TALLINNA TEHNIKAÜLIKOOL
INSENERITEADUSKOND
Ehituse ja arhitektuuri instituut

# MEASUREMENT AND SIMULATION BASED INDOOR AIR QUALITY ASSESSMENT OF TWO NATURALLY VENTILATED DETACHED HOUSES IN FINLAND

## MÕÕTMISANDMETEL JA SIMULATSIOONIL PÕHINEV SISEKLIIMA ÕHU KVALITEEDI ANALÜÜS KAHE LOOMULIKU VENTILATSIOONIGA SOOME ERAMU NÄITEL

MASTER THESIS

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Tallinn 2021

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# AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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# THESIS TASK

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**Thesis topic**:

(in English) *Measurement and simulation based indoor air quality assessment of two naturally ventilated detached houses in Finland*

(in Estonian) ……………….........................................................................................

**Thesis main objectives**:

1. To analyze the indoor air quality in two naturally ventilated detached houses in Finland based on measurements
2. To analyze the impact of wind on the air quality and airflow rates of the naturally ventilated detached houses based on dynamic simulations
3. To develop algorithms for a simple tool to evaluate the annual temporal need for boosting natural ventilation to reach good air quality in a detached house in typical Finnish climate

**Thesis tasks and time schedule:**

| No | Task description | Deadline |
|---|---|---|
| 1. | Literature review | 06.01.19 |
| 2. | Analysis of measured data from two naturally ventilated detached houses in Finland | 04.11.19 |
| 3. | Creating models in building performance simulation software IDA-ICE 5 of the detached houses | 06.01.20 |
| 4. | Modelling the airflow rates and indoor air quality with the simulation models with various duct sizes and ductwork element sizes | 13.01.20 |
| 5. | Development of analytical models for evaluation of hourly airflow rates | 03.03.20 |
| 6. | Finalizing the thesis | 18.05.20 |

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# FOREWORD

This thesis is initiated by the Finnish Cultural Foundation.

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For assisting and consulting the author would like to thank the supervisors Martin Thalfeldt (PhD) and Kimmo Lylykangas (PhD). Author would also like to thank Mika Vuolle and Federica Marongiu from Equa Simulation Finland OY for support and advise with IDA ICE simulations.

In this thesis stack ventilation with ground duct was assessed by two methods - measured data in test houses and computer simulations with IDA ICE software.

Keywords: Stack ventilation, $CO_2$ concentration, ground duct, solar chimney, IDA ICE, energy efficiency

# Abbreviations

ACH – air changes per hour
AHU – air handling unit
ETHE – earth tunnel heat exchanger
HVAC – heating, ventilation, air conditioning
PM – Particulate Matter
VOC – volatile organic compound

# 1. INTRODUCTION

Room ventilation is most common possibility for extracting contaminants and excess humidity from internal air and keep air quality above required minimum level. Insufficient ventilation is related to personal health issues and reduced satisfaction with room climate [1].

On the other hand – meeting the internal air quality level by efficient air exchange increases building energy consumption. In EU, buildings account for 40 % of total energy consumption. The sector is expanding, which is bound to increase its energy consumption. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union’s energy dependency and greenhouse gas emissions [2].

Based on EU Council Directive 2010/31/EU each member state establishes legal requirements for buildings in order to fulfill common climate- and energy reduction goals in EU.

Finding a balance between energy efficiency of buildings and good indoor climate is a challenge for HVAC engineers and officials who create regulations in this topic.

Due to energy efficiency requirements most common solution for building ventilation is mechanical ventilation with heat recovery, however in detached houses natural stack ventilation is sometimes preferred for its advantages, especially in rural areas – no noise of ventilators, no traffic noise from external environment, low cost and easy to build.

In this master thesis two detached houses with stack ventilation system are investigated – one in Närpiö, Finland and second in Fiskars, Finland. House in Närpiö uses mixed ventilation system where bedrooms are equipped with solar chimney exhaust system and living rooms and utility rooms are connected to mechanical air extract system. All the rooms get intake air by earth tunnel heat exchanger(ETHE) which is a circular duct placed into the soil under the building allowing intake air to warm or cool before being divided to rooms. Different zones are separated by internal doors which are equipped with sealing, while doors are closed both types of ventilation systems function independently.

House in Fiskars uses mixed ventilation system – stack ventilation with additional exhaust air fan in bathroom. This fan in controlled by controller which reacts to humidity level and $CO_2$ concentration in rooms.

Both houses have been built in recent years and internal climate parameters have been measured and logged after construction was finished – $CO_2$ level, air temperature and relative humidity. Collected logger data has been analyzed with Microsoft Excel.

Computer models were created in IDA ICE software for both of the buildings in order to compare theoretical result with measured data and to assess stack ventilation possibility for future buildings in design phase.

## 1.1. Indoor air quality and ventilation

European standard EN 12599 gives guidelines for designing indoor environmental quality and determines parameters for assessing indoor air quality of buildings.

By this standard indoor environmental classification is divided to 4 categories and described as in following table (Table 1).

Table 1. Categories of indoor environmental quality [3]

| Category | Level of expectation | Description |
|---|---|---|
| I | High | Should be selected for occupants with special needs (children, elderly, persons with disabilities). |
| II | Medium | The normal level used for design and operation. |
| III | Moderate | Will still provide an acceptable environment. Some risk of reduced performance of the occupants. |
| IV | Low | Should only be used for a short time of the year or in spaces with very short time of occupancy. |

Indoor environmental category for new normal residential buildings is II.

Air quality of building can be evaluated in the buildings, where people are the main pollution source, by measuring the average $CO_2$ concentration in the building, when building is fully occupied. This can be done either with representative samples of room air or by measuring the concentration at the exhaust air [4].

Standard gives different classification for bedrooms and occupied living rooms which can be used in design phase of the building. Outdoor $CO_2$ concentration is presumed 400 ppm (Table 2).

Table 2. Design values of $CO_2$ concentration and air flow rates

| **Category** | **Design $CO_2$ concentration for living rooms (ppm above outdoors)*** | **Design air flow rate for living rooms ($CO_2$ emission 20 l/h per person) l/s per person** | **Design $CO_2$ concentration for bedrooms (ppm above outdoors)*** | **Design air flow rate for bedrooms ($CO_2$ emission 13,6 l/h per person) l/s per person** |
|---|---|---|---|---|
| I | 950 (550)* | 10 | 780 (380)* | 10 |
| II | 1200 (800)* | 7 | 950 (550)* | 7 |
| III | 1750 (1350)* | 4 | 1350 (950)* | 4 |
| IV | 1750 (1350)* | 4 | 1350 (950)* | 4 |

***outdoor $CO_2$ concentration is presumed 400ppm**

Design operative temperature (C°) in residential building living spaces (bedrooms, living rooms, kitchens etc.) [3] is presented in Table 3.

Table 3. Design operative temperature in living spaces of residential buildings

| Category | Minimum operating temperature for winter season (approx. 1,0 clo) |
|---|---|
| I | 21 |
| II | 20 |
| III | 18 |
| IV | 16 |

Relative humidity in residential buildings is normally not controlled. Relative humidity should stay below 60% in order to prevent condensation risk, mold growth etc.

To require that the conditions are within a given category for 100 % of the time, will often result in over dimensioned technological systems of the building, which most of the year will operate at a low efficiency. Therefore, a certain deviation part of the year should be accepted [4]. Yearly allowed deviation is 3% during occupancy time, in addition weekly and monthly maximum allowed deviation values apply.

## 1.2. Overview of literature

Indoor climate impact to health and well-being of building habitants has been investigated in different studies. Also natural ventilation performance in residential and non-residential buildings.

Strøm-Tejsen et al. (2015) conducted an experiment in student dormitory where they investigated room air quality influence to sleep quality of students, their ability to concentrate on the next day, their mental state and physical complaints. Different groups experienced different ventilation solutions with different ACH rates. Groups who experienced high ACH gave better results in sleep quality scale, logical thinking tests in the following morning, higher subjective ratings in ability to concentrate, feeling better and healthier [5].

Study conducted by Tallinn University of Technology in 2015 shows that high $CO_2$ level in schools' decreases learning outcomes of pupils by up to 21% compared to schools where $CO_2$ concentration stays in very good or good level [6].

Earth tunnel heat exchanger (ETHE) in one possibility to use thermal properties of ground for heating or cooling ventilation intake air before entering to building ventilation system. Since ground temperature is more or less constant during whole year, this can be used to reduce building cooling energy, needed during the cooling period, or to reduce heating power during heating period. Bansan et al. (2013) conducted an experiment where air temperature change in underground air intake duct was measured. In the duct, with a length of 100m, air temperature drop can be up to 20 °C, however it depends of properties of soil and air velocity in the ETHE [7].

Solar chimney is a passive part in stack ventilation system which can provide additional ventilation boost by heating up extract air in exhaust air chimney.
Clito Afonso et al. (1999) investigated solar chimney as an opportunity to improve stack ventilation and found that it can increase ventilation rate up to 22% [8].

## 1.3. Technological solutions for ventilation systems

Modern HVAC systems in typical modern detached houses and in apartment buildings are still rather simple – most often these systems will work independently and can be adjusted separately. In public buildings HVAC systems are controlled by common automation system.

Until 10-20 years ago most common ventilation system for dwellings was natural stack ventilation system – air exchange was created due to air pressure difference caused by height gradient and temperature difference between outdoor and indoor (Figure 1.1)

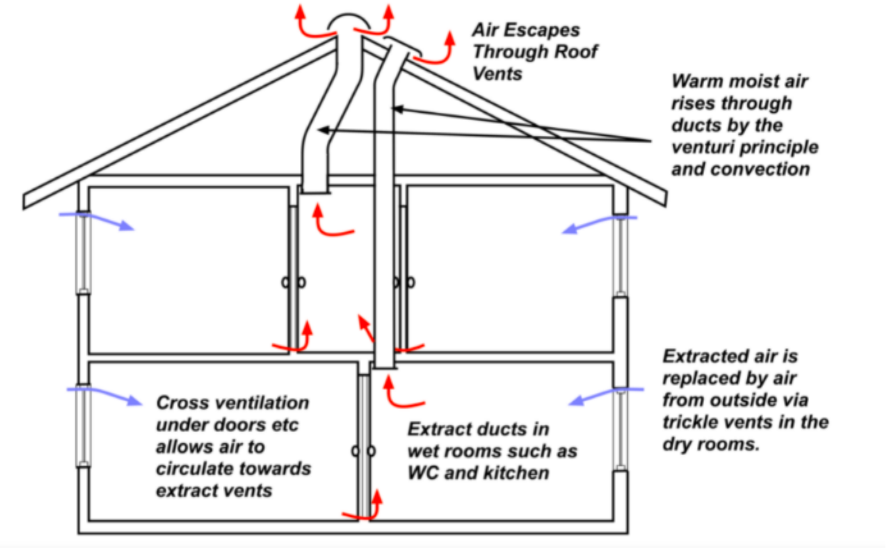


Figure 1.1. Stack ventilation. [9]

Advantages of stack ventilation:

1) No extra noise from ventilators
2) Low cost to build and maintain

Disadvantages of stack ventilation:

1) Air flows can't be controlled since air pressure gradient and temperature difference is constantly changing
2) Limited possibilities to clean supply air

Most common modern dwelling ventilation system consist of ventilation unit and ductworks. Ventilation unit has integrated supply air and extract air ventilators, heat recovery system, heating coil, filters, valves and automation with user interface (Figure 1.2).

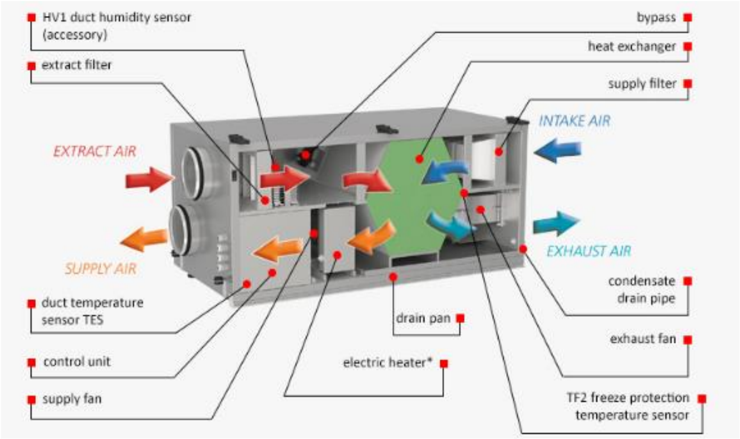


Figure 1.2. Ventilation unit with heat recovery [10]

Advantages of ventilation systems with heat recovery:

1) Controlled air flow rates
2) Energy efficiency – up to 95% of thermal energy is transferred from exhaust air to supply air by heat exchanger
3) Controlled supply air temperature
4) Supply air can be filtered in unit

Disadvantages of ventilation systems with heat recovery:

1) Noise generated by ventilators
2) Energy consumption of ventilators
3) Cost to build and maintain the system

In cold climates supply air needs often extra heating after heat exchanger and during summer period intake air needs cooling to prevent overheating inside the building. Since temperature in ground is more constant through the year this can be used to pre-heat or pre-cool incoming air in building ventilation systems. Ground duct heat exchanger for intake air can be used in stack ventilation system or in combination with ventilation units. In order to get good effect from earth heat exchanger, high thermal conductivity of duct material and soil is essential.

## 1.4. Definition and calculation of indoor air quality parameters

Indoor air quality can be characterized by different parameters:

1) Temperature (t), °C – air temperature. Suitable temperature range is correlated with metabolism level. Suitable air temperature for dwelling is commonly 20-23 °C.

2) Relative humidity (RH), %. Describes the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature. Suitable RH range for dwelling is 40-60%. Higher RH level may cause mold in buildings, low RH level for longer period may cause different health issues – dry skin, allergies, nose bleeding etc.

