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Determining the best location of carbon dioxide sensor in a classroom

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DESCRIPTION

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Determining the best location of carbon dioxide sensor in a classroom

Abstract

Aim of this Thesis work was to give a review to demand control ventilation system and to investigate a better location of building automation systems carbon dioxide sensor in recently renovated D-Building of Mikkeli University of Applied Sciences. There was installed a demand control ventilation system and occupants are complaining about bad indoor air quality. One classroom was chosen for investigations.

Research was conducted with four stages. First, carbon dioxide concentrations measured by existing sensor were compared to two calibrated detectors. Second, measurements of maximum and minimum air flow rates were conducted. Third, levels of carbon dioxide were measured during long occupancy period in three different places: one – at location of existing sensor, two other locations were chosen according to guidelines for wall-mounted sensors given by ASHRAE organization. Last stage was to determine the air flow patterns in the room.

Results of this work are given in graphs and tables. Due to low occupancy density during measurements it is possible only to assume that the better place for sensors location is according to ASHRAE recommendations, but here more investigations are needed.

Subject headings, (keywords)

Carbon dioxide, investigation, demand control ventilation, sensor location

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CONTENTS

I INTRODUCTION

The task of contemporary building engineers and manufactures is to create such systems and products and invent such units which will be highly effective, reliable, consume less energy and provide occupants comfort at the same time.

Nowadays, energy is expensive and its production results in environmental pollution. The increase of exhausted amounts of CO_2 gas is connected with global climate change. According to the Kyoto Protocol EU should reduce CO_2 emissions by 8%. This could be achieved by paying more and more attention to total energy consumption, saving and prevention of its possible wasting.

Creating smart systems in buildings like heat recovery units, demand control ventilation, more energy efficient units etc. could save big amounts of energy. On the one hand saving energy is a positive and crucial part of the question but on the other hand will such innovation systems meet all the demands of existing building norms and codes or, what is more necessary, do they even meet the requirements to air quality of building's occupants? Are they applicable for all cases? How should components of these systems interact with each other?

System like demand control ventilation is very sensitive to significant number of factors like occupancy density, type of activity held in the room, opening of the windows, breaks during school days, location of sensor etc. It must be designed and installed very carefully so that it will meet all the requirements of norms and occupants comfort.

This thesis refers to investigation of installed DCV ventilation in recently renovated D-building, Mikkeli University of Applied Sciences. Field measurements and investigation of different locations of carbon dioxide sensor location in the classroom D317 were conducted. This room was chosen because of occupants complaints on low air flow rates and bad odors of "new building". I will study CO_2 levels in two different places in room D317.The locations will be chosen according to ASHRAE recommendations and compared to building automation system CO_2 sensor measurements. Moreover, I will study air humidity and temperature, air flow patterns and try to suggest better a place for sensor location, according to measured levels of carbon dioxide.

II THEORETICAL BACKGROUND

2.1 Demand Control Ventilation

Design of heating ventilation and air conditioning systems is mainly based on assumed occupancy of the ventilated area because needed ventilation rates are usually defined as liters per second per person. But during time this assumed occupancy can vary significantly. This may cause a problem of over ventilation and bigger air flow rates supplied to the building when it is needed and thus wasting of money and energy as well. This problem is very acute for building where people spend their time partly like administrative buildings, offices or working places and schools. /1, p. 1234/

Sensor-Based Demand Control Ventilation (SBDCV) give us an brilliant opportunity to supply air only according to its demand at a right time. Generally, Sensor-Based Demand Control Ventilation has two important advantages, firstly better control of indoor air quality because of controlled level of pollutants and secondly less energy load and the second is better humidity control. In humid climates DCV controls amount of supplying outside humid air. /2, p. 2/

Properly applied and well-functioning sensor-based demand control ventilation provides adequate indoor air quality and occupants comfort and saving of money and energy at the same time.

These SBDCV systems are going to be very effective in buildings with following characteristics:

- only one or several pollutants dominate in air, so by controlling its concentrations, we can easily control the other contaminants
- large buildings with unpredictable variation of occupancy during the day
- locations with expensive energy
- areas with big heating or cooling loads /2, p. 9/

Most popular modern SBDCV systems are based on sensors which monitor CO_2 levels or levels of volatile organic compounds (VOC), also known as AQS (air quality sensors). Last type of sensor one can not indicate the exact ventilation rates in comparing to carbon dioxide sensors because they can only mark the increase of indoor contaminants on certain level. In this case ventilation is based on current presence or absence of contaminant so ventilation rates could conflict with given norms. Such sensors can be used only in places where special equipment can produce big amounts of some pollutant occasionally or VOCs could be emitted during special type of cleaning.

The basic idea of demand control ventilation assumes that only one contaminant, most frequently CO_2, is present in the ventilated area and according to this supplied air flow rate can ensure that general levels of it will be effectively reduced. Still the base ventilation rate which is supplied in the room in minimum case of contaminants level should be at least 15% to 50% of maximum level if the building is one year old or more. But base ventilation rate of recently build or renovated buildings should be much higher because of new building components producing gases and odors. Their levels can be higher than carbon dioxide levels and it will disturb the occupants. / 13, p.1215/

2.2 CO_2 in indoor air

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Carbon Dioxide is one of the most frequent gas found in the atmosphere. Metabolic processes of human body product CO_2 and we exhale it at approximately 38.000 ppm (parts per million), then it is immediately mixed with environment and level reduces to acceptable rates. Also it is necessary to emphasize the relation between human body odors and CO_2 levels in the environment. Because of the fact that CO_2 emissions are related with human metabolism, which increase with higher activity it also could be a good indicator for other human emitted bioeffluents. /4, p. 1/

Indoor levels of carbon dioxide usually vary at 400 – 2000 ppm, and outdoor rates are usually between 350-400 ppm but in strongly industrialized areas or areas with heavy traffics its concentration can come up to 800. /10, p.1/
In low concentrations CO_2 is not harmful for humans at all, but its increased levels in the buildings can attest to high contaminations of indoor air. But how affect the higher levels of carbon dioxide on person health? Figure 1 shows effects of different carbon dioxide levels on humans health.

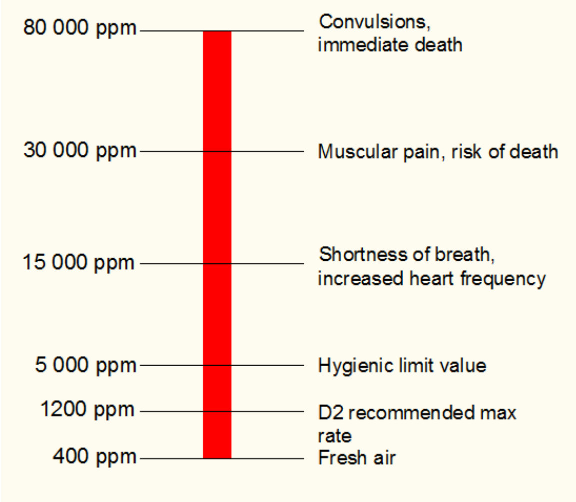

Fig. 1 Effect of increased levels of CO_2 on human body /10, p. 3/

2.2.1 Levels of CO_2 recommended by some authorities

Many organizations and authorities all over the world establish different levels of carbon dioxide inside the buildings to avoid over ventilations and define acceptable rates of carbon dioxide, some of them are shown in Table 1.

Table 1. Levels of CO_2 /10, p.2/

5 000 ppm	Maximum concentration during an 8-hour working-day according to for example the Swedish Work Environment Authority
2 000 ppm	According to many investigations this level produces a significant increase in drowsiness, tiredness, headache and a common discomfort
1 000 ppm	According to the American ASHRAE 62-1989 this is the recommended maximum carbon dioxide concentration in a room. It is also a recommended as the maximum comfort level in many other countries, i.e. Sweden and Japan. It corresponds to an airflow (a need of fresh air) of approx 7 litres/second and person.
800 ppm	The company Ericsson, for example, suggests this value as a maximum carbon dioxide level. It is also a maximum permitted concentration for offices in California. It corresponds to an airflow (a need of fresh air) of about 10 litres/second per person.
400 - 600 ppm	Risk for over - ventilation
350 - 450 ppm	A common outdoor concentration

2.2.2 Levels of CO2 recommended by Finnish and Russian building codes

Finland's National Building Code D2, Part 2.3 Air Quality gives maximum level of carbon dioxide in the building:

" 2.3.1

Buildings shall be designed and constructed in such a way that the indoor air does not contain any gases, particles or microbes in such quantities that will be harmful to health, or any odours that would reduce comfort.

2.3.1.1 The maximum permissible indoor air carbon dioxide content in usual weather conditions and during occupancy is usually 2,160 mg/m^3 (1,200 ppm)" /5, p 9/

At the moment in Russia there are no norms which limit carbon dioxide concentrations in dwellings, but there are norms for factory spaces.

Russian National Norm GN 2.2.5.2100-06 " General requirements to air quality in working zones" gives following values of carbon dioxide level in occupied zone in factories 9 000 mg/m^3 (5000 ppm) (part 2.2.5). /6, p.12 /

In dwelling spaces it is assumed that CO_2 levels will be less than 1250 ppm if we will follow given instructions to calculate needed air flow rate. There are three ways to calculate it:

- according to number of occupants to the activity normally held in the space,
- according to area of the space,
- according to needed times of air change in the room
-

These three values are calculated and then the biggest value is chosen. /7, p. 3-15/

2.3 CO_2 based Demand Control Ventilation

An active ventilation control by CO_2 levels is a simple but powerful and very efficient method of maintaining proper level of air quality in the occupied zone.

Although DCV is relatively recent invention, basic principles of the relation between ventilation control and carbon dioxide levels was mentioned already in 1916 in mechanical engineer's handbook by McGraw-Hill. At this point book established principles of today's demand control ventilation. The handbook recommended that carbon dioxide levels should not exceed 8 or 10 parts in 10 000, or 800 to 1,000 ppm. Some engineering designs and demonstrations of first DCV installations occurred already in 1970s, demand control ventilation did not catch much attention from HVAC engineers until 1990s and only in 1997 ASHRAE Standard 62-1989 stated that under certain controlling conditions applying of variable air volume ventilation systems can be used to create acceptable indoor air flow rates in dependence to occupancy. /9, p. 2/

Nowadays more and more administrative, educational, office and other buildings with big variety of occupancy levels during days are equipped with carbon dioxide sensors. But why CO_2 based Demand Control Ventilation is so popular? The answer to this question is very simple: CO_2 levels are easy predictable and as said before the source of it is human. Human physiology is well learned at the moment and it means that all the humans under certain age and holding quite the same activity exhale same amounts of CO_2, so it could be easily used as indicator of indoor air quality and rate of occupancy. The ratio between occupancy and carbon dioxide levels is direct so it means that for instance doubling of persons number in the room will lead to doubling of CO_2 products. Following table show us CO_2 concentrations according to activity level. /4, p.1/. Table 2. shows state carbon dioxide concentrations according to occupancy density.

