.35	22.37	↗
27/10/19 at 10:20	**19.57**	**29.44**	**27.06**	**24.46**	$\Delta T_{Top\ CV1 - WF}$
27/10/19 at 10:56	13.86	24.53	24.53	24.01	↘
27/1 0/19 at 11:55	13.11	22.10	22.10	23.61	↗
27/10/19 at 13:00	13.52	23.52	23.52	23.65	↘