3) $CO_2$ concentration, ppm –parts per million. Describes the ratio of one gas to another, in this case $CO_2$ molecule particle ratio to air molecule particle ratio. $CO_2$ concentration in external clean air is approximately 400 ppm. Commonly up to 1000 ppm in residential buildings is considered very good. $CO_2$ concentration between 2000-5000 ppm concentrations may cause reduced cognitive performance, dizziness, headache, sleepiness etc. $CO_2$ concentration from 5000 ppm, when exposure for longer period may cause serious health problems and even death for humans [5].

4) Volatile organic compounds (VOCs), ppm. VOCs are compounds that have a high vapor pressure and low water solubility. Many VOCs are human-made chemicals that are used and produced in the manufacture of paints, pharmaceuticals, and refrigerants. Construction materials can be often a source for different VOCs in dwellings [12]

5) Particulate Matter (PM), micrograms per cubic meter - solid particles and liquid droplets found in the air e.g. dust, dirt, smoke.

6) Carbon monoxide and other gases (PPM)

7) Radon – gaseous radioactive compound forms as the result of uranium in soil or rock breaking down; it can also be released from building materials, such as granite. Radon level is measured in units picocuries per litre (pCi/L) or becquerels per cubic meter (Bq/m3)

Some of listed parameters are easy to be measured and monitored – temperature, relative humidity, $CO_2$ level. Some of the parameters – VOCs, radon level, PM are more difficult to be measured and unhealthy concentration can be avoided in dwellings by not using incorrect materials (VOCs emissive), by using proper constructive preventive solution (radon blocking films etc.) and by ensuring sufficient air exchange rate. To assess air exchange rate, best indicator is $CO_2$ level.

# 2. METHODOLOGY

## 2.1. Measurement methodology and tools

To measure and record air quality parameters sensors Produal HDH-M-RH were used. Specifications of room sensors is presented in Table 4 and in Appendix 1. Time interval between recordings was 60 minutes.

HDH-M transmitters are designed for detecting and controlling carbon dioxide concentration, temperature, and humidity in room spaces. The transmitter information can be used for demand-based ventilation control, for example.

Table 4. Produal HDH-M-RH transmitter with sensors

| **Parameter** | **Value** |
|---|---|
| Dimensions (W x H x D) | 87 x 86 x 30 |
| Connection | can be connected to any system that supports Modbus RTU protocol by using the RS-485 connection. ML-SER tool is needed in commissioning for making the Modbus settings. |
| Mounting | on the wall surface or on the standard flush mounting box (60 mm hole distance) |
| Range, $CO_2$ (ppm) | 0…2000 |
| Accuracy, $CO_2$ (ppm) | ±40 |
| Range, temperature (C°) | 0…50 |
| Accuracy, temperature (C°) | ±0.5 |
| Range, relative humidity (%) | 0…100 |
| Accuracy, relative humidity (%) | ±2 |

## 2.2. Case study 1: Närpiö

Närpiö house is 2-floor wooden-frame single family house in traditional Finnish architecture, non-heated attic and gable roof.

On the first floor there are living room, kitchen, sauna with shower room, technical room and guest room. On the second floor there are bathroom, 3 bedrooms and open hall with home-office area (Figure 2.1 and Figure 2.2).

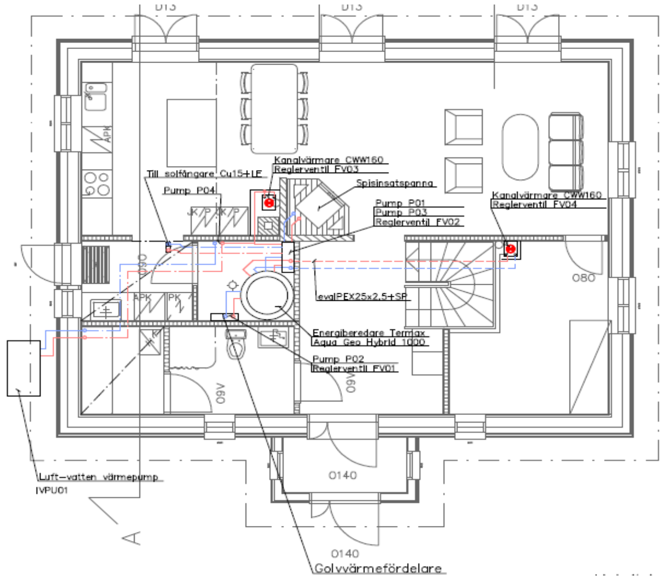


Figure 2.1 1st floor plan of Närpiö house

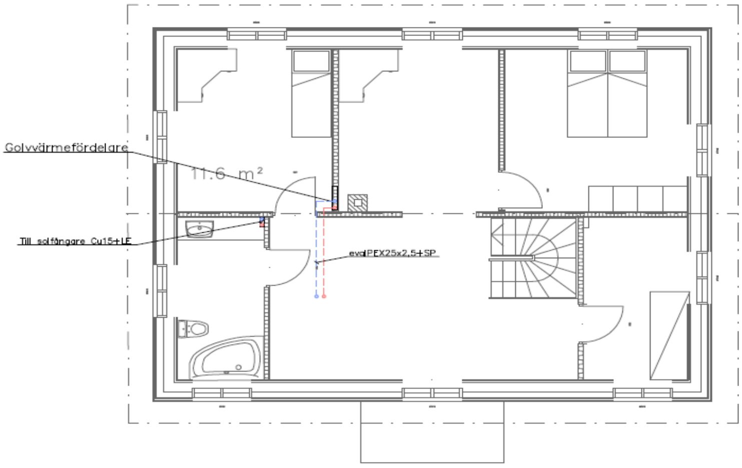


Figure 2.2. 2nd floor plan of Närpiö house

Ventilation system of the building is hybrid – part of the building is equipped with natural stack ventilation system; part of the building is mechanically ventilated. Supply air is transferred to building via ground installed ventilation duct where air is either heated or cooled before entering to the building by ground. Filter and water-coil is installed into the duct. Supply air is distributed to rooms by internal ductwork. Sound attenuators are used to prevent noise transfer from one room to another (Figure 2.3). House in inhabited with married couple without children, only master bedroom and living room are occupied in the building.

Both supply air and extract air connections are located in bedrooms – supply air ducts are connected to ground duct, extract air ducts are connected to solar chimney on the roof (Figure 2.3, Figure 2.4).

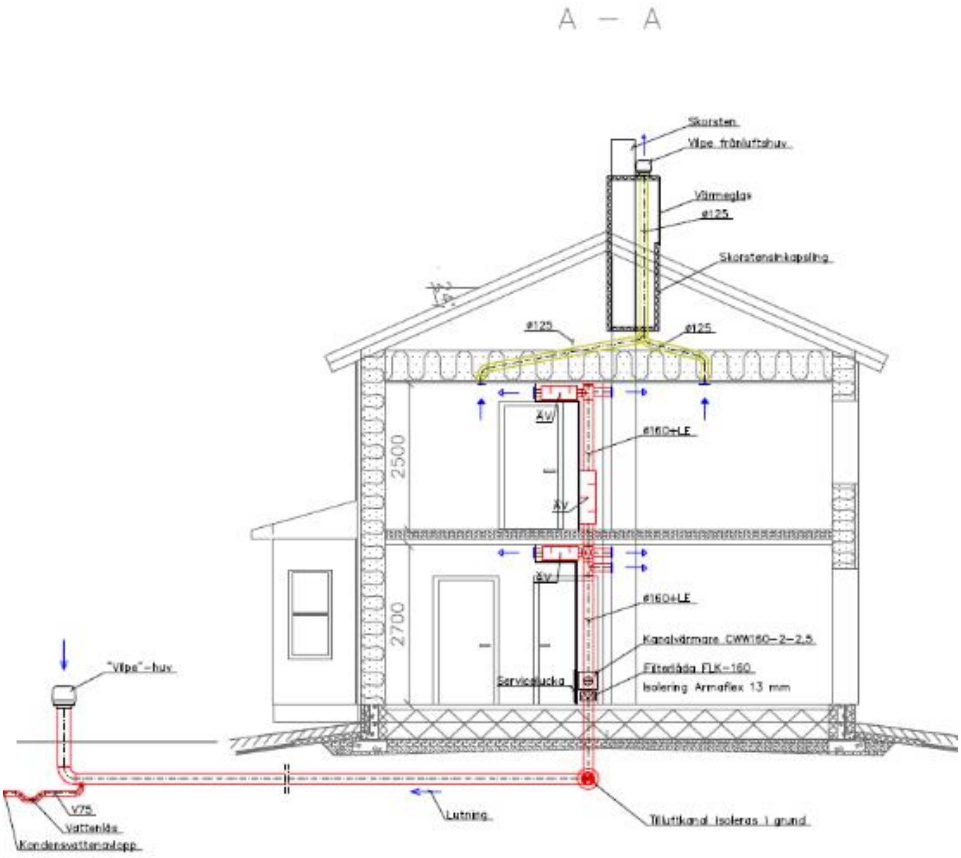


Figure 2.3 Section cut of Närpiö house

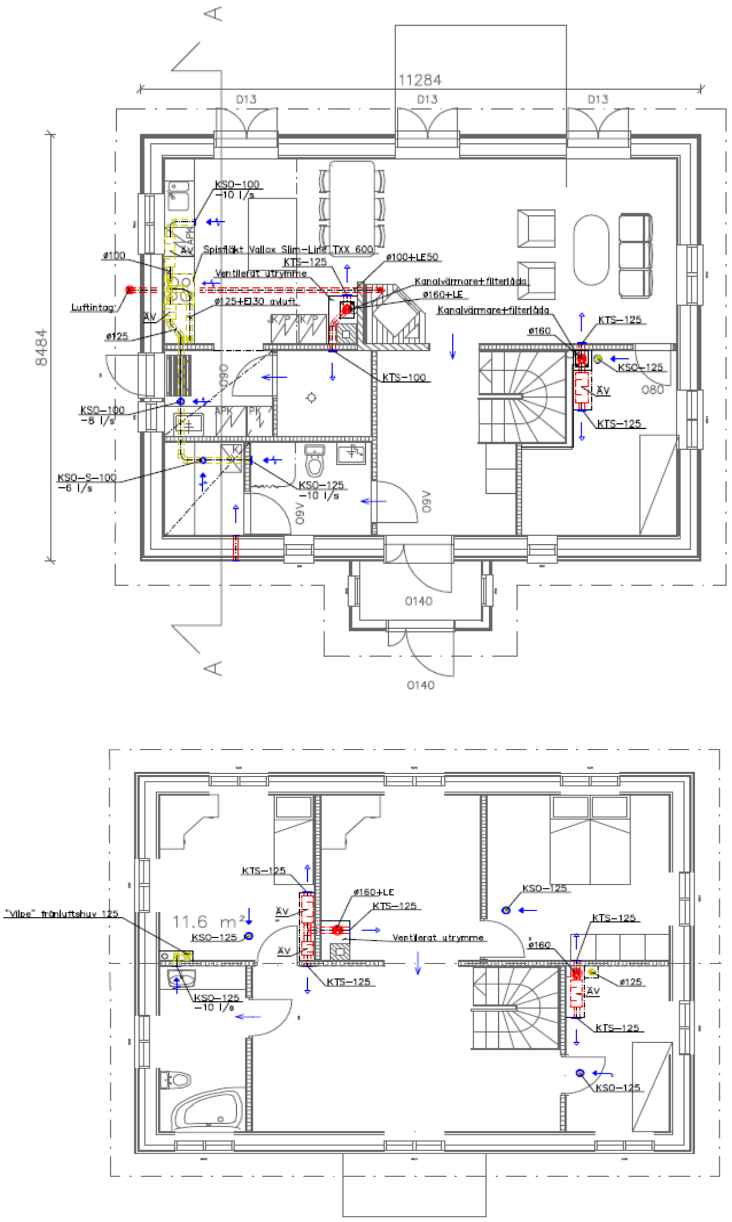


Figure 2.4. Ventilation plan of 1st and 2nd floor of Närpiö house

First floor ventilation (except bedroom) is solved by using extraction ventilator which is integrated to kitchen hood, exhaust air is directed to the roof. Air is supplied by previously described supply system to living room and to technical room and extracted from kitchen and sauna. Additional duct for supplying fresh air directly from outdoors has been installed to sauna.

Supply air for the office and hall on the second floor, is supplied by supply air valve in the office area. Transferred air is sucked from the bathroom on the second floor to extract ventilator in kitchen hood and jointed with rest of the exhaust air before exhausted in roof duct (Figure 2.5).

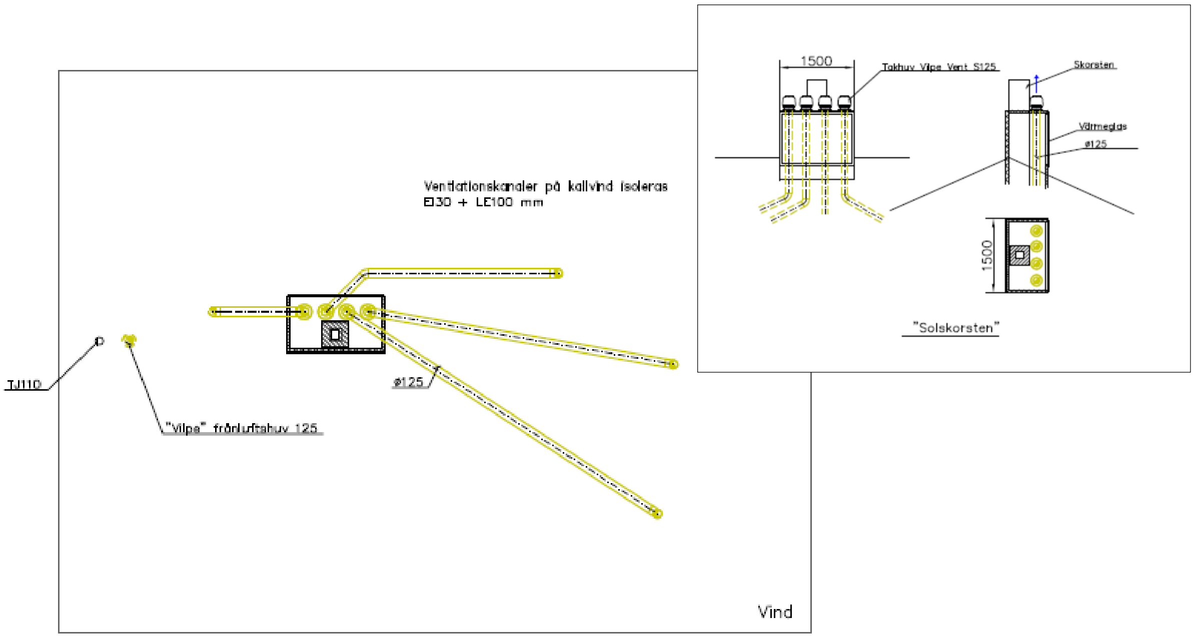


Figure 2.5. Extract air ducts in attic and solar chimney

House is heated by water-underfloor heating. Heating energy is produced by combined air-to-water heat pump, boiler-stove, solar collectors and back-upped with electric heaters in accumulator tank (Figure 2.6).