Table 2. State CO_2 concentrations according to occupancy category /4, p.1/

Occupancy category	Activity Level	Steady State CO concentration
Classrooms (age 9 plus)	1,0 met	1025 ppm
Restaurant Dining Rooms	1,4 met	1570 ppm
Conference/Meeting	1,0 met	1755 ppm
Lobbies/Prefunction	1,5 met	1725 ppm
Office Space	1,2 met	990 ppm
Sales	1,5 met	1210 ppm

According to book “Achieving desired indoor climate” steady state concentrations can be determined by the following formula /16, p.128/

$$c_r = c_s + \frac{M}{V}$$

Where c_r is indoor (room) concentration, mg/m^3

c_s is supply (outdoor) air concentration, mg/m^3

M is pollutant source strength mg/h

V is ventilation rate, m^3/h

Figure 2. shows different ventilation rates per one person and amounts of carbon dioxide. Here we can see so called equilibrium concentrations when carbon dioxide produced by humans is in balance with that amounts that dilutes with environment air. This points are similar to all numbers of occupants under office-level activity (1, 2 met) and can serve like anchor for carrying out DCV control.

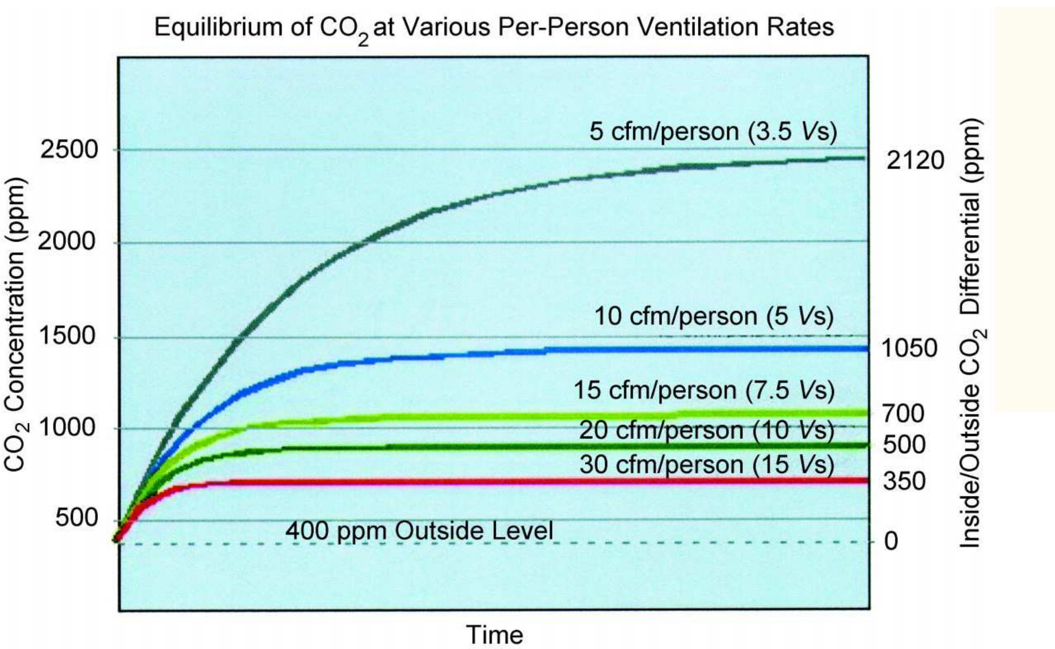

Figure 2. Equilibrium of carbon dioxide at various ventilation rates. /4, p.3/

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Going back to what we said before, most modern ventilation systems are designed to supply certain amounts liters per second per person.
Finland National Building Code D2 gives us following guidelines to define air flow rates:
"3.2.2
During periods of occupancy, an outdoor air flow to ensure healthy, safe and comfortable quality of indoor air shall be supplied to the occupied premises.

> 3.2.2.1 Design values, given in Appendix 1, are primarily used for design of outdoor air flow rates for different room types. The outdoor air flow rates are determined primarily on the basis of the number of occupants. In case there are insufficient grounds for designing air flow rates on the basis of the number of occupants, then such design shall be based on outdoor air rate per surface area." /5, p. 13/

And further option:

"3.2.3
It shall be possible to control the air flow rates of a ventilation system according to loads and air quality, to correspond to the occupancy conditions." /5, p.13/

ASHRAE standard 62-2001 *Ventilation for Acceptable Indoor Air Quality* gives us two ways to define needed amounts of air. First option is classic decision to provide needed ventilation rates according to number of occupants and another to maintain proper indoor air quality. Second Option in contrast to first suggest the variable amounts of supplied outdoor air (from 0% to 100%) which will maintain indoor level of carbon dioxide on particular recommended level approximately 700 ppm more then outside (equal to 7.5 l/s). In this case CO_2 levels serve as representative of indoor air quality and just like thermostats adjust cooling or heating energy supplied to the consumer in dependence of its need, CO_2 sensors measure and define air flow rates supplied to the room. And this gives us great potential to save additional energy.
/8, p.91/

Generally DCV using carbon dioxide sensors consists of two main parts: CO_2 sensors that observe CO_2 levels in the building and the air handling unit which adjust outdoor air flow rates according to data given by sensors. Carbon Dioxide sensors monitor all the time the building area and send signals to air handling unit, which define air supplied to the room.

2.5. CO_2 sensors

First sensors designed especially for HVAC installations appeared in the market in 1990. /4, p.2/ First sensors had several significant disadvantages like difficulty to calibration or even non reliability. Now, market of different detectors is widely increased and improved significantly. /13, p. 1218/

Now Carbone Dioxide sensors are significantly improved and have been available for about 20 years and now annually about 60 000 sensors for ventilation systems are purchased and this is not the limit. Average costs of sensors have dropped up to 50% from 400 euro to 200 euro without installation. Almost all large HVAC companies offer different types of such sensors.
The most technologies in detectors is so named interactive, so it means that gas should somehow physically or chemically interact with the detector itself. /2, p.3/
Main type of CO_2 sensors are:

- infrared
- electrochemical
- photo- acoustic
- mixed gas sensors

CO_2 is very inert therefore the conventional interaction cannot be used and because of this the most wide used type is non-dispersive infrared sensors (NDIR).

2.5. 1 NDIR sensor

The technology of NDIR sensor is based on fact that every gas adsorbs light at certain wavelengths. CO_2 molecules adsorb infrared light at wavelength 4,2 microns, according to this NDIR carbon dioxide sensors calculate how much light was absorbed and therefore gets the measurement of CO_2 level in environment. The apparatus has a chamber where comes the environment air. This chamber has a light source at one end and light detector on another, which is provided with selective optical filter that admit light only at wavelength 4,2 microns.

Figure.3 shows IR sensor with second detector with optical filter intended to wavelength where no light absorption is. This is used to correct optical changes over time which may result because of sensors drifts. Drifts may occur because particles may come to sensor.

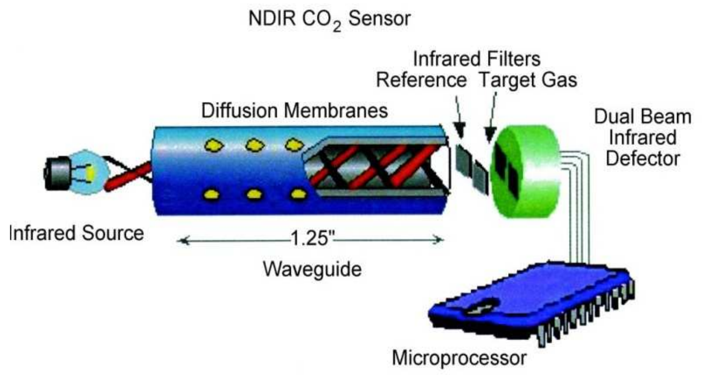

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Fig. 3 NDIR sensor /4, p.3/

With the lapse of time infrared source become older and this may cause problems. In order to prevent it sensors with most stable characteristics must be used. Also there are such options like dual-beam system (shown on Figure 3) which prevent both incoming of particles and aging of the sensor and possibility of nighttime calibration of sensors itself when space is not occupied and not so many particles are inside.

2.5. 2 Photo acoustic sensor

Photo acoustic sensor operates by diffusing air into a sensors chamber and expose it with light at wavelengths absorbed by carbon dioxide molecules. As it absorbs light energy the airs temperature in the chamber increase and causes extra pressure pulses. They are measured by piezo-resistors and transmit data to the processor that calculates CO_2 level (Figure 4).

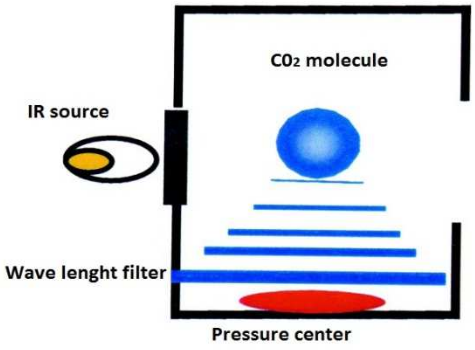

Fig.4 Scheme of Photo acoustic sensor /4, p.3/

This type of sensors are not sensitive to dirt and dust but they are liable to light source aging. Also accuracies and sensitivity of photo acoustic sensors can be influenced by different kinds of vibrations and changes of atmospheric pressures. That's why a lot of this type sensors also include pressure correcting sensor inside. This help to achieve more accurate measurements. /13, p.

2.5. 3 Electrochemical sensor

Electrochemical sensor measures current conducted across a gap filled with electrochemical solution. Diluted carbon dioxide decreases pH value of the solution and frees conductive metal molecules. In order to this, current signals of increased CO_2 level. /2, p.5/

2.5. 4 Mixed gas sensor

Mixed gas sensor detects CO_2 in indoor air but along with other gases. Therefore they are not so widely used in applications of DCV. /2, p.5/

Detectors can send values to the air handling unit via wires or wireless. Hard wire sensors require both signal and power wire and wireless sensors work using batteries. One battery will last for 2-3 years for operating of detector and data measured by sensor led via wireless network to the control center of the whole building. /2, p.7/

2.6 Types of control of DCV system

Various types of control can be used in DCV system according to needed effect:

- Simple set point control. Damper or AHU is activated if CO_2 level increases given set point value
- Proportional control. Ventilation system adjusts air flow rates according to levels of carbon dioxide
- Proportional integral control. Air intake is controlled not only by CO_2 but also by its changing rate.
- Two-stage control for zone-based DCV. In this systems both CO_2 levels and temperature controls the adjustment.

2.7 Location of CO_2 sensors according to ASHRAE recommendations

Determining of right location of sensors is one of the most crucial things about DCV installation. Sensors should be placed so that they monitor and measure proper values of carbon dioxide levels, because according to the data they give air handling unit will supply needed amount of air to the occupied space. Therefore, if sensors show lower values of CO_2 in the room environment because of draughts or too high location there can be risk of less ventilated spaces, which will cause indoor air quality problems.

Placement of sensors can be determined according to type of the building and different conditions. Sensors could be wall mounted in the room or duct-mounted.