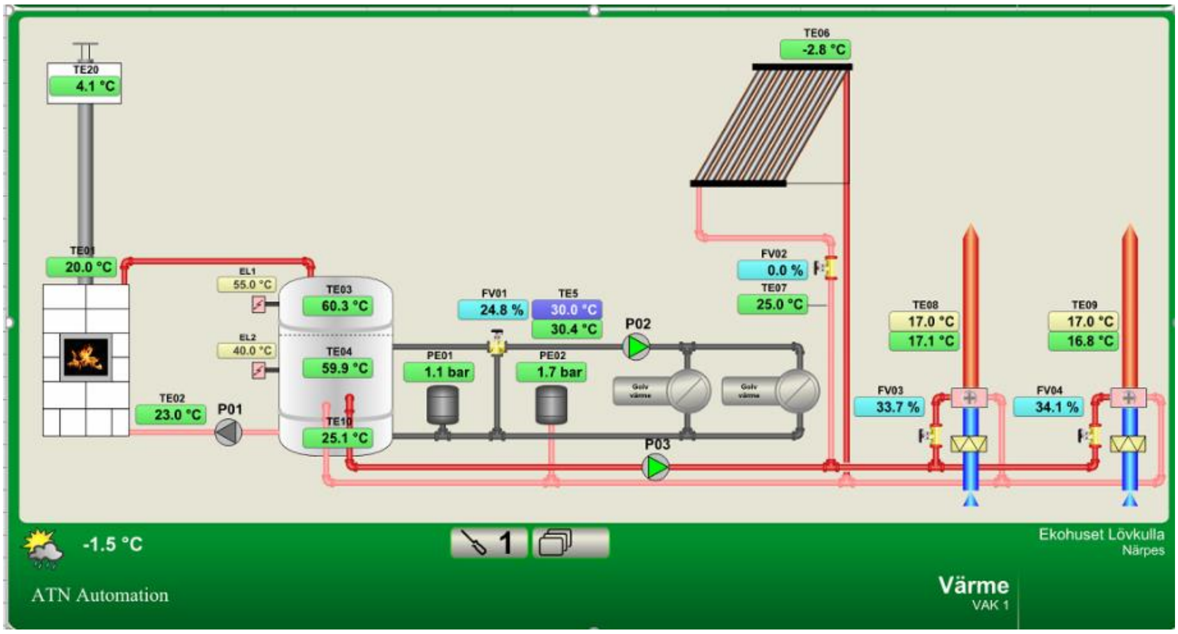


Figure 2.6 Functional principle of the heating system of Närpiö house [13]

Sensors for measuring indoor climate in the house, have been placed to the living room, to the shower room, to the kitchen, to the guest bedroom, to the bedrooms on the second floor, to the bathroom on the second floor. All the sensors record hourly parameters – temperature, relative humidity, $CO_2$ concentration (Figure 2.7).

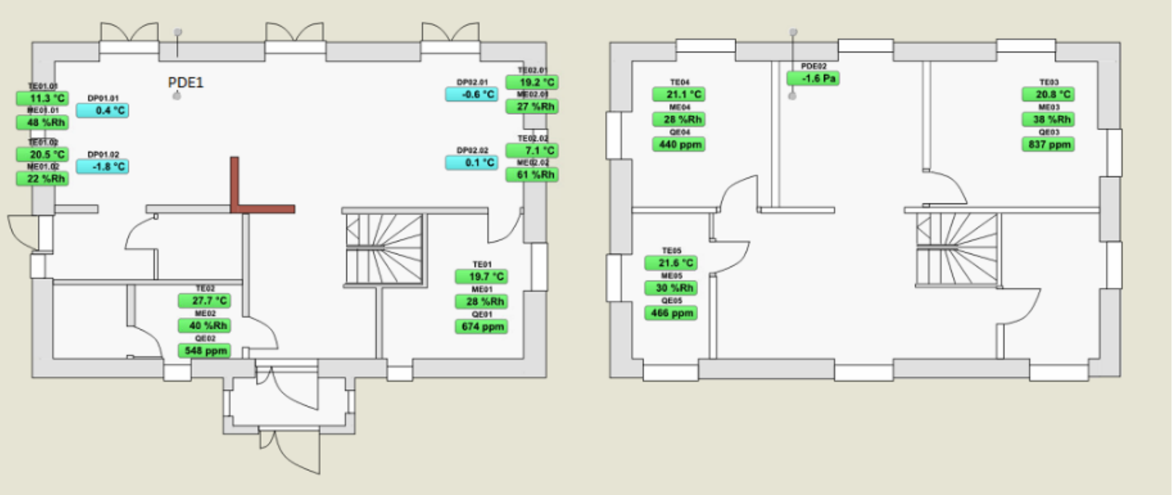


Figure 2.7. Locations of sensors

## 2.3. Case study 2: Fiskars

House in Fiskars is a 2-floor wooden-frame single family house in traditional Finnish architecture, no attic, gable roof. On the first floor there are living room with open kitchen, bathroom, technical room and one bedroom. On the second floor there are bathroom, 2 bedrooms, storage and open hall (Figure 2.8).

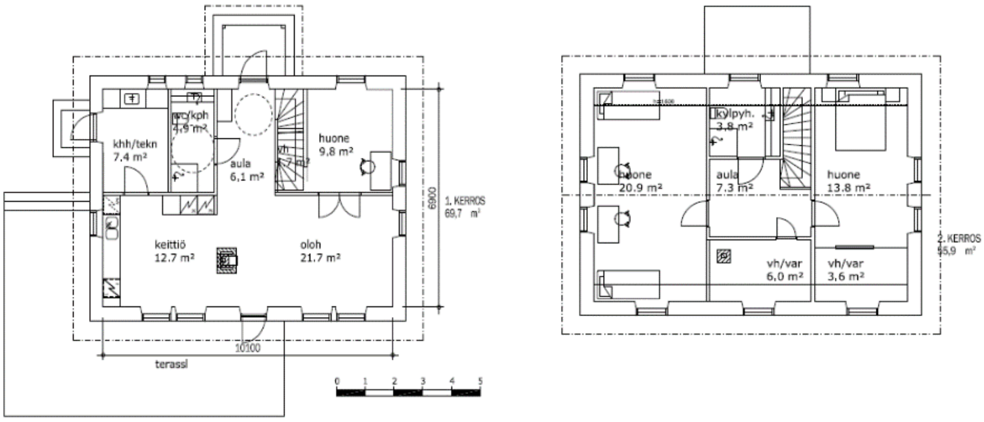


Figure 2.8. 1st and 2nd floor of Fiskars house

House is equipped with stack ventilation system with additional duct fan. External air is transferred to building via ground installed ventilation duct where air is either heated or cooled before entering to the building by ground. $CO_2$ level, RH is monitored and duct fan is used to boost the stack ventilation if $CO_2$ level of RH level requires it. Setpoints for ventilator schedule are unknown.

House is inhabited by a family with children. Bedroom where logger data is collected is inhabited by teenager child. Since family needed more bedrooms than it was initially planned in the building, one larger bedroom was divided to two. Unfortunately, one of the new bedrooms doesn't have any air supply duct for fresh air after the partition was built.

## 2.4. IDA-ICE simulation layout and setup

Dynamic simulation model was created by using IDA Indoor Climate and Energy (IDA ICE) software, version 5.0 BETA, which has, compared to previous versions, improved functionality for simulating ventilation system with ground duct. Functionality for modelling solar chimney was not available at the moment when simulations were performed. Normal ventilation duct chimney was used in simulation model.

### 2.4.1. Envelope of the building

Both of the houses are built with wood-frame insulated construction, 2 floors, gable roof. Thermal transmittance values, used in simulation model, are presented in Table 5. Infiltration value was set to 0, since infiltration can't be considered as a part of ventilation system.

Table 5. Thermal transmittance values

| **Element of construction** | **Thermal transmittance ($W/m^2 \cdot K$)** | **Description** |
|---|---|---|
| Wall | 0,19 | Wood frame wall with 250mm insulation |
| Slab on the ground | 0,18 | Concrete slab on ground, 200mm insulation |
| Ceiling of 2nd floor | 0,1 | 450mm insulation |
| Windows | 0,9 | g=0,59 |
| Doors | 1,1 | |
| Internal walls | - | Insulated wooden frame walls, covered with gypsum boards |
| Internal floors | - | 250mm wood joist internal floor with insulation |

Values of the thermal bridges are presented in Table 6.

Table 6. Thermal bridges

| **Thermal bridge** | **Value (W/m·K)** |
|---|---|
| External wall / external wall | 0,05 |
| Roof / external wall | 0,2 |
| External window perimeter | 0,05 |
| External door perimeter | 0,1 |
| Slab on the ground / external wall | 0,1 |

### 2.4.2. Climate file

Helsinki Vantaa reference climate file was used for simulations.

### 2.4.3. Internal gains

Internal heat gains of lightning and equipment was set up according to Finnish building code. Occupant metabolism rate and occupant presence schedule was respectively set up according to room usage and findings made by analyzing logged data.

Table 7. Internal gains in simulation model

| **Internal gain** | **Value (W/m$^2$)** | **Usage rate (%)** |
|---|---|---|
| Lights (W/m$^2$) | 6 | 60 |
| Equipment (W/m$^2$) | 3 | 60 |
| Occupation* | - | - |

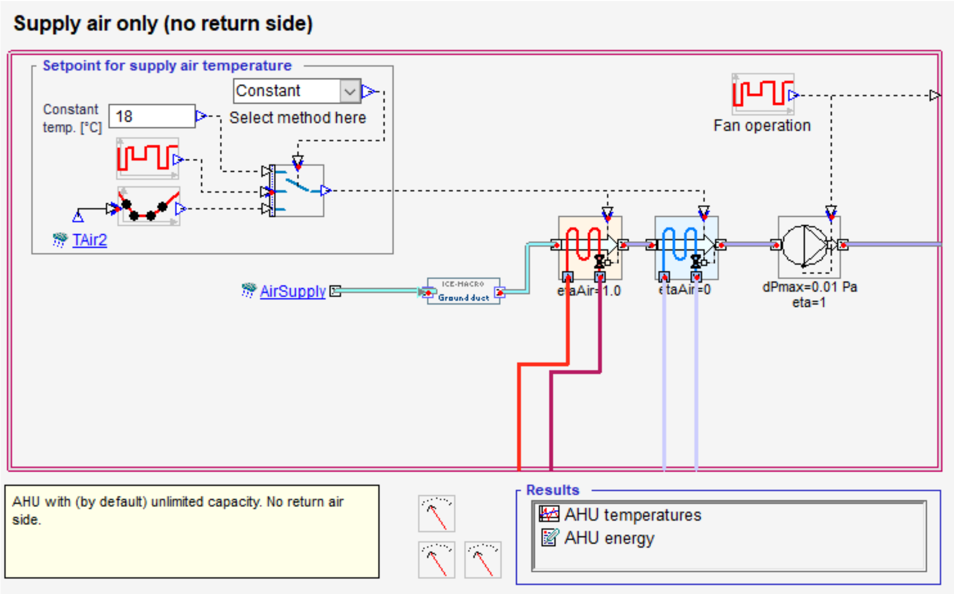
*according to analyzed data in case studies

### 2.4.4. Heating and cooling systems

Ideal heaters were used for zone heating and for ventilation air heating. No cooling system was used.

### 2.4.5. Ventilation system with ground duct

Ventilation system with supply side only was used. Ground duct for air intake was added. Supply air temperature was set to 18 °C. Ventilator was turned off so that only stack effect and wind effect were affecting ventilation airflow.



Supply air only (no return side)

Setpoint for supply air temperature

Constant temp. [°C] 18

Select method here: Constant

AHU with (by default) unlimited capacity. No return air side.

Figure 2.9. Ventilation system in IDA ICE

Parameters of the ground duct are presented in Table 8.

Table 8. Parameters of the ground duct

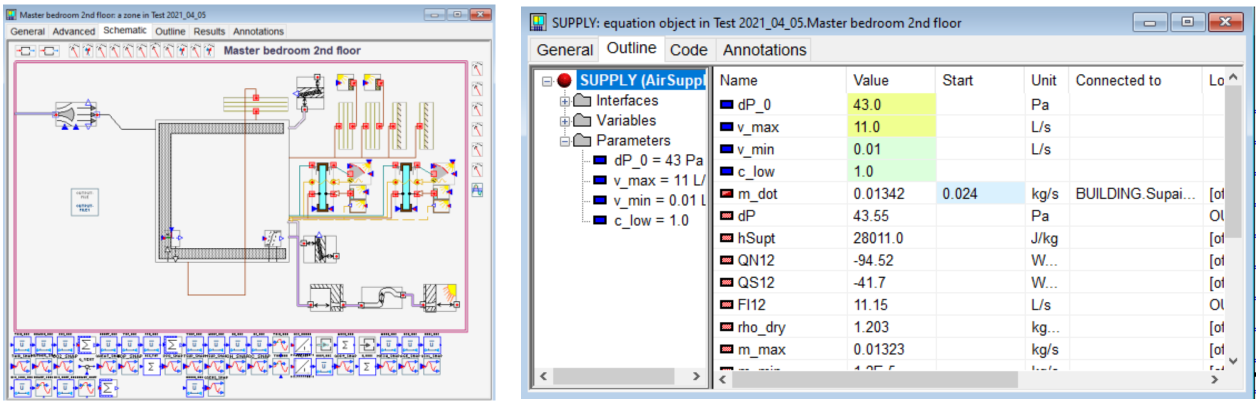
| **Parameter** | **Value** |
|---|---|
| Length (m) | 10 |
| Diameter (mm) | 160 |
| Depth in the ground (m) | 1,5 |
| Thickness of duct wall (mm) | 5 |
| Thermal transmittance of duct wall ($W/m^2 \cdot K$) | 1,4 |

Aerodynamic calculations were made to find estimated pressure losses in ductwork of the building. Results of these calculations are presented in Table 9. Airflow for bedroom was estimated 10 l/s and total airflow of the intake air in ground duct was estimated 30 l/s.

Table 9. Pressure losses in ducts

| **Pressure losses in ducts** | **Pressure loss (Pa)** | **Air flow (l/s)** |
|---|---|---|
| Friction losses | 5 | 30/10 |
| Dynamic losses | 3 | 30/10 |
| Losses in air intake grill | 5 | 30 |
| Losses in filter | 15 | 30 |
| Losses in air heater | 7 | 30 |
| Losses in room supply air terminal | 10 | 10 |
| $\Sigma$ | **45 Pa** | |

Due to the nature of stack ventilation, airflows are not constant and pressure loss values are dependent of the airflow speed. I model calibration phase this value was changed to get the best possible correlation between measured data and modelled data.
Model parameters were set up in zone level and in Schematic level (Figure 2.10, Figure 2.11).



SUPPLY: equation object in Test 2021_04_05.Master bedroom 2nd floor

SUPPLY (AirSuppl
Interfaces
Variables
Parameters
dP_0 = 43 Pa
v_max = 11 L/
v_min = 0.01 L
c_low = 1.0

| Name | Value | Start | Unit | Connected to | Lo |
|---|---|---|---|---|---|
| dP_0 | 43.0 | | Pa | | |
| v_max | 11.0 | | L/s | | |
| v_min | 0.01 | | L/s | | |
| c_low | 1.0 | | | | |
| m_dot | 0.01342 | 0.024 | kg/s | BUILDING.Supai... | [o |
| dP | 43.55 | | Pa | | O |
| hSupt | 28011.0 | | J/kg | | [o |
| QN12 | -94.52 | | W... | | [o |
| QS12 | -41.7 | | W... | | [o |
| FI12 | 11.15 | | L/s | | O |
| rho_dry | 1.203 | | kg... | | [o |
| m_max | 0.01323 | | kg/s | | [o |

Figure 2.10. Setup of simulation model

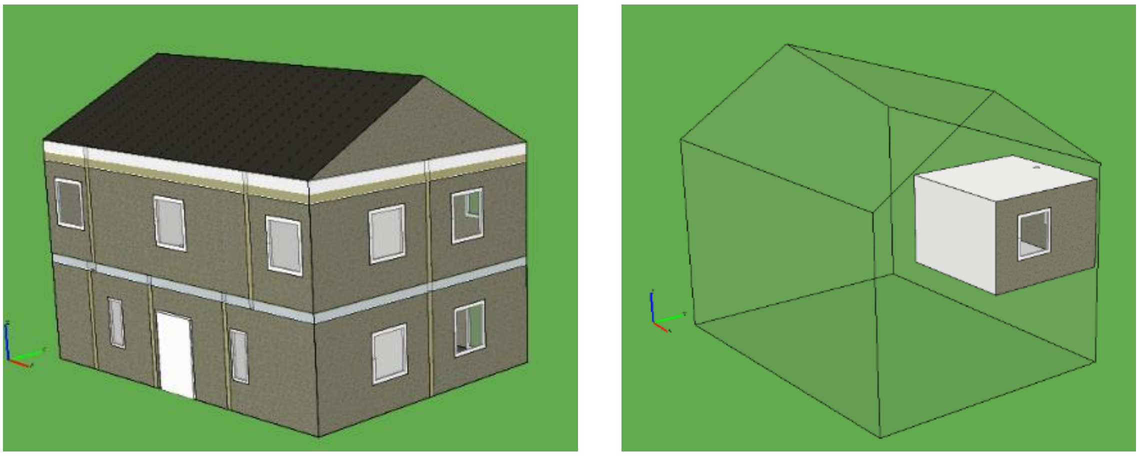


Figure 2.11. Simulation model and bedroom zone model of Närpiö house

# 3. RESULTS

## 3.1. Analysis of measured data of a naturally ventilated detached house in Närpiö

### 3.1.1. Occupation schedule in Närpiö house

Logged data is available from March 2017 until December 2018. Logger data shows that people moved permanently into the house in the last days of 2017, therefore data only from 2018 January until 2018 December has been analyzed in detail (Figure 3.1).

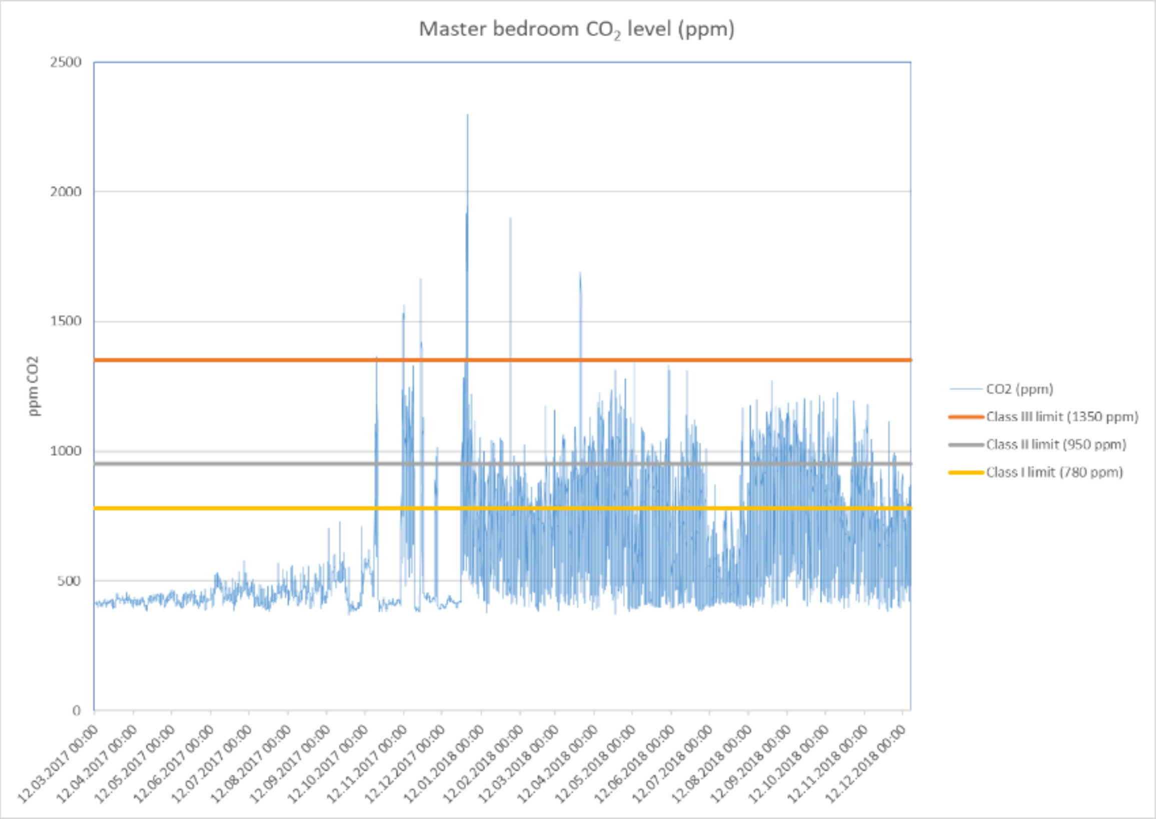


Figure 3.1 $CO_2$ level in master bedroom of Närpiö house

Data analyze, based on year 2018, shows that master bedroom daily occupation period is between 9 PM and 9 AM (Figure 3.2)

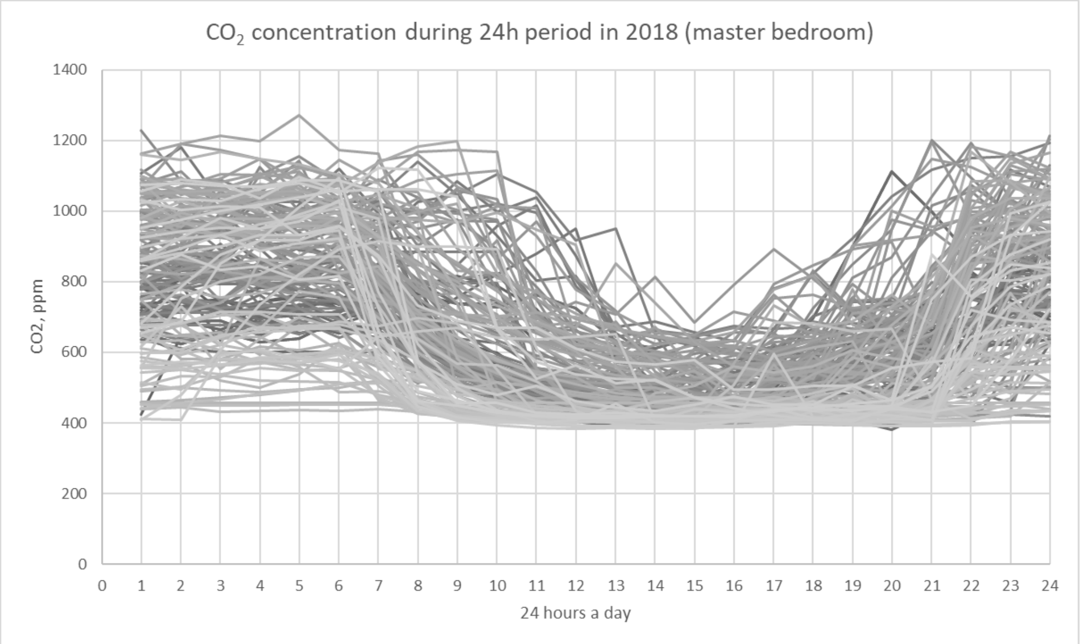


Figure 3.2 Närpiö house master bedroom daily inhabitants occupation period

Living room occupation period is between 4PM and 8AM (Figure 3.4).

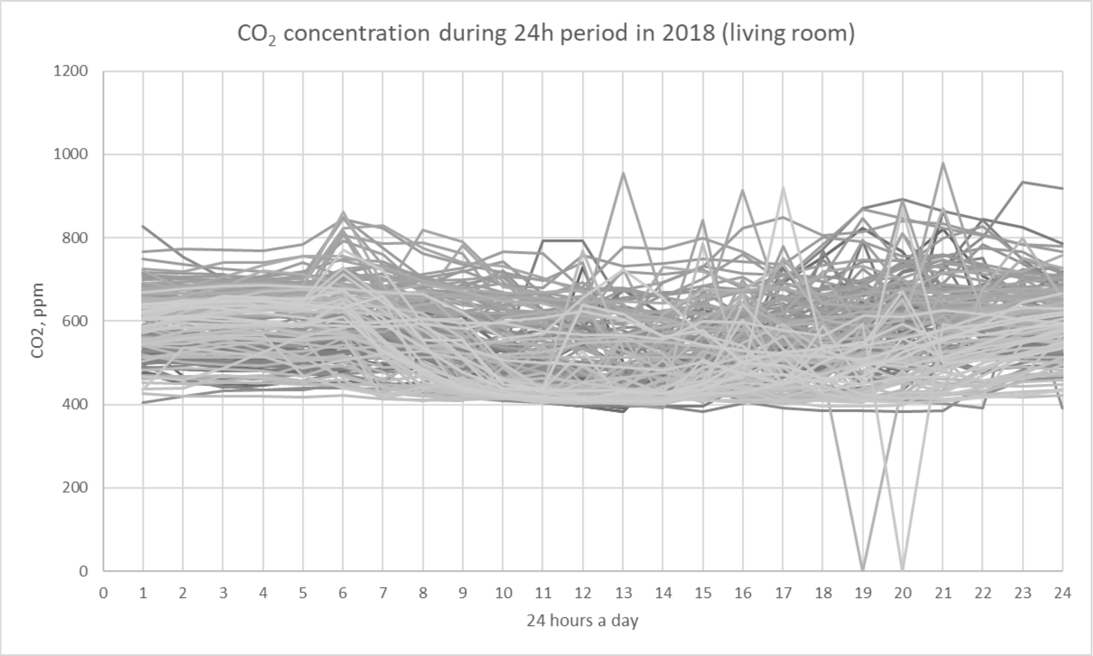


Figure 3.4 Närpiö house living room daily inhabitants occupation period

### 3.1.2. Internal climate in master bedroom of Närpiö house

Internal climate in the master bedroom by $CO_2$ concentration can be considered sufficient but not good – $CO_2$ level meets requirements of I category of internal climate for 46,4 % of the time, requirements of II category of internal climate for 33,3% of the time, requirements of III category for 20 % of the time. Category III limit is exceeded during 0,33 % of the inhabitants' occupation time in 2018 (Figure 3.5).