American organization of HVAC engineers (ASHRAE) gives following guidelines for installation of DCV and CO_2 sensors in buildings. As said in ASHRAE Journal from February 2001, article “Demand Control Ventilation using CO_2”: “Generally, it is recommended that sensors be installed it the occupied zone rather in ductwork. This is because return air tends to be an average of all spaces being conditioned and may not be representative of what is actually happening in a particular zone”. /4, p.4/

2.7.1 Duct-mounted sensors

Duct-mounted sensors are typically located in the air-return duct or inside the return air space, before it entering the exhaust air device. This location is used when one air handling unit serves all zones with similar levels of occupancy and activity of people and ventilation system operates continuously. Duct-mounted location of sensors can lead to inaccuracies in measurements because of leakages in ducts or infiltrations. This type of location is not recommended when the building is divided into several ventilation zones.

2.7.2 Wall-mounted sensors

Wall-mounted sensors can be mounted like thermal sensors. Detectors should be placed exactly in occupied zones within space where people sit or stand (holding main activity). All areas where draughts can cause inaccurate measured values of carbon dioxide should be avoided. Draughts and leakages can be found near windows, doors, air intakes or exhaust air units. Also direct breathing on sensor affect the measurements, therefore, sensors should be placed so that people will not be closer than 0,6 m to sensor /4, p. 4/

Consequently to this, it could be evaluated that location of sensor is one of the most crucial factors of installing the demand control ventilation. Depends on its' measured values certain amounts of air are supplied to the occupied zone and on it relies occupants comfort. So it is really necessary to avoid mistakes and room and place for sensor should be studied well so that the detector will show real values and the system will work properly.

2.4 Investigation of occupancy density and DCV in Norvegian schools

In year 2002 81 schools in Oslo, Norway were selected to research how much energy can be saved by using a demand-control ventilation based on carbon dioxide levels (DCV- CO_2), demand control ventilation based on infrared occupancy sensor (DCV-IR) and constant air volume system (CAV). There was 157 classrooms selected intended for an average 22 occupants with daily period of usage 4 h.

Most of Norwegian schools mostly equipped with CAV systems, which are designed to reduce highest expected indoor pollutants levels: "…Normal practice for CAV is to provide a classroom with 270 dm^3/s or 330 dm^3/s fresh air, depending on the pollution load from building materials". /1, p. 1234/

The air flow rate stays constant during operational hours which may come up to 24 hours and this will guide to over-ventilation and wasting of energy. DCV-CO_2 and DCV-IR are good alternatives to CAV systems. It has been shown in Sweden that DCV-IR can reduce energy consumption of ventilation system up to 50%, also infra-red-occupancy sensors are much cheaper than carbon dioxide detectors.

Outdoor concentrations are approximately 350 ppm, Norwegian guidelines gives a maximum indoor level of 1000 ppm for schools. The needed air flow rates for different ventilation systems were calculated based on following assumptions and then compared to each other:

> " CAV: Designed for 30 occupants (7 dm^3/s person) and additional 1 $dm^3/s(m^2)$ due to pollution load from materials. This airflow is maintained during the entire operating time of the air-handling unit.
> DCV-CO_2: Designed for the actual number of occupants present and a minimum airflow of 1 $dm^3/s(m^2)$ when the CO_2 level is less than 700 ppm. The minimum airflow is maintained until the CO_2 level rises to 900 ppm after the start of the lesson. The ventilation rate is then increased and regulated to keep the CO_2 concentration at a steady-state level of 900 ppm. At the end of the lesson, this ventilation rate is maintained until the CO_2 level drops below 700 ppm when the ventilation rate is reduced to minimum (1 $dm^3/s(m^2)$). The CO_2 level of 900 ppm was chosen because the Norwegian regulations recommend a maximum of 1000 ppm, combined with the fact that mixing ventilation has an overall relative ventilation efficiency of less than 1.0 in practice compared to perfect mixing [7]. Another consequence of the choice of 900 ppm is that the resultant

ventilation rate is approximately the same as CAVand DCVIR for a full classroom with 30 occupants during steady-state conditions.
DCV-IR: Designed for 30 occupants (7 dm^3/s person) plus an additional 1 $dm^3/s(m^2)$ for the pollution load from the building materials. An infrared occupancy sensor controls the ventilation rate between minimum airflow (when the classroom is unoccupied) and the design airflow (when the classroom is in use). The minimum airflow is 1 $dm^3/s(m^2)$. In each case, the air supply distribution principle in the classroom is fully mixed.” /1, p. 1235/

Inspection shows that in 74 % of cases school rooms occupancy density is lower than they are designed for. Research show that based on this and calculations of energy savings DCV-CO_2 strategy can help to reduce air flow rates up to 56% in comparing to CAV systems during 6-hours operation period and up to 31% during 24-hours operational period and DCV-IR up to 74% in case of 6-hours operation, 36% for 24-hours operation. Figure 5 shows air volumes of three strategies in dependence of operating hours.

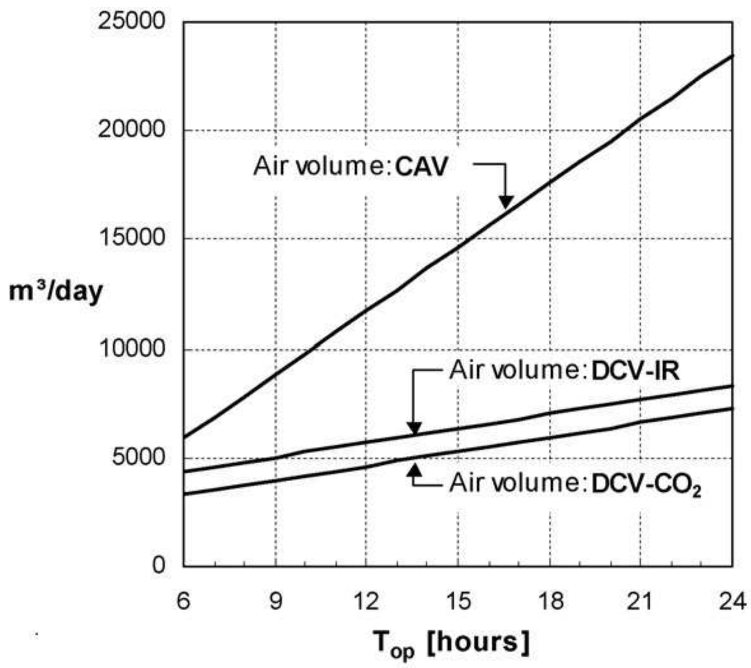

Figure 5. Air volumes of three strategies in dependence of operating hours /1, p.1234/

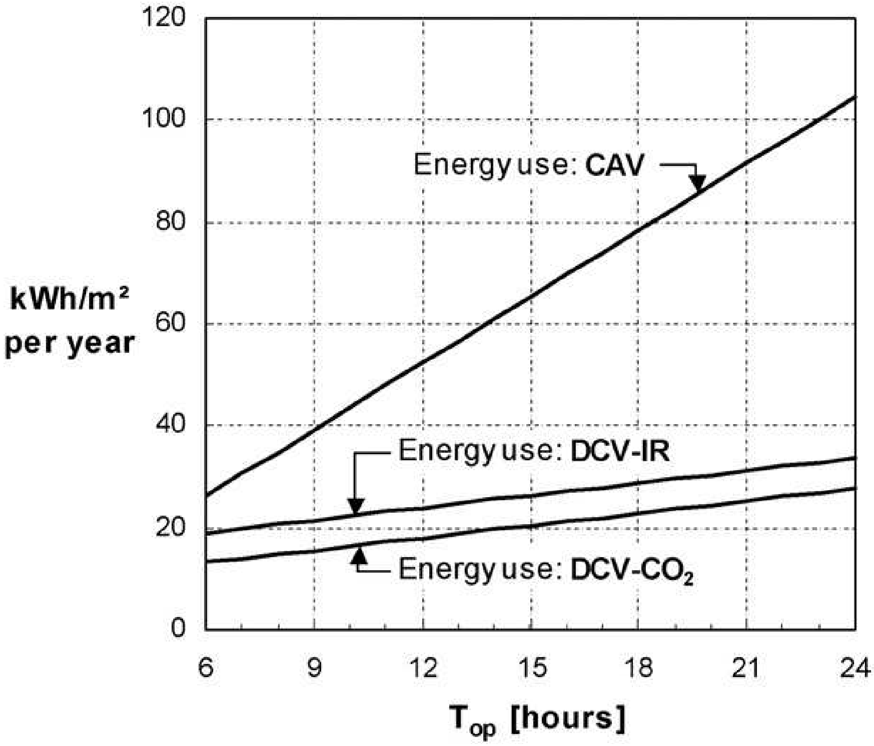

Figure 6. Energy use of three strategies in dependence of operating hours /1, p.1234/

Figure 6 shows energy savings of three strategies in dependence of operating hours. Research shows that the DCV-CO_2 is able to save up to 50% of energy during 6-hours operational use and 24% for 24-hours usage./1, p1236/

III INVESTIGATION OF CLASSROOM D317 IN D-BUILDING

3.1 Overview of the classroom

D-building of the main campus of Mikkeli University of Applied Sciences has been recently renovated and new classrooms for students were built. Also, demand control ventilation system, using carbon dioxide sensor was applied.

One room was chosen for this study because of an incident that one student suddenly fainted without specific reasons for that and occupants complaints about bad indoor air quality, odors and lack of fresh air supplied to the room. The room is situated on the 3rd floor of D-Building and it's number is D317. It is provided for lectures and seminars for nursing students, total amount of seats provided for students is 20.

The area of the room is 107 m^2 and it is provided with three supply air terminal units and two exhaust. Figure 5 and 6 show pictures of the class room and the placement of supply (model JTC) and exhaust (model EVA) air terminal units, both made by Flaktwoods company. Supply air devices are connected via ducts with size 250 mm to one air handling unit TK 43, situated on the 4th floor in the machine room. Main duct of supply air flow has size of 315 mm and comes to the room from corridor. There a damper is installed on the main duct.

The damper works in conjunction with CO_2 sensor. It sends information to building control system built up by Schneider Electric and according to this the damper reduces or increases the required amount of air. Maximum flow rate supplied to this room is 350 dm^3/s, maximum amount of exhaust air is also 350 dm^3/s.

At the moment DCV system has been adjusted so, that supply air flow rates cannot be reduced more that 40% during the occupational period. This step was taken to provide needed amount of air so that the occupants would not complain about odors of newly repeated building. The set point at which there air flow rate increases is 750 ppm.

Figure 7. shows the picture of the room and Figure 8. Shows the placement of the supply air devices.