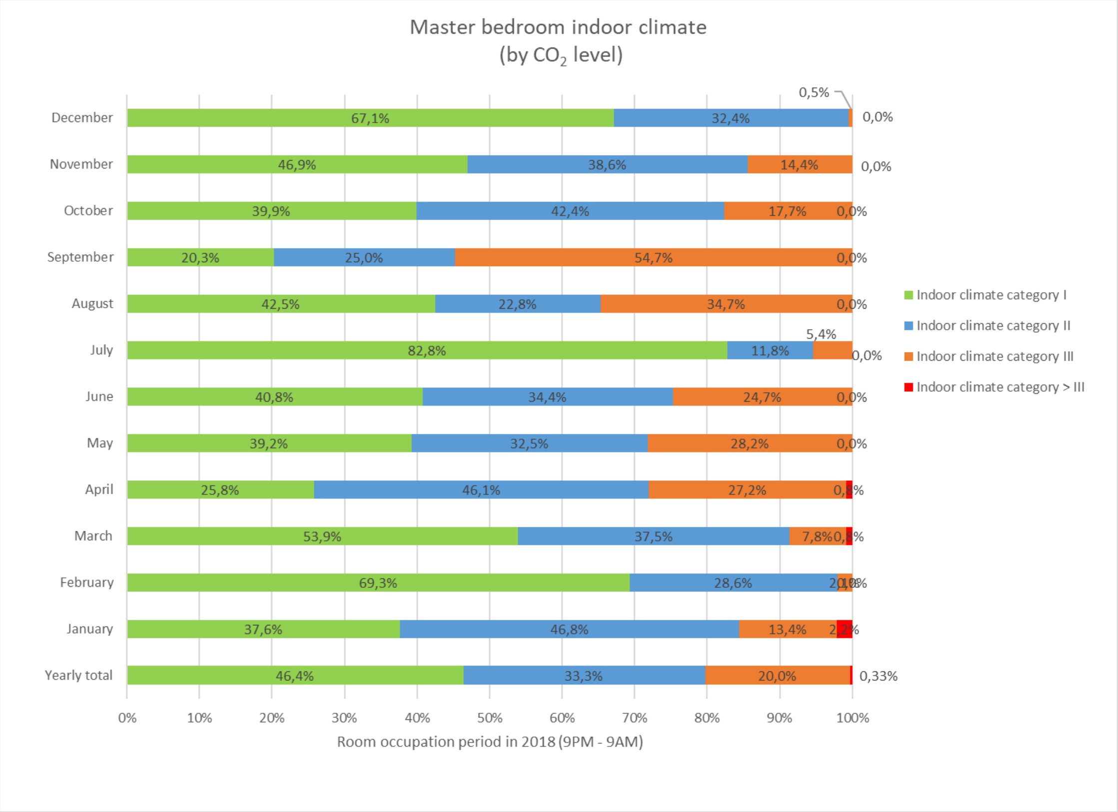


Figure 3.5. Master bedroom indoor climate classification in 2018 by $CO_2$ concentration

Analyzed data shows that, during the year 2018, $CO_2$ level is lower while external temperature is lower (December-March) (Figure 3.6). Low $CO_2$ level in July and August correlates with vacation period. On a yearly basis this room can be considered as an internal climate class III by $CO_2$ concentration value since deviation over class III is less than 3%.

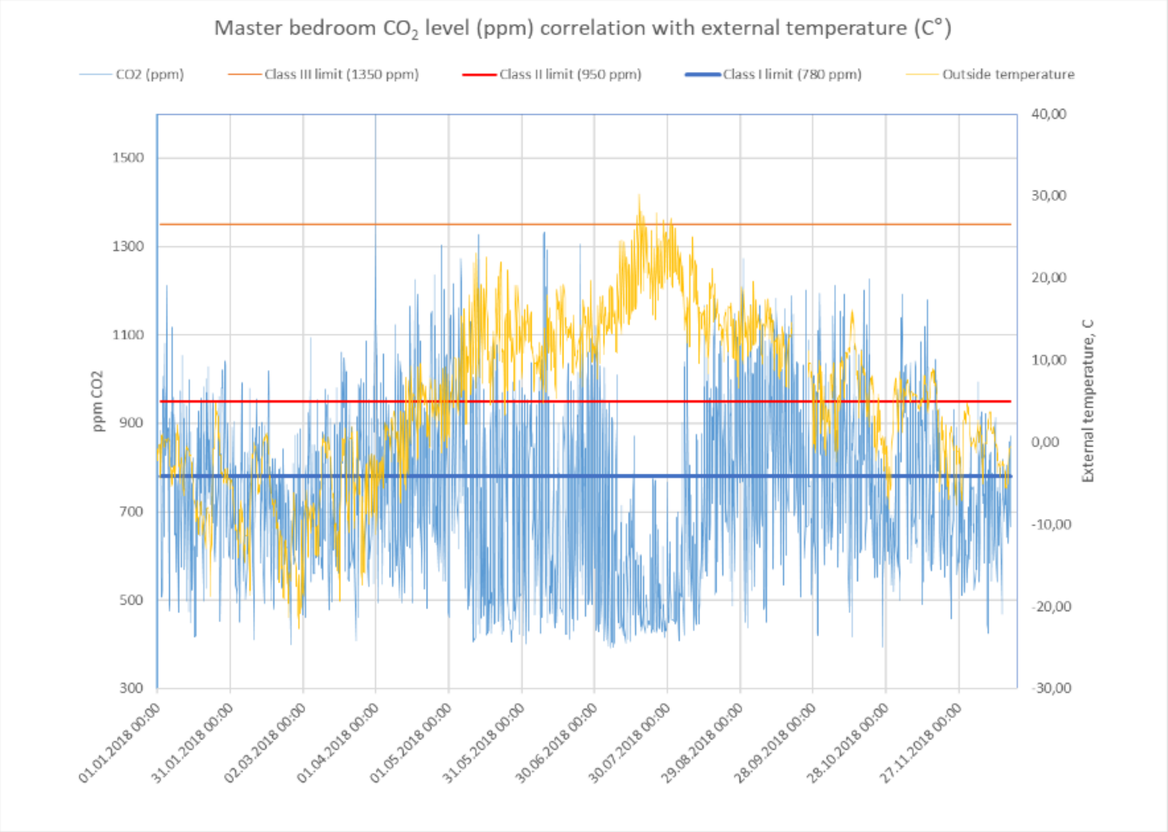


Figure 3.6 Närpiö house master bedroom $CO_2$ level correlation with external temperature

Relatively high $CO_2$ levels are common during the spring and the autumn while external temperature exceeds 0 degrees °C but stays below 10 °C (Figure 3.7). Average internal $CO_2$ level decreases while external temperature rises above 10 degrees. Reason for this might be extra ventilation by opened windows.

A strong correlation between average external temperature and $CO_2$ concentration in April and May (Figure 3.8) becomes visible in detailed view.

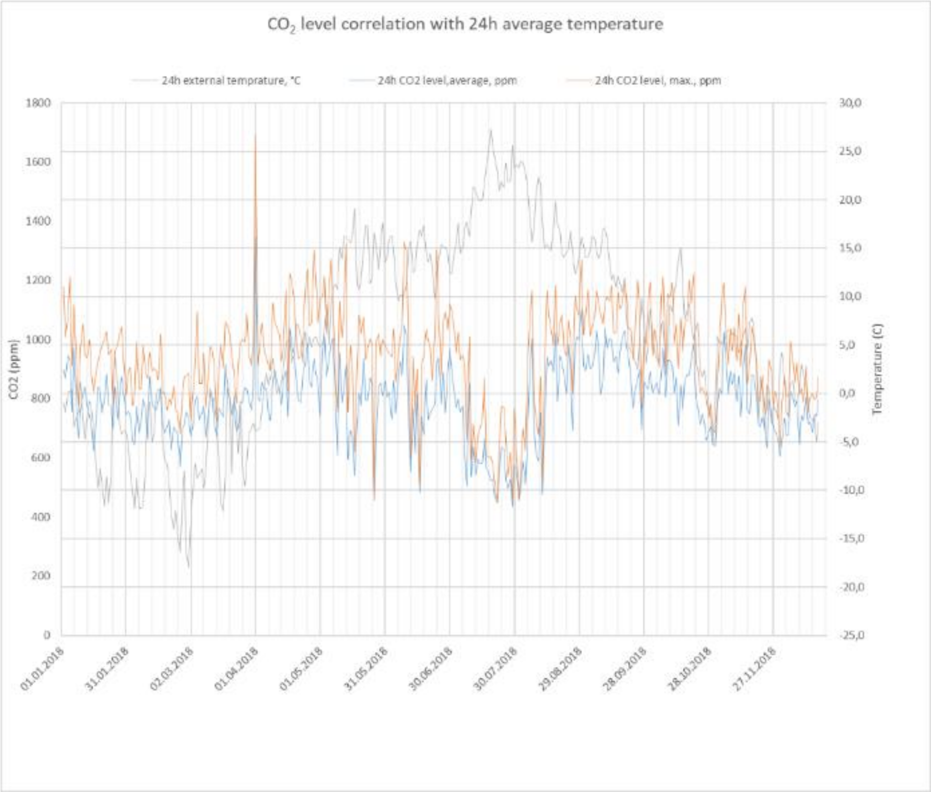


Figure 3.7. $CO_2$ level correlation with external 24h average temperature in Närpiö master bedroom

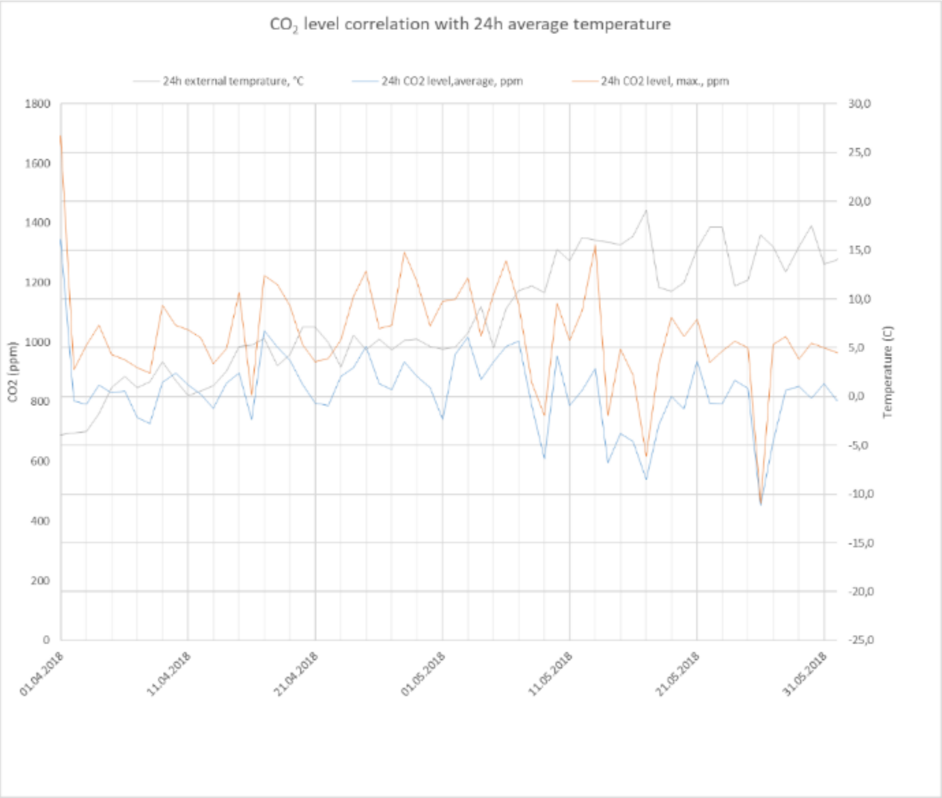


Figure 3.8 Internal $CO_2$ level correlation with external 24h average temperature April-May 2018

Relative humidity varies from 25% in winter to 75% in summer. Room thermostat setpoint is between 18-20 C° (Figure 3.9).

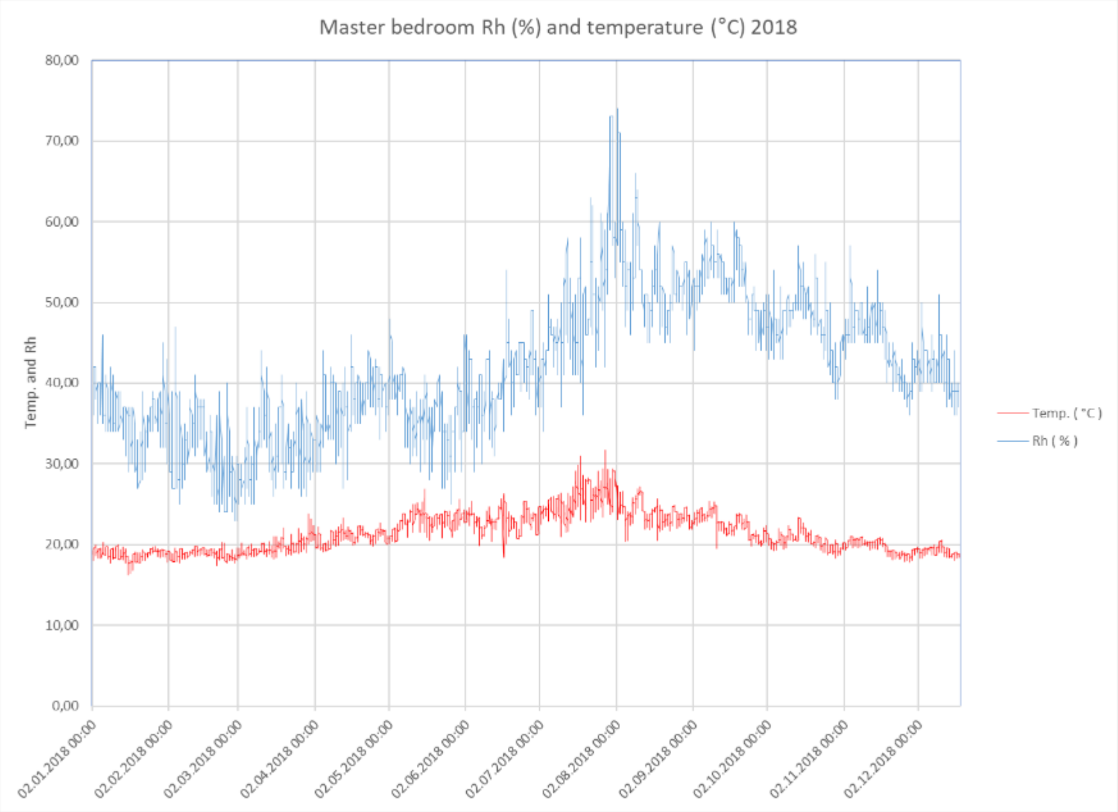


Figure 3.9 Relative humidity and room temperature in master bedroom of Närpiö house

### 3.1.3. Internal climate in living room of Närpiö house

Internal climate in living room by $CO_2$ concentration can be considered very good – $CO_2$ level stays below category I upper limit 98 % of the time, 1,6% of the time in category II, 0,3% of the time in category III. Category III limit is exceeded during 0,04% of the inhabitants' occupation time in 2018 (Figure 3.10). On a yearly basis this room can be considered as an internal climate class I by $CO_2$ concentration value since deviation over class I is less than 3%.

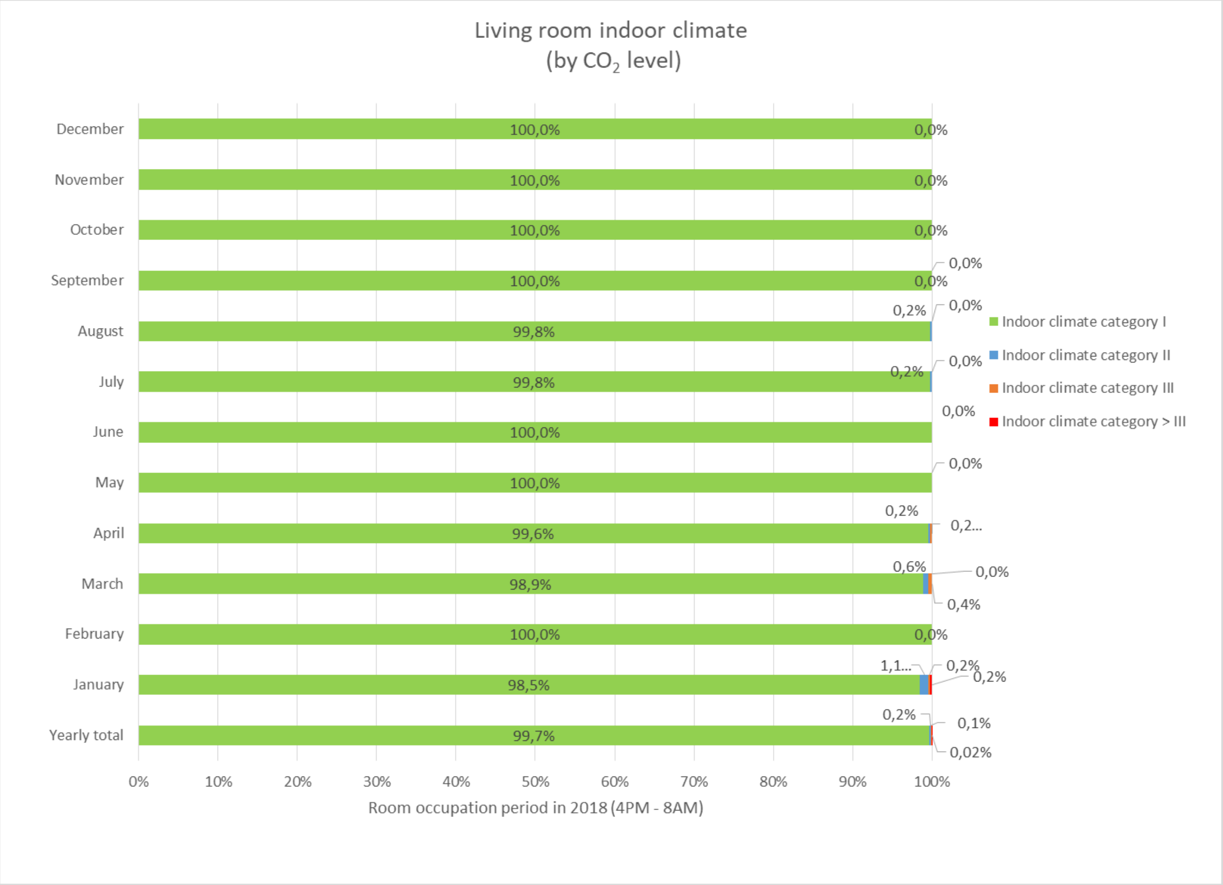


Figure 3.10. Living room indoor climate classification in 2018 by $CO_2$ concentration

Analyzed data shows that during the year 2018 $CO_2$ concentration is rather stable during the whole year. Small raise in $CO_2$ concentration raise is visible in August and in September (Figure 3.11).

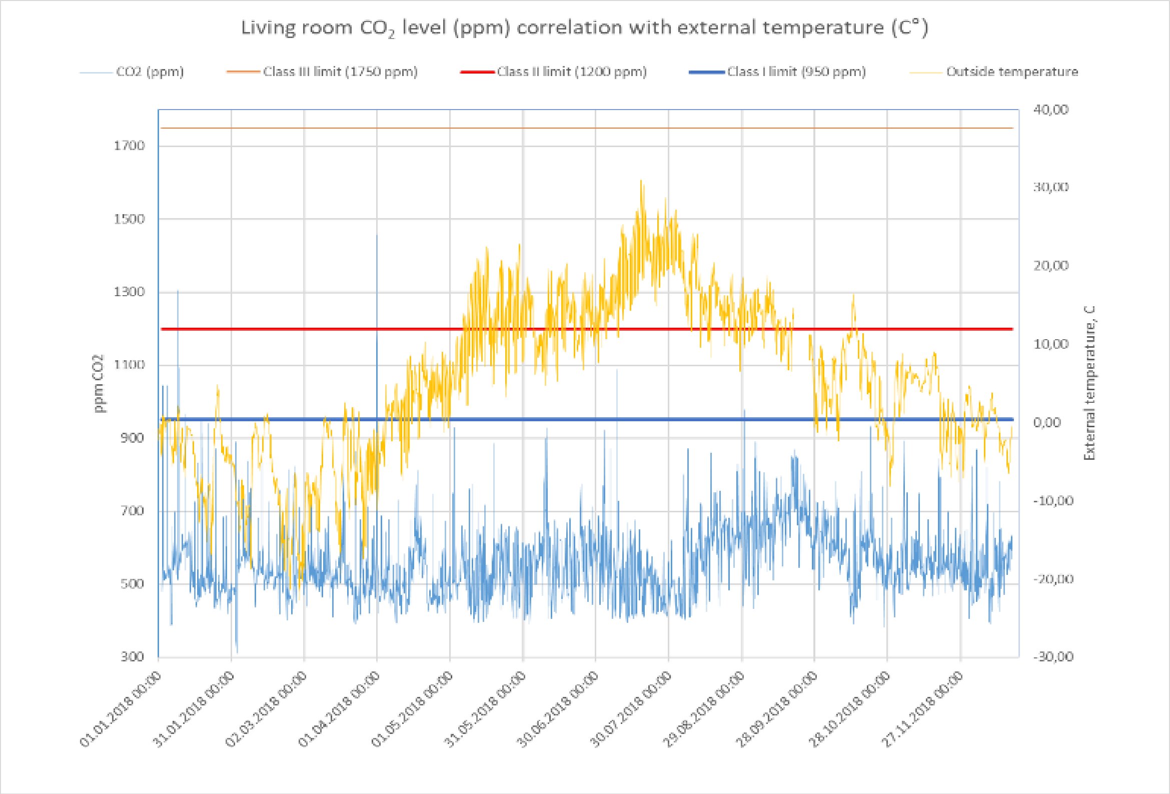


Figure 3.11 Närpiö living room $CO_2$ level correlation with external temperature

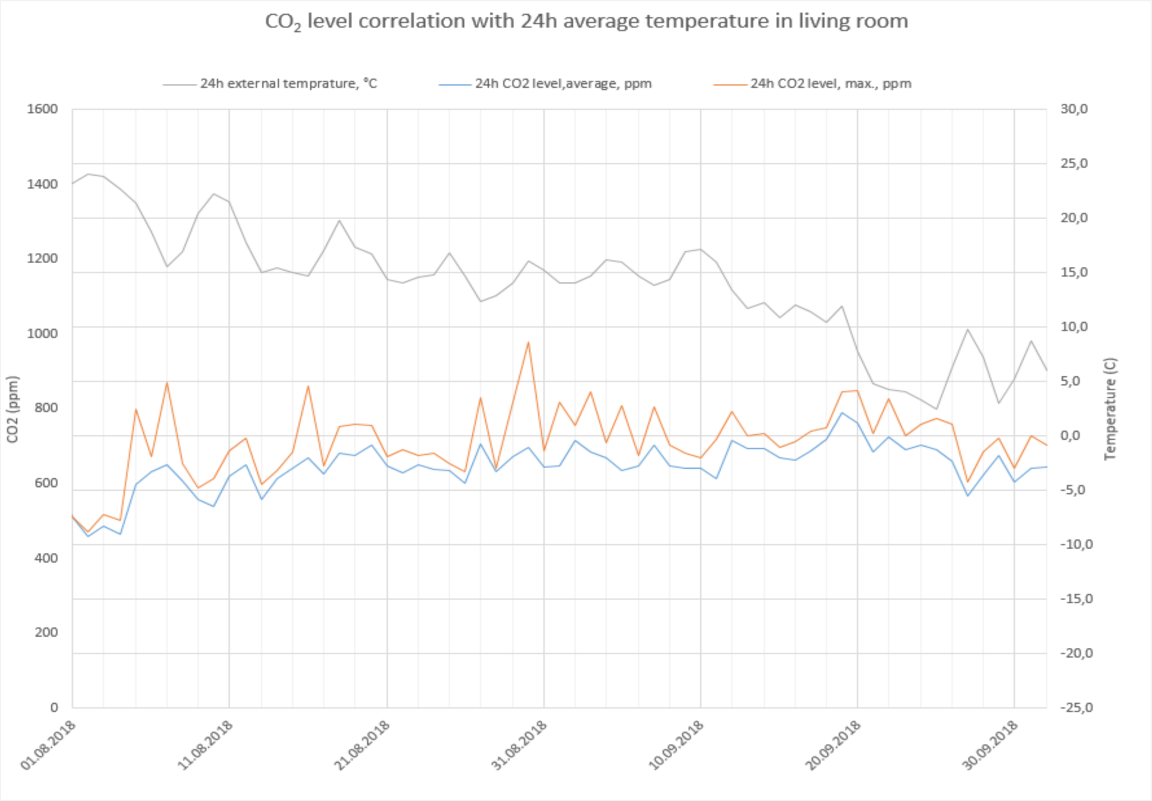


Figure 3.12 Internal $CO_2$ level correlation with external 24h average temperature August-September 2018

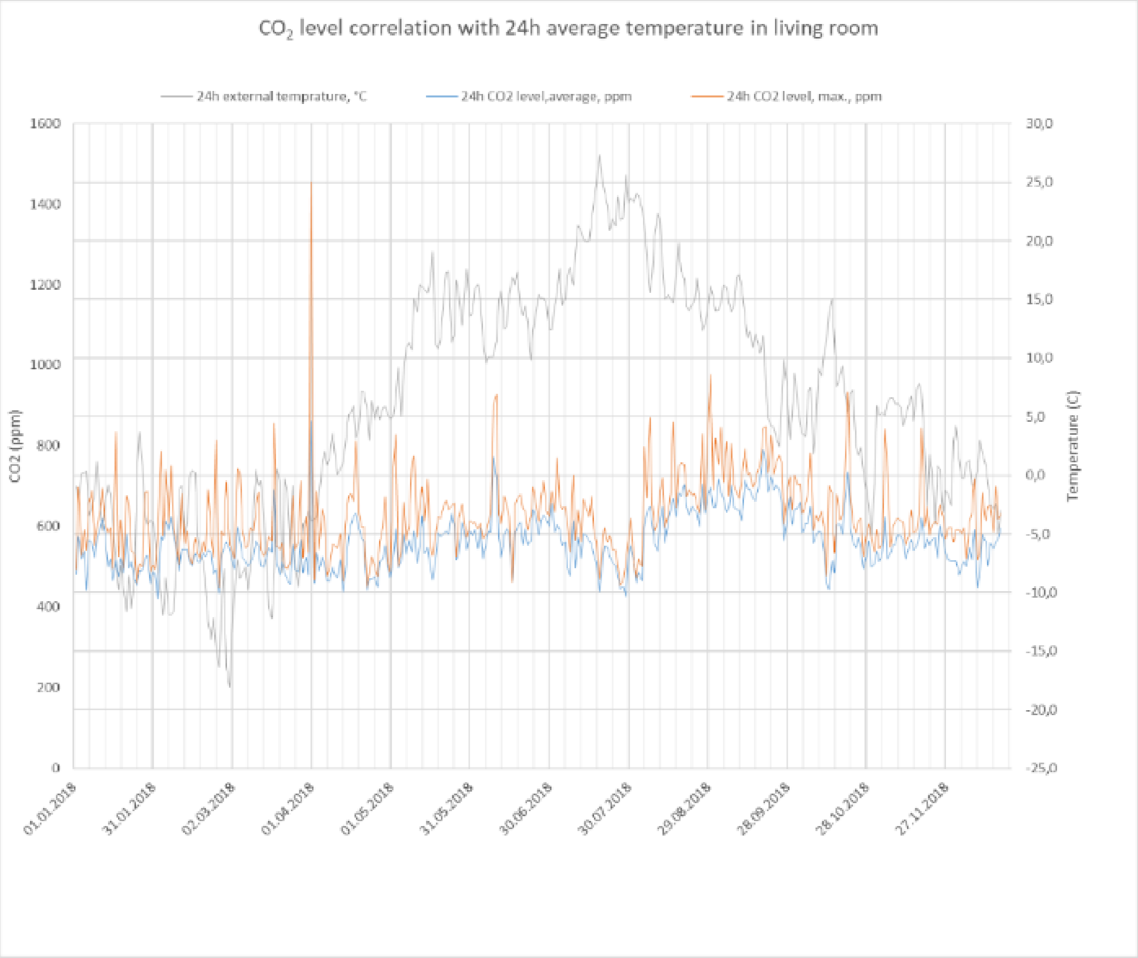


Figure 3.13 $CO_2$ level correlation with external 24h average temperature in the living room of the house in Närpiö

Relative humidity varies from 25% in winter to 75% in summer with additional peaks up to 95%. Room thermostat setpoint is between 22-24 C° (Figure 3.14). Reason for high peaks in RH value are unknown, reason might be that living room is used for drying the laundry, but this hypothesis can’t be verified.