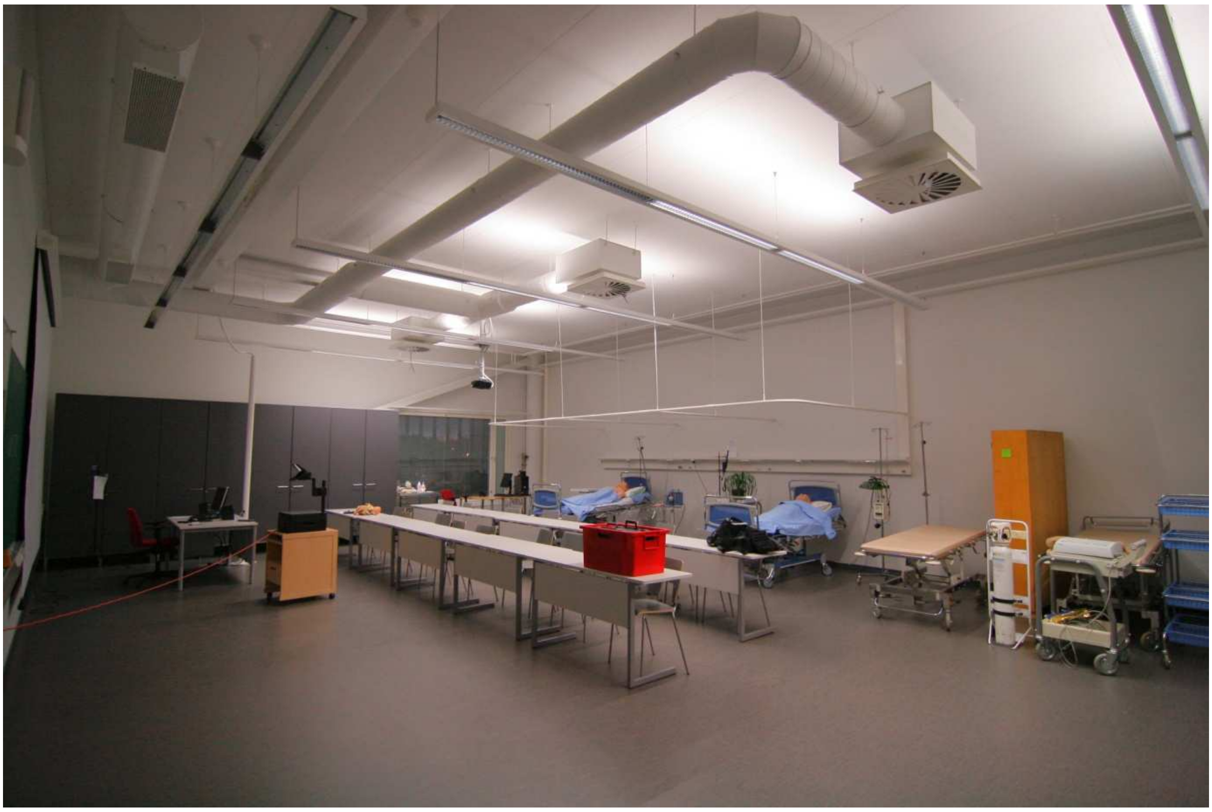

Figure 7. Picture of investigated D317 room

Figure 8. Placement of supply air terminal units in D317

The current location of carbon dioxide sensor is near the entrance door as shown in Figure. 7. According to ASHRAE recommendations and installation guidelines this placement might be not optimal. Because of drafts and air leakages caused by the movements of the door or untightness of the door the carbon dioxide sensor may show lower levels of CO_2 compared to the room and this will make the ventilation system to decrease air flow rates. Therefore, air quality in the room may be low and occupants' comfort could be harmed.

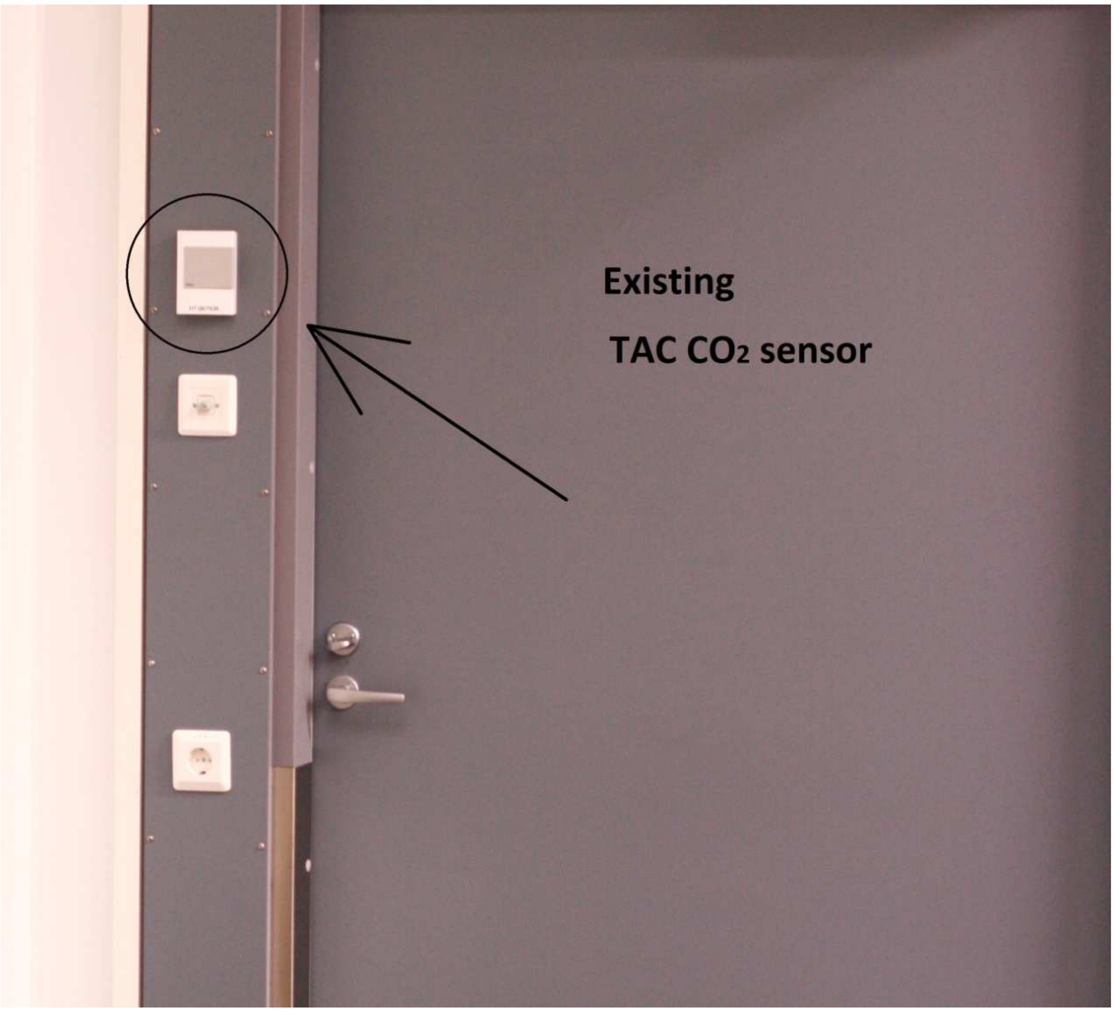

Fig.7 Current location of system's carbon dioxide sensor

Type of sensor used in the room is TAC SCR100 by Schneider Electric, shown on Figure. 8. This is an infrared type of sensor intended for wall mounting. It measures carbon dioxide in the ambient of the room in concentrations up to 2000 ppm and transfers data into a 0 – 10V or 0 – 5V output signal. Accuracy of the sensor is +/-5% of measured value.

Figure 8. TAC SCR100 by Schneider Electric / 11 /

3.2 Methods

3.2.1 General determination

For determination of best location of DCV sensor measurements of air humidity, air flow pattern, temperature and carbon dioxide levels in different parts of the room were made. Also outside air levels of carbon dioxide were measured, too.

Measurements were made in the room in three main steps:

1. Comparison of measured values of carbon dioxide by three sensors – two TSI IAQ Calc and existing systems' sensor during period of occupation.
2. Measurements of the minimum and maximum air flow rates from every supply air device when no occupants were in the room.
3. Measurements of carbon dioxide levels, humidity and temperature during period of occupancy.
4. Measurements of air velocities and studying and air flow pattern of the room by using smoke machine.

Measurements were made by the following list of devices

- Temperature and humidity were measured by EBRO EBI 20
- Air flow rates by TSI Airflow device by TSI company
- Carbon dioxide levels by TSI IAQ Calc by TSI company
- Smoke to study air flow patterns was created with Stairville smoke machine SF-80

3.2.2 Comparison of three sensors

Comparison of three sensors was made to estimate the difference between values measured by calibrated TSI sensor and existing sensor by building automation system. This is needed to define possible inaccuracy of existing sensor and make a correction for data it gives.

First, calibration was made with a bag fixed tightly around the sensor, two tanks with gas of 0 ppm and 1000 ppm, small plastic tube and TSI IAQ sensor placed inside the bag to see CO_2 concentration in it. Picture of installation is shown on Figure 9.

Figure 9. Installation of "bag" comparing of sensors

It was assumed that the bag will be filled up with gas which contains certain amount of carbon dioxide and then we could check the measured data of building automation system and learn the possible difference and systems' sensor inaccuracy.

Second, two TSI sensors were placed close by existing TAC sensor and were recording carbon dioxide levels during one lecture from 11-45 to 15-15 p.m. Picture of installation is shown on Figure 10.

Figure 10. Picture of installation for comparing of three sensors results

Afterward results given by two sensors were compared to data given by building automation system.

3.2.3 Measurements of maximum and minimum air flow rates

Measurements were made with minimum air flow when all occupants have left the room and with the maximum air flow rate when around the systems sensor approximately 1900 ppm level of carbon dioxide was generated.
Level of carbon dioxide near the system's sensor was measured by TSI IAQ Calc, which was calibrated beforehand.

TSI Airflow device was used with two plastic tubes was used to measure the pressure difference in the supply device. Tubes from measuring device are connected with tubes from air terminal unit and air flow is determined.

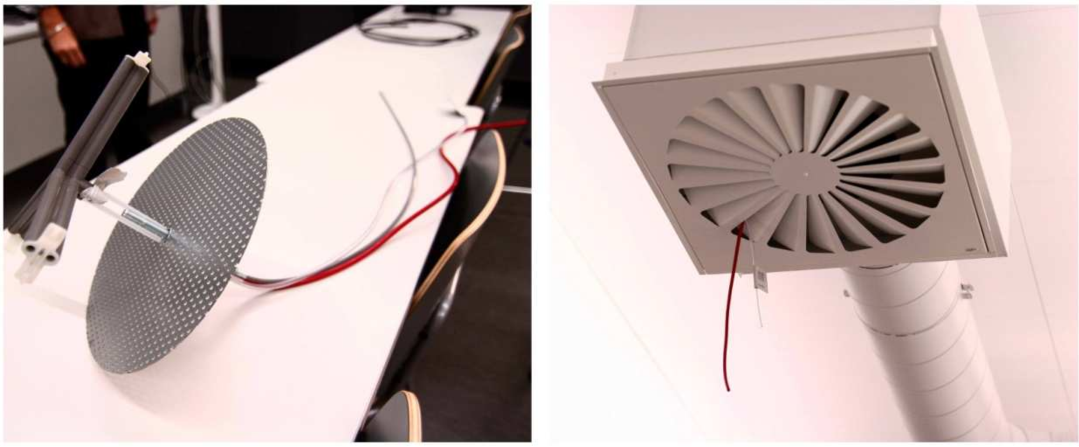

Figure 9. Supply air terminal device and the control plate of the terminal device

3.2.4 Measurements of carbon dioxide levels

Second step of measurements took place during lectures when occupants were inside the room. Two measuring instruments TSI IAQ Calc (Figure.10) and two Humidity and Temperature Sensor EBI 20 by EBRO (Figure 11) were placed in two corners of the room according to ASHRAE Recommendations in ASHRAE Journal, February 2001:

> “Location of Wall-Mount Sensors**.** Criteria for placement of wall-mount sensors are similar to those for temperature sensors. Avoid installing in areas near doors, air intakes or exhausts or open windows. Because people breathing on the sensor can affect the reading, find a location where it is unlikely that people will be standing in close proximity (2 ft [0.6 m]) to the sensor. One sensor should be placed in each zone where occupancy is expected to vary. Sensors can be designed to operate with VAV based zones or to control larger areas up to 5,000 ft2 (465 m2) (if an open space)”. /4, p. 4/

Figure 10. TSI IAQ Calc /12/

Figure 11. EBRO humidity and temperature sensor EBI20 /14/

Also, it has to be taken into account at this point that the occupant's activity in the classroom can be different in different parts of it so the metabolic rate and therefore level of exhaling carbon dioxide can vary. Because right part of the room is intended for simulating nursing processes which requires standing and moving so the metabolic rate and exhaled carbon dioxide amounts will be higher, one sensor was placed there between beds with dolls-patients on the high of 1,6m. Also, this location meets other ASHRAE requirements – it is enough far from exhaust and supply terminal units and from door and window. Location of sensors is shown on Figure 11.