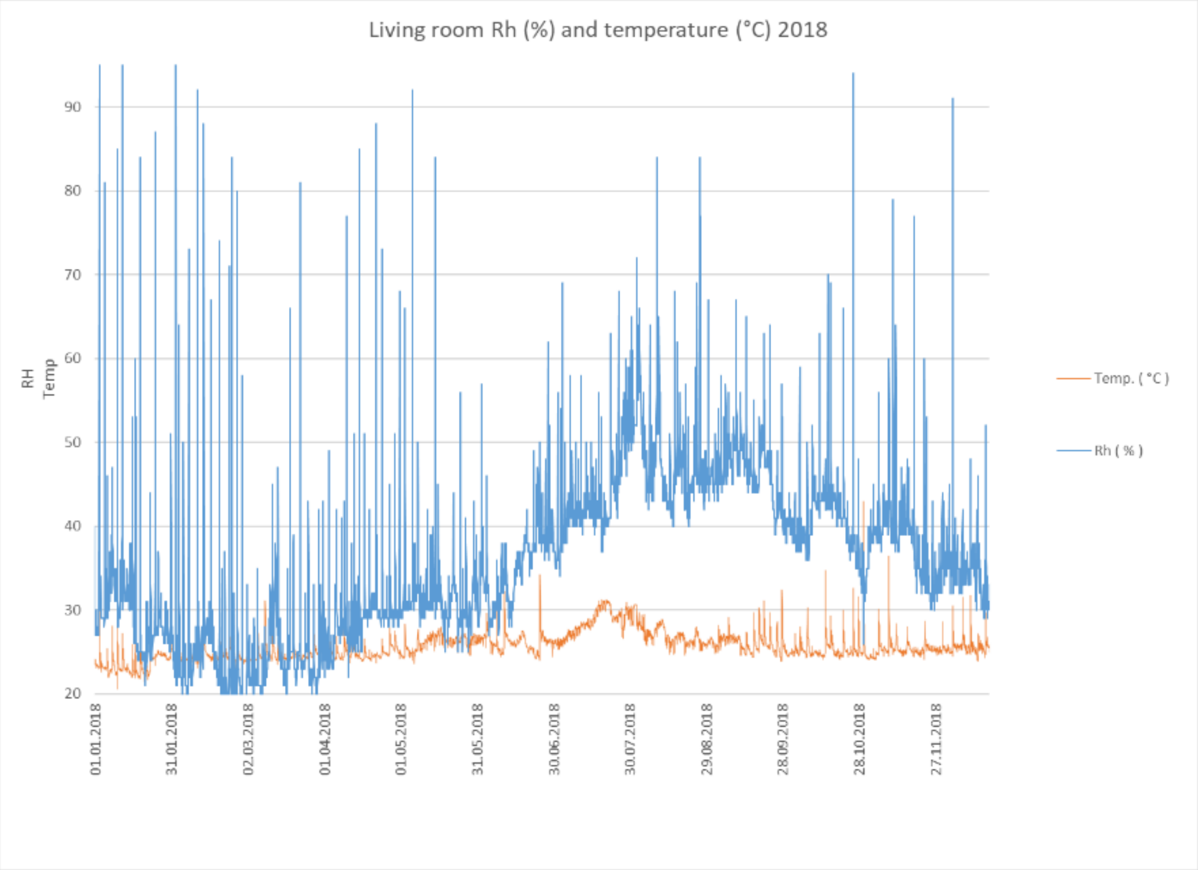


Figure 3.14 Relative humidity and room temperature in master bedroom of Närpiö house

## 3.2. Analysis of measured data of a naturally ventilated detached house in Fiskars

### 3.2.1. Occupation schedule in Fiskars house

Logged data is available from April 2015 until June 2015. Data analyze shows that typical occupation time in bedroom is between 5PM and 7PM (Figure 3.15). Occupation time graphs do not follow distinctive pattern. This can be explained by fact that room habitant, teenaged child, is likely using the room not only for sleeping but also spending the time in the room during the afternoons and during daytime in weekends.

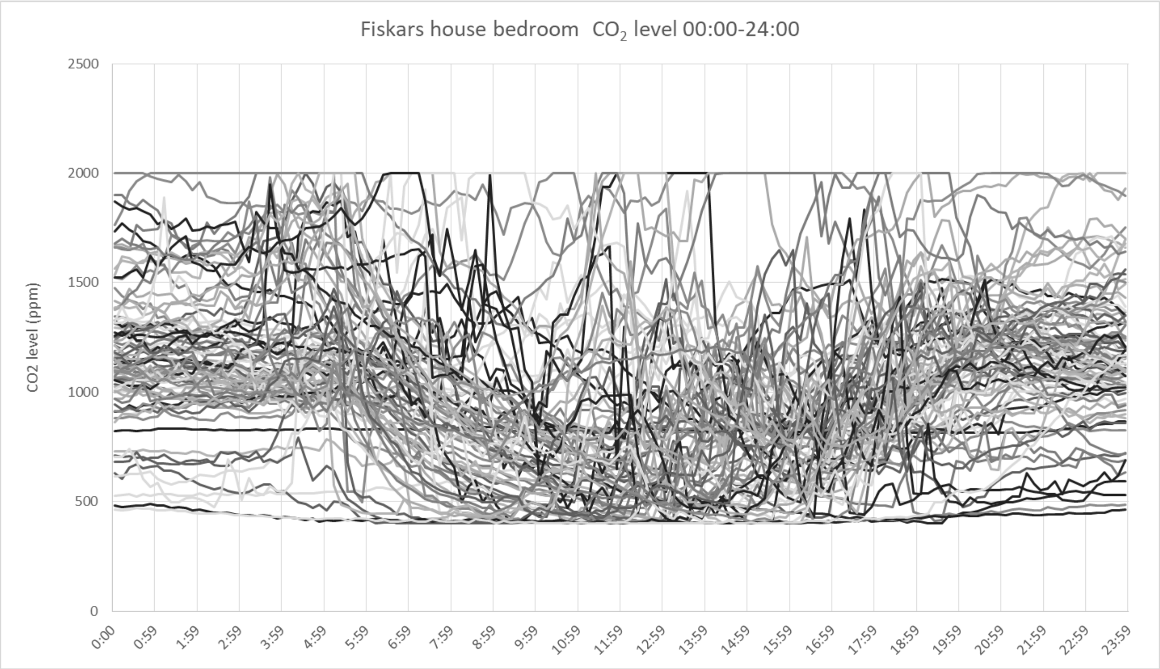


Figure 3.15. Bedroom occupation time in Fiskars building

According to analyzed logger data, living room is occupied by habitants mostly between 4PM until 9AM (Figure 3.16).

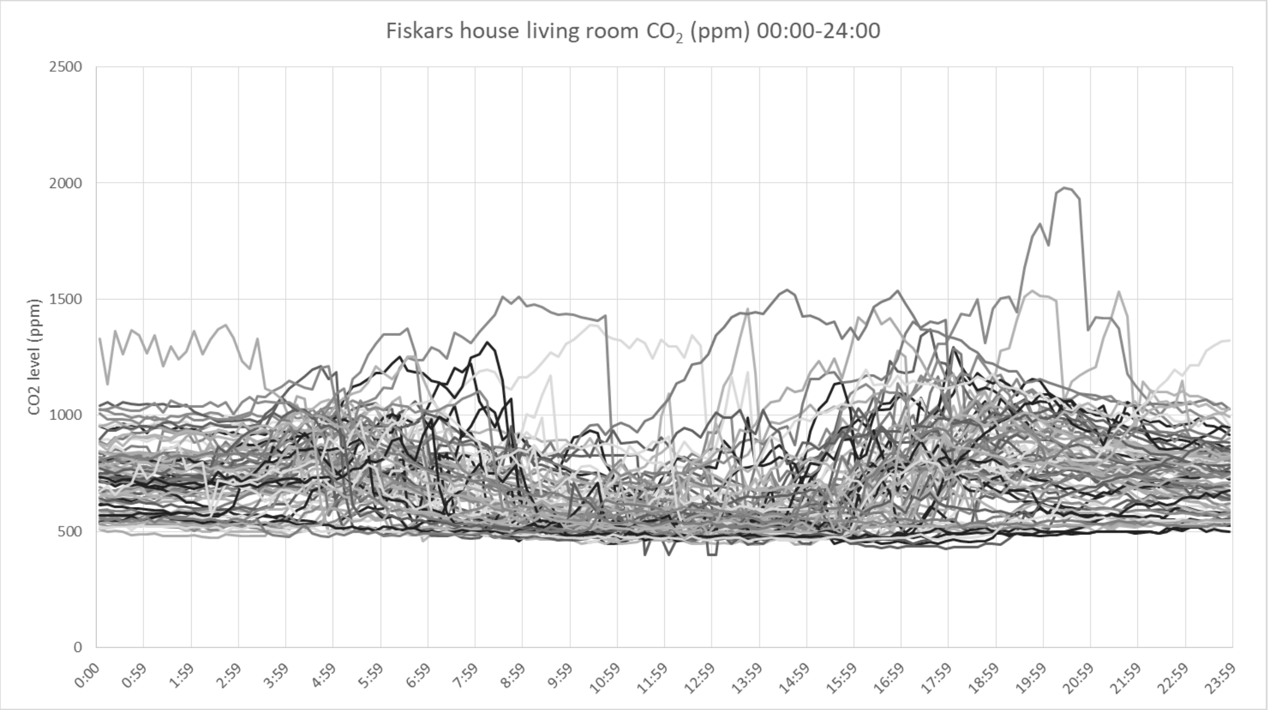


Figure 3.16. Living room occupation time in Fiskars building

### 3.2.2. Internal climate in the bedroom of the Fiskars house

Since this bedroom doesn't have incoming supply air duct $CO_2$ level is high during occupation time (Figure 3.17), often reaching maximum value of sensor measuring range.

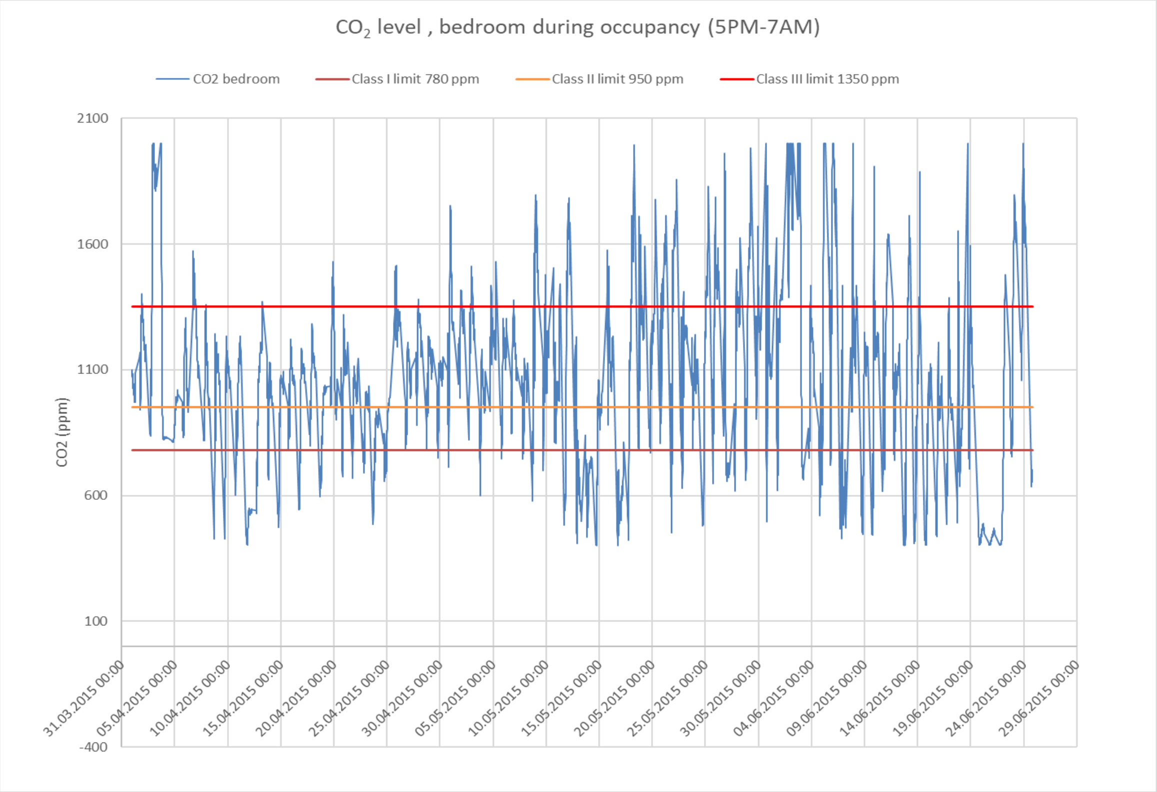


Figure 3.17. CO$_2$ concentration in the bedroom in Fiskars house

$CO_2$ concentration exceeds III category upper limit 17,9% of the time during the occupation period of the bedroom (Figure 3.18). Less than 34% of the occupation time $CO_2$ concentration meets requirements of I or II category. Room does not correspond to internal climate class III minimum requirements.