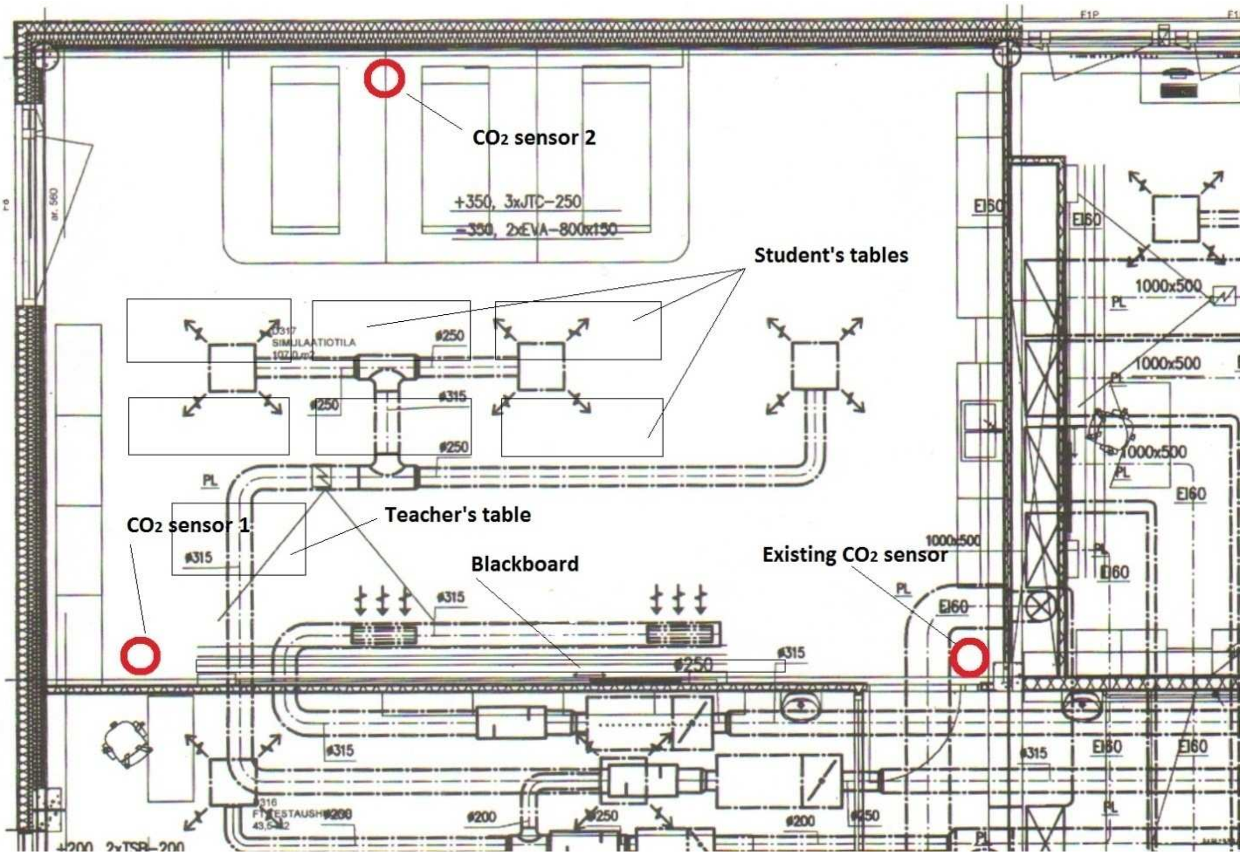

Figure 12. Plan of sensor's location in the room

The Second place chosen situated on the left side near teachers desk in the corner (CO_2 Sensor 1). Sensors are placed at the height of 1,2 meters because activity held in this part of room is sitting. Required distances from door and window and supply and exhaust terminal units were maintained.

Picture of installation is shown on Figure 12. It consists of TSI IAQ Calc sensor for measuring carbon dioxide, sensor EBRO EBI 20 for measuring humidity and temperature and a note which contains text in Finnish: "On-going CO_2 measurements! – Do not touch! Do not breath towards the sensor!"

Two installations were left for a time period from 10.00 a.m. to 18.00 p.m. and were recording carbon dioxide levels in these two parts of the room every five minutes. Number of occupants attending to each lecture was manually recorded also.

Figure 13. Picture of installation

3.2.5 Determination of air flow patterns in the room

Air flow patterns in ventilated room are mainly determined by the location of the supply air devices. It is assumed that during the lectures all gas exhaled by occupants is mixed in the air and that it will follow the air flow patterns in the room. Therefore, air flow patterns near locations of sensors are checked with help of smoke machine to show how the air flows go near the location of sensors.

Smoke or fog machine is a mechanical device that uses either inert gas or electric pump to propel mineral oil or water glycol mixture to vaporize it. /15/

Figure 14. A air flow patterns determination with a smoke machine

IV RESULTS

4.1 Comparing of results measured by three carbon dioxide sensors

4.1.1 Comparing of results measured with “bag” method

First “bag” method of sensors’ values comparing wasn’t successful. During experiments with 0ppm gas, values measured by TSI IAQ Calc were decreased only by 376 ppm and then goes upwards. According to systems’ sensor data smallest carbon dioxide level during experiment was 407 ppm. Results of measurements are given in Table 3.

Table 3. Results of measurements by filling the bag with 0 ppm gas

Time	TSI Sensor	System sensor	∆ CO2
14:27	572	523	-49
14:28	484	523	39
14:29	499	473	-26
14:30	444	407	-37
14:31	424	561	137
14:32	376	526	150
14:33	445	644	199

In the same way, during filling the bag with 1000 ppm the highest level showed by TSI sensor was 730 and then according to it level of CO_2 goes down.
Results of measurements are given in Table 4 below.

Table 4. Results of measurements by filling the bag with 1000 ppm gas

Time	TSI Sensor	System sensor	Δ CO2
14:36	730	789	59
14:37	644	699	55
14:38	672	598	-74
14:39	713	640	-73
14:40	618	603	-15
14:41	568	737	169
14:42	557	614	57

4.1.2 Comparing of results measured by three sensors

Results of measured by two TSI sensors and building automation sensor values are given in Appendix 1. Figure 15 shows three recordingss, so that it is noticeable that existing sensor shows bigger values at approximately 50 ppm rate.

In comparing, TSI sensors have little difference, their carbon dioxide curves are going along each other. It means that systems sensor data values should be corrected with mean value, which is according to equation:

$$c = \frac{\sum (c_{existing} - C_{TSI})}{n}, \Delta c = 65\,ppm$$

Where $C_{existing}$ – CO_2 value measured with existing sensor,

C_{TSI} – mean value measured by TSI sensors

c - number of samples

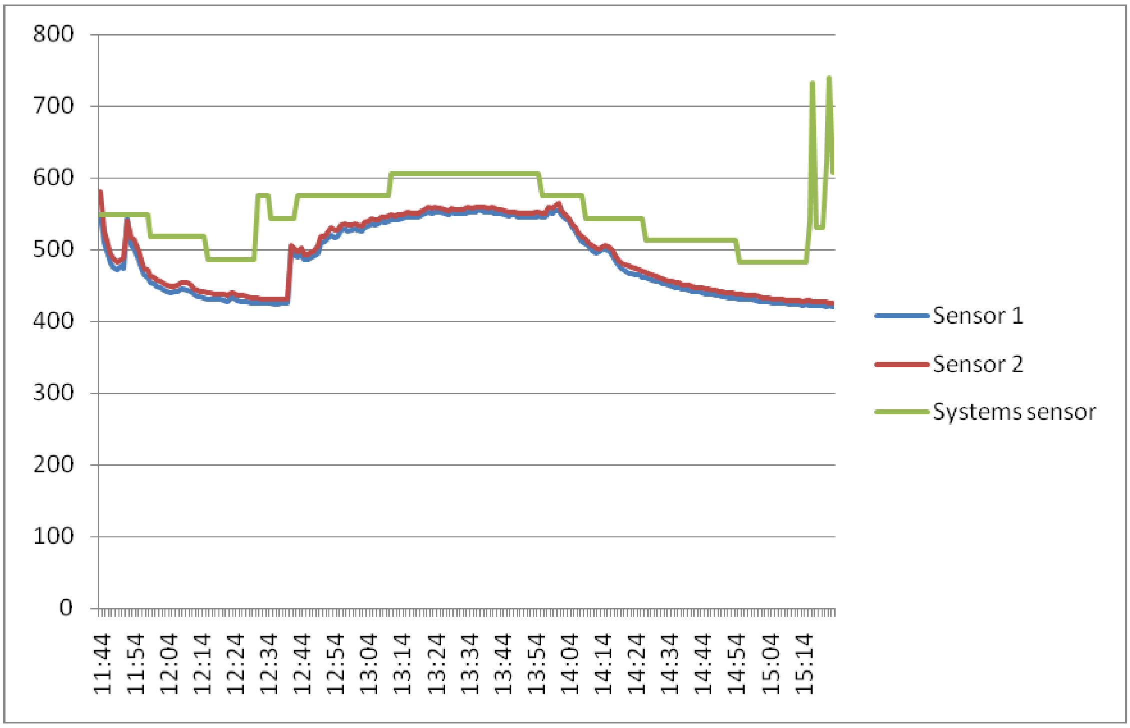

Figure 15. Measured values of carbon dioxide by three-sensors

4.2 Results measurements of minimum and maximum air flow rates

Measuring of air flows at each supply air unit was done during no occupancy period. Results of it are shown in Table 3 and Table 4.

Table 3. Minimum air flow rates from each supply terminal device

	I	II	III	Total
Avg., dm^3/s	39	45	55	141
Min., dm^3/s	32	39	49	122
Max., dm^3/s	43	50	60	154

Carbon dioxide levels measured by TSI IAQ Calc near the system's sensor avg. 549 ppm, value measured by system's sensor according to given information by Schneider Electric maintenance personal 554 ppm.

Table 4. Maximum air flow rates from every supply terminal device

	I	**II**	**III**	**Total**
Avg., dm^3/s	106	112	131	349
Min., dm^3/s	86	103	127	317
Max., dm^3/s	114	120	138	373

Carbon dioxide levels measured by TSI IAQ Calc near the system's sensor app. 1500 ppm, value measured by system's sensor according to information given by Schneider Electric maintenance personal 1800 ppm.

Air exchange rate for room can be calculated by following equation:

$$n = \frac{Q}{V},$$

Where Q-total supply air flow rate, in maximum case 1256 m^3/h, in minimum case 508 m^3/h

V – volume of the room, 428 m^3

In case of the maximum flow rate air exchange rate will be 2,9 1/h and in case of minimum flow rate 1,2 1/h

Concentrations of carbon dioxide were high enough to increase air flow rates to its maximum because according to data given by Schneider electric the set point of carbon dioxide at which ventilation achieves its maximum is 750 ppm.

Classroom intended for 20 students and one lecturer, maximum air flow rate is 350 l/s it means that for one person it is supplied 16,7 dm^3/s of fresh air. According to the Figure the equilibrium point of carbon dioxide is approximately 330 ppm. In case of minimum air flow rate – 140 dm^3/s, amount of air per person is 6,7 dm^3/s and the equilibrium point will be 1000 ppm.

4.3 Measurements of carbon dioxide levels

Appendix 3 contains table which shows measured carbon dioxide levels every five minutes in the room and also measured levels by system's existing sensor every ten minutes and also it's corrected value in accordance to calculated mean difference between building automation system and TSI sensors.

Figures 16 and 17 showing graphs of carbon dioxide levels measured by two sensors in the room during whole day and one existing sensor.

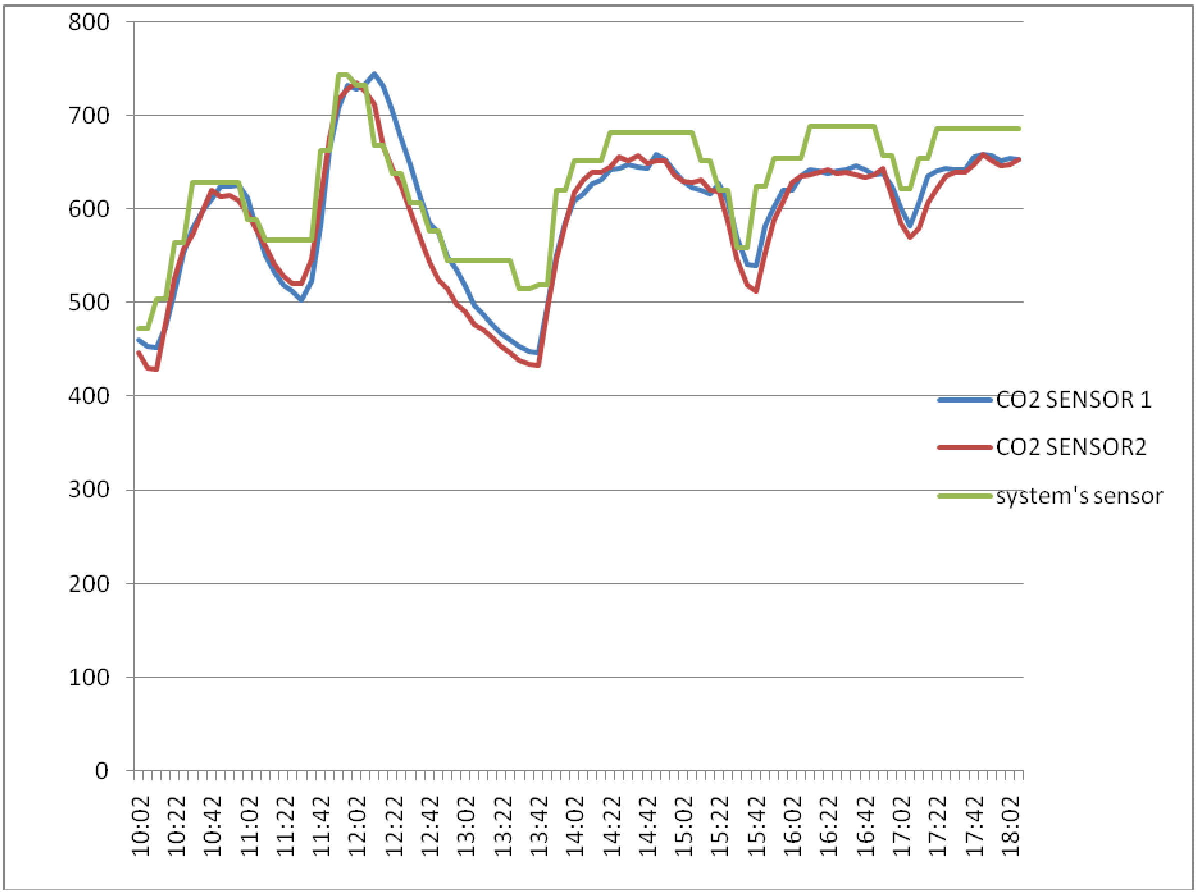

Figure. 16.Carbone dioxide levels in the classroom during whole day including ucorrected existing sensors data

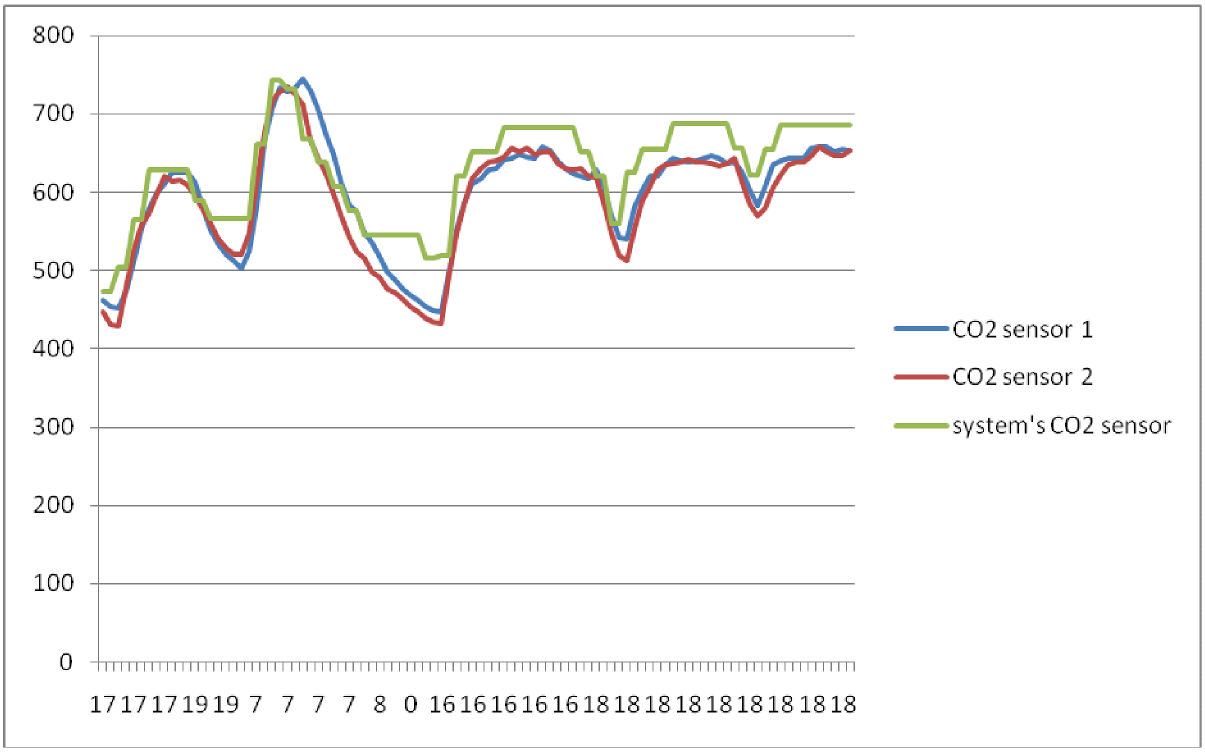

Figure. 17. Carbone dioxide levels in the classroom according to number of occupants including uncorrected existing sensors data.

Figures 18 and 19 showing graphs of same data by TSI sensors, but data of existing sensor is corrected with 65 ppm value.

Figure 20. shows changing of number of occupants during whole studying day

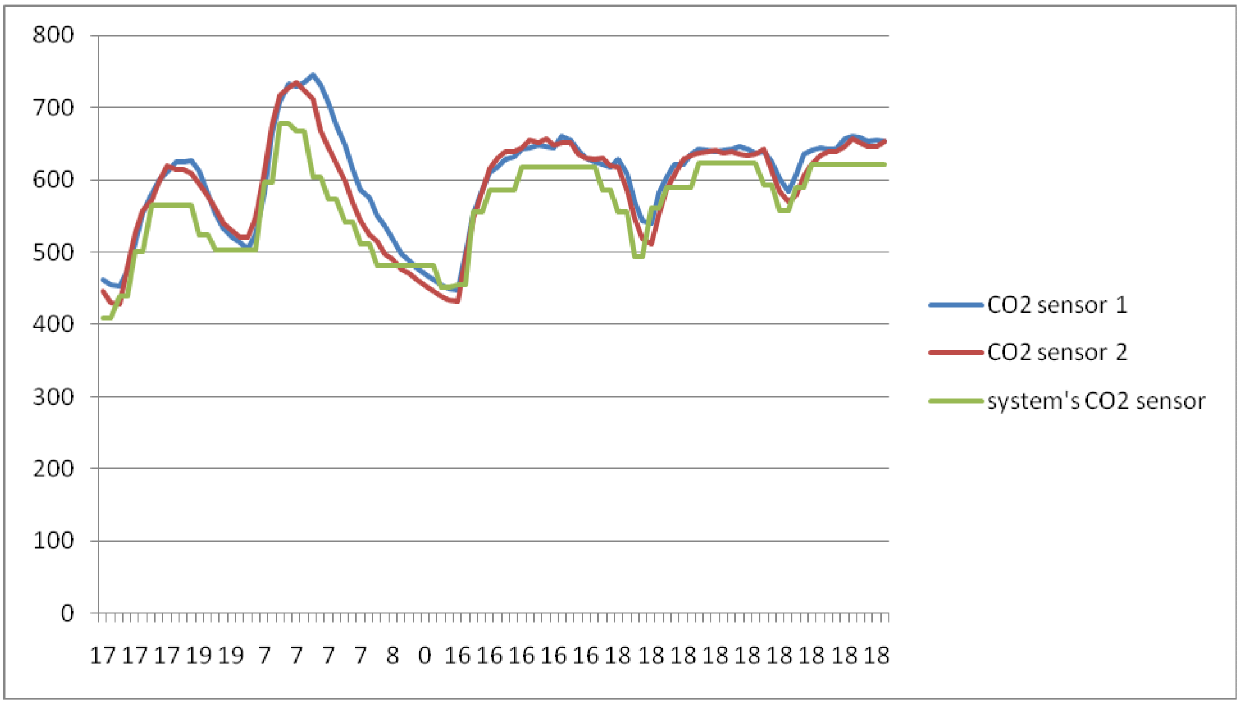

Figure 18. Carbone dioxide levels in the classroom during whole day including corrected existing sensors data

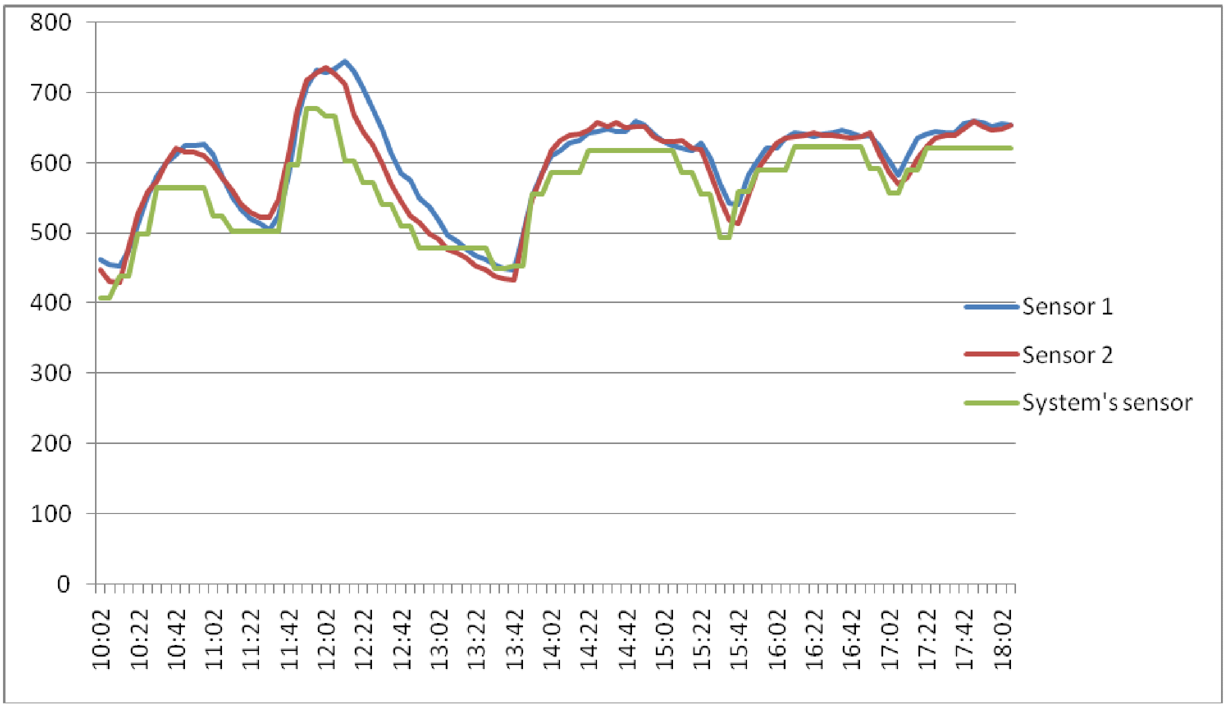

Figure. 19. Carbone dioxide levels in the classroom according to number of occupants including corrected existing sensors data

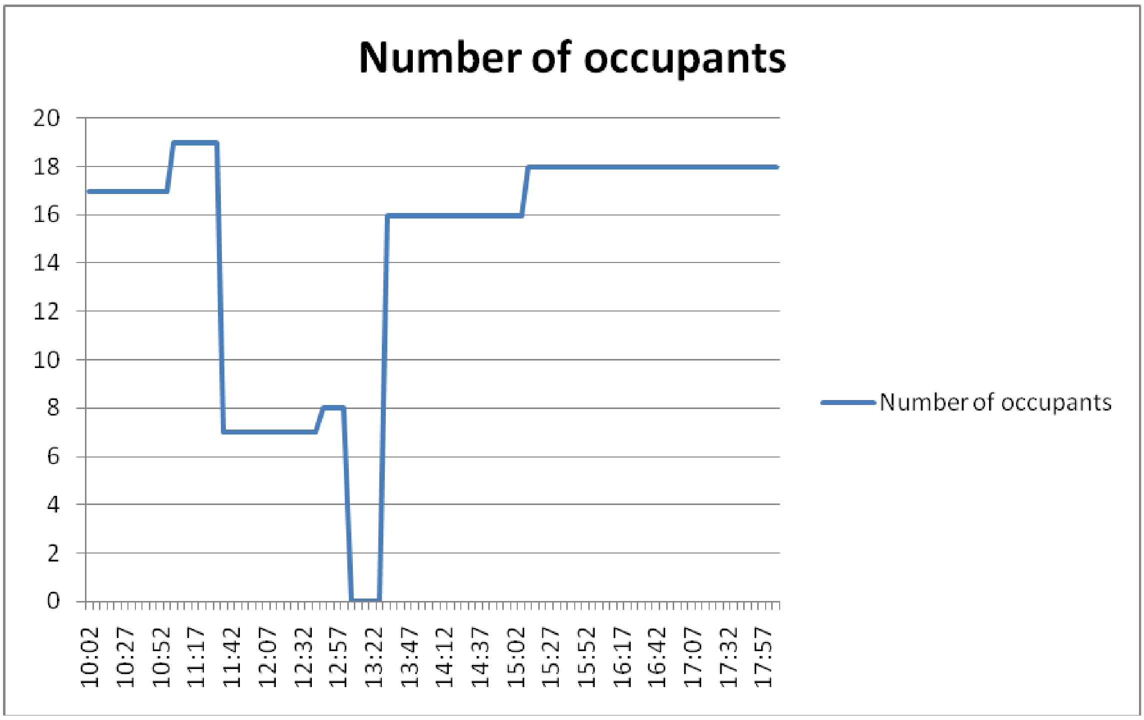

Figure. 20 Number of occupants during studying day

According to formula given in book “Achieving the desired indoor climate” steady state conditions can be calculated by the formula

$$c_r = c_s + \frac{M}{V}$$

Where c_r is indoor (room) concentration, mg/m^3

c_s is supply (outdoor) air concentration, mg/m^3

M is pollutant source strength mg/h

V is ventilation rate, m^3/h /16, p.128/

Maximum occupancy density in D317 was 19 occupants and the minimum air flow rate is 141 dm^3/s, 1 person produces 33g of CO_2 per hour.

Therefore, assumed steady state conditions for room will be 2121,4 mg/m^3 or 1162 ppm.

Results of measuring of relative humidity and temperature are given in Appendix 4. Mean value of humidity is 27,1% and temperature 22,6 ^{o}C.

4.4 Air flow patterns near sensors locations

By using a smoke machine it was estimated that mixing in the room is effective and goes at a high rate. Air flows stream down from supply air devices mixing with each other and then spreading horizontally all over the room.

It is assumed that carbon dioxide exhaled by occupants mixed fully to the surrounding air and follows air flow streams.

Figures 21, 22, 23, 24 show how the air distributes along the room.

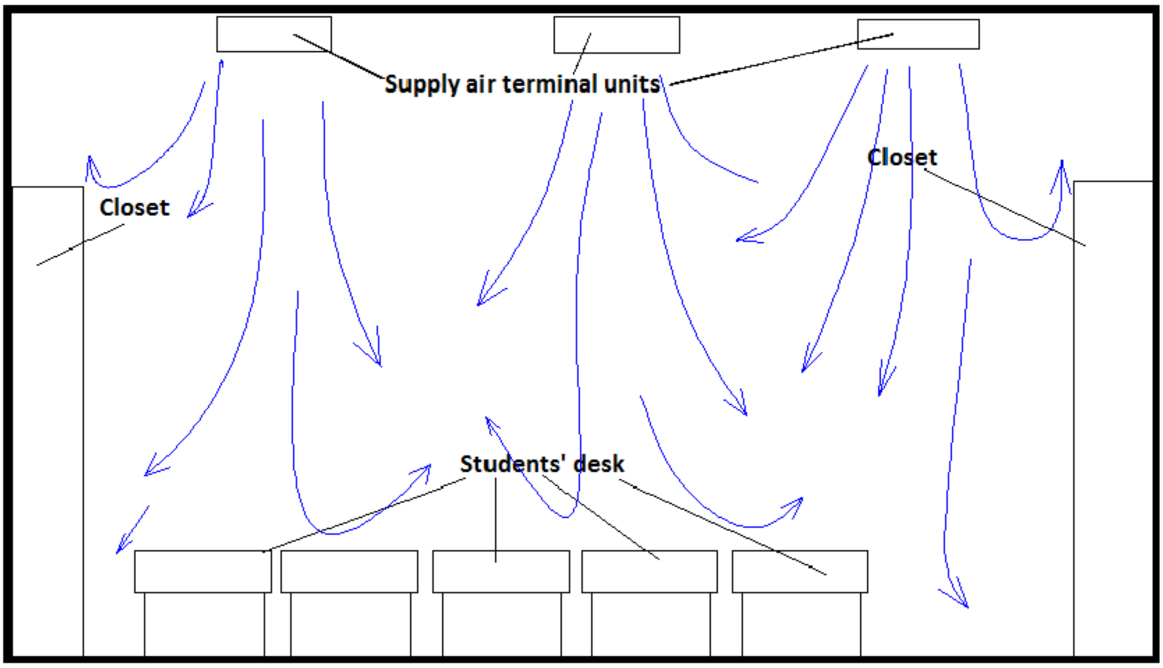

Figure 22. Air flow pattern of the room

Figure 22. Direction of air flows at point Sensor 1

Figure 23. Direction of air flows at of existing CO_2 sensor

Figure 16. Direction of air flows at of point Sensor 2

V DISCUSSION

Installing of Demand Control Ventilation is an excellent way to save money in buildings with varying type of occupancy like in case of D317. But this system is a very sensitive installation. Plenty amount of factors, not only mentioned in this work but also many others should be taken into account by designing and installing of the system. Designer must make the system so that all its' part will work properly in conjunction together.

Only this way the system will give its benefits and satisfy needs of occupants. This is how we can achieve both best indoor air quality and significant economy and also protect the environment by reducing amount of energy consumed and therefore emissions of polluting gases to atmosphere.

According to results given by measurements in this Thesis work it can be evaluated how many factors have influence to carbon dioxide sensors and comfort of occupants and emphasize that the right location of sensor is one of the most crucial things by installing demand control ventilation.

Results comparing of three sensors defines that buildings automation sensor shows bigger values at approximately 65ppm rate. Measurements of carbon dioxide in the room shown on the graph with corrected values define that Sensor 1 which location was near blackboard. Values of carbon dioxide levels were higher during whole day approximately for 7 to 10 ppm than Sensor 2 which location was near simulation beds. This range wasn't high enough, moreover, the carbon dioxide level didn't achieve maximum set point of 750 ppm because the highest level shown by TSI Sensor 1 in the corner was 745 ppm.

Based on this investigation it can be assumed that the best place for carbon dioxide sensor will be in the corner near the blackboard and teacher table where TSI Sensor 1 showed the biggest values, but still more investigations are needed. The difference between values given by three sensors wasn't very high, so there needed more field studies under higher occupancy.

Air flow patterns in the room showing a well mixing of the air, so we can assume that there was a full mixing of carbon dioxide to the indoor air.

According to the results of humidity and temperature got it is clear that both of these factors are quite equal in the volume of the room, also the requirement of operative temperature value is met.

But not only the location of the carbon dioxide detector has influence on indoor air quality in the room and occupants comfort. It is a significant factor that D-building MUAS has been renovated and taken into commissioning less that year ago, so the levels of indoor contaminants and odors produced by new building materials are very high and the minimum air flow rate in the building should be not less that 50 – 60 % of the maximum flow rate. Due to this other than carbon dioxide indoor contaminates will gas off and won’t harm anyhow occupants comfort and health.

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APPENDIX 1

Results of measurements of carbon dioxide by three sensors in one location needed to compare it

Time	Sensor 1	Sensor 2	Systems sensor
11:44	548	581	548
11:45	509	525	548
11:46	498	513	548
11:47	481	494	548
11:48	475	488	548
11:49	472	482	548
11:50	478	486	548
11:51	474	487	548
11:52	544	539	548
11:53	506	516	548
11:54	503	514	548
11:55	490	503	548
11:56	479	491	548
11:57	464	473	548
11:58	461	471	548
11:59	454	463	517
12:00	452	460	517
12:01	448	457	517
12:02	446	455	517
12:03	444	452	517
12:04	441	450	517
12:05	440	449	517
12:06	441	449	517
12:07	442	450	517
12:08	445	454	517
12:09	445	453	517
12:10	444	454	517

12:11	441	451	517
12:12	437	445	517
12:13	435	443	517
12:14	434	442	517
12:15	432	441	517
12:16	431	440	486
12:17	431	439	486
12:18	430	438	486
12:19	430	437	486
12:20	430	437	486
12:21	429	437	486
12:22	428	436	486
12:23	433	440	486
12:24	432	440	486
12:25	429	436	486
12:26	428	435	486
12:27	428	435	486
12:28	428	434	486
12:29	426	433	486
12:30	426	433	486
12:31	425	432	574
12:32	425	431	574
12:33	425	431	574
12:34	425	431	574
12:35	425	431	543
12:36	424	430	543
12:37	424	430	543
12:38	425	431	543
12:39	426	431	543
12:40	426	431	543
12:41	499	506	543
12:42	493	503	543
12:43	489	496	574
12:44	494	502	574

12:45	487	493	574
12:46	486	493	574
12:47	490	496	574
12:48	492	498	574
12:49	496	505	574
12:50	509	518	574
12:51	511	519	574
12:52	517	525	574
12:53	521	530	574
12:54	517	527	574
12:55	519	528	574
12:56	527	534	574
12:57	529	537	574
12:58	526	534	574
12:59	527	535	574
13:00	529	537	574
13:01	528	535	574
13:02	526	533	574
13:03	531	538	574
13:04	533	540	574
13:05	536	543	574
13:06	535	541	574
13:07	537	542	574
13:08	539	545	574
13:09	538	545	574
13:10	540	547	574
13:11	541	548	605
13:12	542	547	605
13:13	542	548	605
13:14	543	549	605
13:15	545	551	605
13:16	546	553	605
13:17	545	551	605
13:18	545	551	605

13:19	545	551	605
13:20	548	554	605
13:21	550	556	605
13:22	552	560	605
13:23	550	558	605
13:24	553	559	605
13:25	552	558	605
13:26	552	557	605
13:27	550	556	605
13:28	549	555	605
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13:35	552	558	605
13:36	553	559	605
13:37	556	560	605
13:38	554	559	605
13:39	552	559	605
13:40	553	558	605
13:41	553	559	605
13:42	551	557	605
13:43	551	556	605
13:44	550	556	605
13:45	549	555	605
13:46	547	553	605
13:47	548	553	605
13:48	548	552	605
13:49	546	551	605
13:50	546	551	605
13:51	546	551	605
13:52	545	551	605

13:53	545	551	605
13:54	546	552	605
13:55	547	552	605
13:56	545	551	574
13:57	546	551	574
13:58	553	559	574
13:59	550	558	574
14:00	555	561	574
14:01	555	564	574
14:02	548	555	574
14:03	543	548	574
14:04	539	543	574
14:05	532	537	574
14:06	526	530	574
14:07	518	523	574
14:08	512	518	574
14:09	508	514	543
14:10	505	510	543
14:11	498	505	543
14:12	495	502	543
14:13	497	501	543
14:14	500	504	543
14:15	501	506	543
14:16	498	504	543
14:17	491	499	543
14:18	484	492	543
14:19	477	485	543
14:20	474	481	543
14:21	470	479	543
14:22	467	477	543
14:23	466	475	543
14:24	465	473	543
14:25	464	471	543
14:26	462	469	543

14:27	462	468	512
14:28	459	466	512
14:29	458	464	512
14:30	456	463	512
14:31	455	461	512
14:32	453	459	512
14:33	452	458	512
14:34	450	456	512
14:35	449	456	512
14:36	447	454	512
14:37	446	453	512
14:38	445	451	512
14:39	445	450	512
14:40	443	450	512
14:41	442	448	512
14:42	441	447	512
14:43	441	447	512
14:44	439	446	512
14:45	438	445	512
14:46	438	445	512
14:47	437	443	512
14:48	436	443	512
14:49	436	442	512
14:50	435	441	512
14:51	435	440	512
14:52	433	439	512
14:53	433	439	512
14:54	433	438	512
14:55	431	437	482
14:56	431	437	482
14:57	431	436	482
14:58	430	435	482
14:59	430	436	482
15:00	429	435	482

15:01	428	434	482
15:02	428	433	482
15:03	428	433	482
15:04	427	432	482
15:05	426	431	482
15:06	426	431	482
15:07	425	431	482
15:08	425	430	482
15:09	425	429	482
15:10	424	429	482
15:11	424	429	482
15:12	424	429	482
15:13	423	428	482
15:14	422	427	482
15:15	423	428	482
15:16	422	428	539
15:17	421	427	732
15:18	422	427	530
15:19	421	426	530
15:20	421	426	530
15:21	420	426	622
15:22	421	425	739
15:23	420	425	607

APPENDIX 2

Results of measurements of carbon dioxide in three different locations during period of occupancy

Occupants	Time	Sensor 1	Sensor 2	System's sensor
17	10:02	461	447	473
	10:07	454	431	
	10:12	452	429	504
	10:17	474	478	
	10:22	511	526	565
	10:27	553	558	
	10:32	580	573	629
	10:37	599	598	
	10:42	611	620	629
	10:47	625	614	
	10:52	625	615	629
	10:57	626	609	
19	11:02	612	596	589
	11:07	580	578	
	11:12	551	560	567
	11:17	533	541	
	11:22	520	529	567
	11:27	512	521	
	11:32	503	521	567
7	11:37	524	547	
	11:42	582	611	662
	11:47	665	676	
	11:52	708	717	743
	11:57	733	728	
	12:02	729	735	732
	12:07	734	725	
	12:12	745	712	668

	12:17	731	667	
	12:22	706	644	638
	12:27	675	624	
	12:32	648	598	607
	12:37	613	569	
	12:42	585	544	576
8	12:47	575	524	
	12:52	549	515	545
	12:57	536	498	
	13:02	518	491	545
0	13:07	497	477	
	13:12	488	471	545
	13:17	477	463	
	13:22	468	453	545
	13:27	461	447	
16	13:32	454	439	515
	13:37	449	434	
	13:42	447	433	519
	13:47	496	493	
	13:52	551	547	620
	13:57	586	584	
	14:02	610	617	651
	14:07	617	631	
	14:12	628	639	651
	14:17	631	640	
	14:22	642	645	682
	14:27	644	656	
	14:32	648	652	682
	14:37	645	657	
	14:42	644	649	682
	14:47	659	651	
	14:52	654	651	682
	14:57	641	636	
	15:02	630	630	682

	15:07	624	629	
18	15:12	620	631	651
	15:17	617	620	
	15:22	628	619	620
	15:27	608	586	
	15:32	570	547	559
	15:37	542	519	
	15:42	540	512	625
	15:47	582	553	
	15:52	603	589	655
	15:57	620	608	
	16:02	621	628	655
	16:07	635	635	
	16:12	643	637	688
	16:17	641	639	
	16:22	638	642	688
	16:27	641	638	
	16:32	643	639	688
	16:37	646	636	
	16:42	643	634	688
	16:47	637	636	
	16:52	639	643	657
	16:57	625	613	
	17:02	602	585	622
	17:07	583	570	
	17:12	607	579	655
	17:17	635	606	
	17:22	641	622	686
	17:27	644	635	
	17:32	643	639	686
	17:37	643	639	
	17:42	656	647	686
	17:47	659	658	
	17:52	658	651	686

	17:57	652	646	
	18:02	655	647	686
	18:07	653	653	

APPENDIX 3

Results of measurements of temperature and humidity

time	Sensor 1		Sensor 2	
	Humidity, %	Temperature, °C	Humidity, %	Temperature, °C
10:00:00	27,4	22.1	27.1	22.0
10:15:00	28,5	22.1	28.5	22.0
10:30:00	29,1	22.3	28.8	22.2
10:45:00	29,1	22.3	28.5	22.3
11:00:00	28,3	22.3	27.9	22.3
11:15:00	27,8	22.3	27.5	22.3
11:30:00	28,0	22.3	27.7	22.3
11:45:00	29,3	22.4	28.3	22.5
12:00:00	29,0	22.6	28.1	22.7
12:15:00	28,3	22.6	27.1	22.6
12:30:00	27,3	22.6	26.6	22.6
12:45:00	26,8	22.5	26.1	22.6
13:00:00	26,3	22.5	25.8	22.5
13:15:00	25,8	22.3	25.5	22.3
13:30:00	25,5	22.2	25.4	22.1
13:45:00	26,6	22.3	26.5	22.2
14:00:00	26,4	22.5	26.5	22.5
14:15:00	26,3	22.6	26.1	22.6
14:30:00	25,9	22.7	25.8	22.7
14:45:00	25,7	22.7	25.4	22.8
15:00:00	25.3	22.6	25.3	22.7
15:15:00	25.4	22.6	25.0	22.6
15:30:00	24.8	22.5	24.6	22.4
15:45:00	25.7	22.5	25.6	22.4
16:00:00	26.0	22.7	25.7	22.6
16:15:00	25.9	22.8	25.8	22.7
16:30:00	26.2	22.8	25.8	22.8

16:45:00	26.3	22.8	25.9	23.0
17:00:00	26.3	22.8	25.8	22.8
17:15:00	26.9	22.8	26.6	22.8
17:30:00	27.1	23.0	26.7	22.8
17:45:00	27.2	23.0	26.8	22.9
18:00:00	27.6	23.0	26.8	23.0