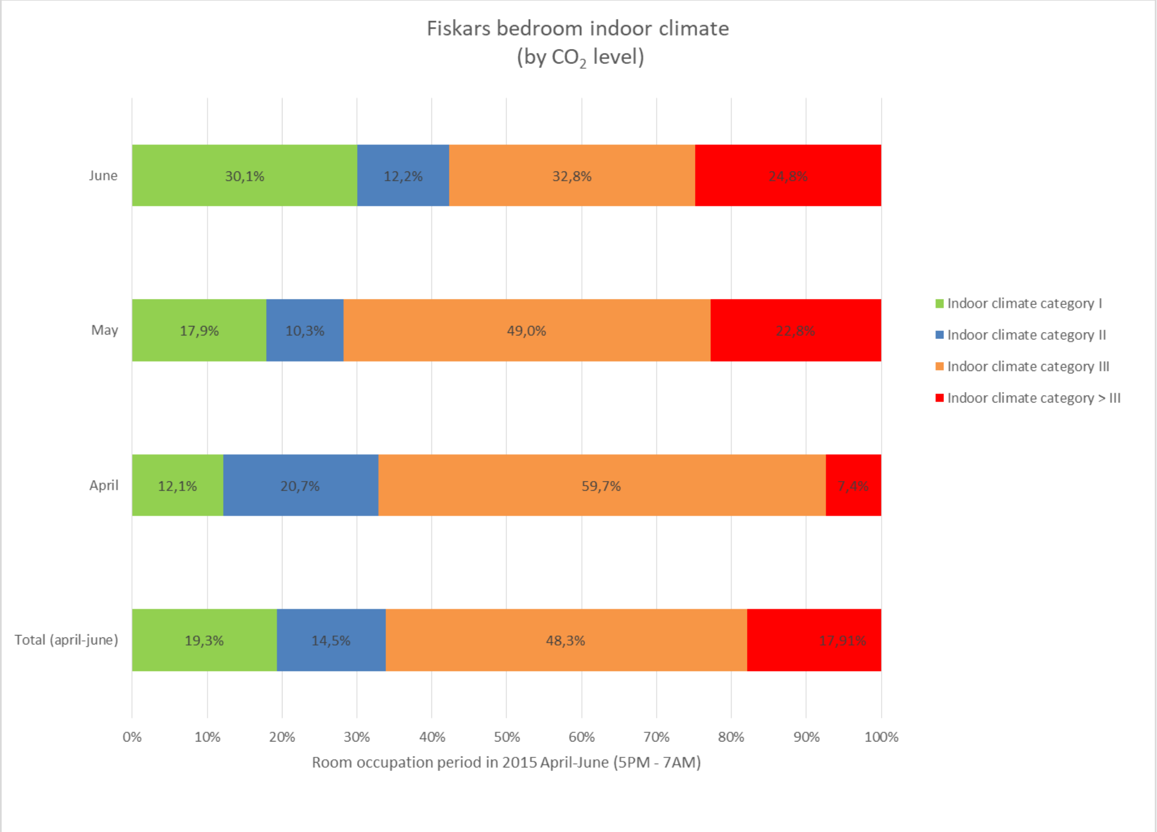


Figure 3.18. Fiskars house bedroom indoor climate classification in 2015 by $CO_2$ concentration

### 3.2.3. Internal climate in the living room of the Fiskars house

$CO_2$ concentration stays most of the time under the class III upper limit during occupation period of the room (Figure 3.19).

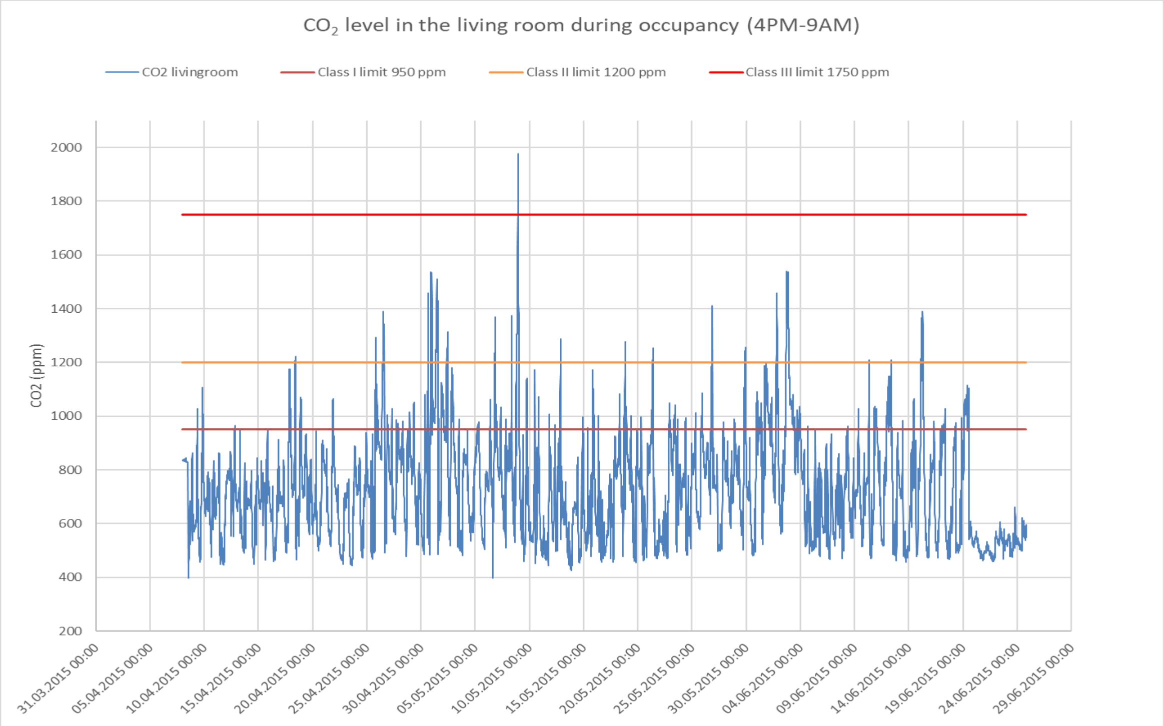


Figure 3.19. $CO_2$ concentration of the living room in Fiskars building

$CO_2$ concentration exceeds category II upper level 1,77 % of the time room occupation period (Figure 3.20). $CO_2$ concentration meets requirements of II category of internal climate for 98% of the time.

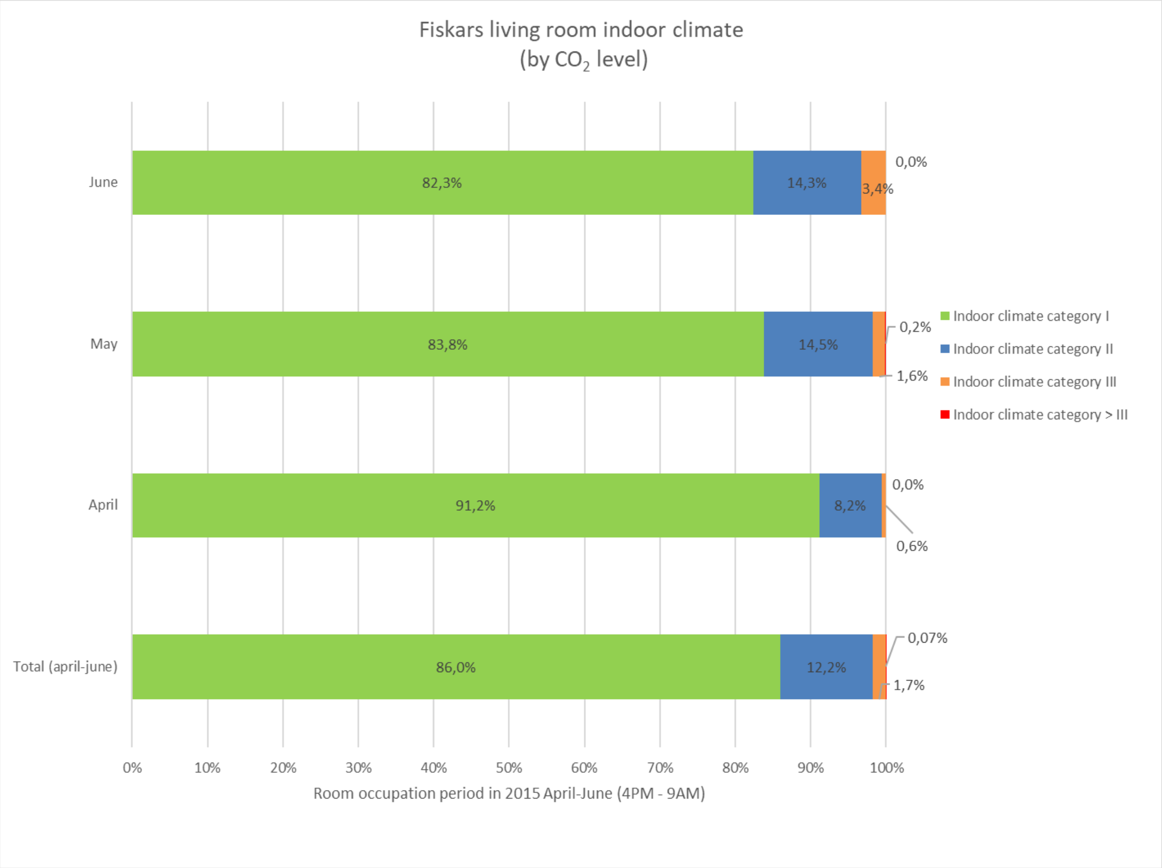


Figure 3.20. 2015 indoor climate classification by $CO_2$ concentration in the living room of Fiskars house

## 3.3. Key findings and discussions

### 3.3.1. Internal climate analysis in the bedroom of the Närpio house

Based on the data analyze following conclusions have been made:

- Analyzed data shows that $CO_2$ concentration in the master bedroom stays in the limits of category I and II for 79,7% of the time during occupancy period (Figure 3.5). Room belongs to II category of internal climate classification.
- $CO_2$ concentration rise from 6PM indicates that bedroom door is not closed outside of occupancy period (9PM-9AM)
- While external temperature rises during summer period, internal $CO_2$ level decreases. This can be explained by extra ventilation by opened windows or by solar chimney. However solar chimney effective functioning period during the day and occupation period of the sleeping room does not correlate and therefore improvement effect of solar chimney for ventilation of sleeping room is not considerable.
- There is evident correlation between external temperature and $CO_2$ concentration – stack ventilation effect.
- Bedroom ventilation level is sufficient while external temperature is below 0 C°
- Bedroom ventilation level is sufficient while external temperature increases over 10 C°. Most likely reason behind this is extra ventilation through opened windows.

### 3.3.2. Internal climate analysis in the living room of the Närpio house

Based on data analyze following conclusions have been made:

- Analyzed data shows that in the living room $CO_2$ concentration stays 99,7% of the time in category I limits during the occupancy period (Figure 3.5).
- $CO_2$ concentration doesn't have high peaks; general level of $CO_2$ is rather low – reason might be that living room is part of the larger open space in the building or ventilator might affect air exchange rate. Working time of ventilator is not logged.
- No significant correlation between season and $CO_2$ concentration in the living room. NB! Living room and bedroom are located on different floors.
- $CO_2$ concentration doesn't fall remarkable during night time – it may indicate that bedroom door is not closed

- Small raise in $CO_2$ concentration raise is visible in August and in September (Figure 3.11).
- There is no evident correlation between external temperature and room $CO_2$ concentration

To find out if door between bedroom and living room is opened during some nights, extra graph has been created. Hypothesis is that if the bedroom door is opened then $CO_2$ concentration should rise and not fall in the living room during that night. For example such period is last third of October, where $CO_2$ concentration makes a visible reduction (Figure 3.21).

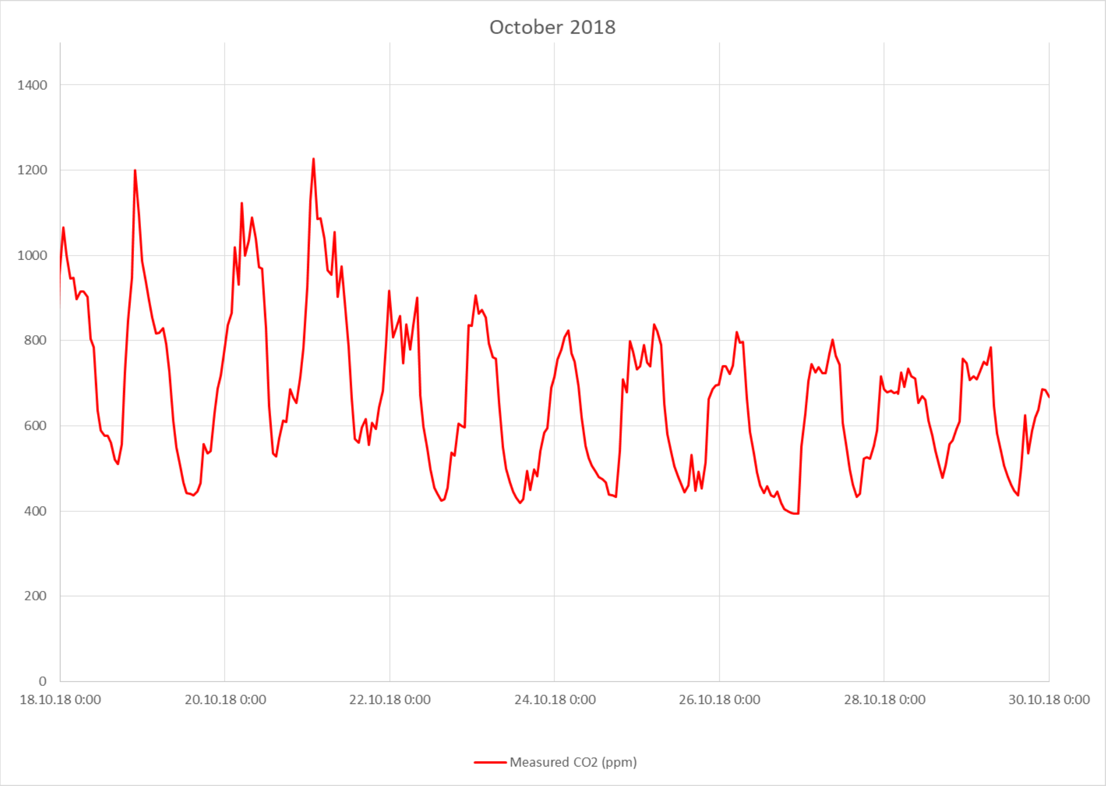


Figure 3.21. CO2 concentration during last third of October

If reduction in $CO_2$ concentration is caused by the opened door between living room and bedroom from 22nd of October then graph should visualize $CO_2$ concentration rise in the living room compared to nights before 22nd of October (Figure 3.22).

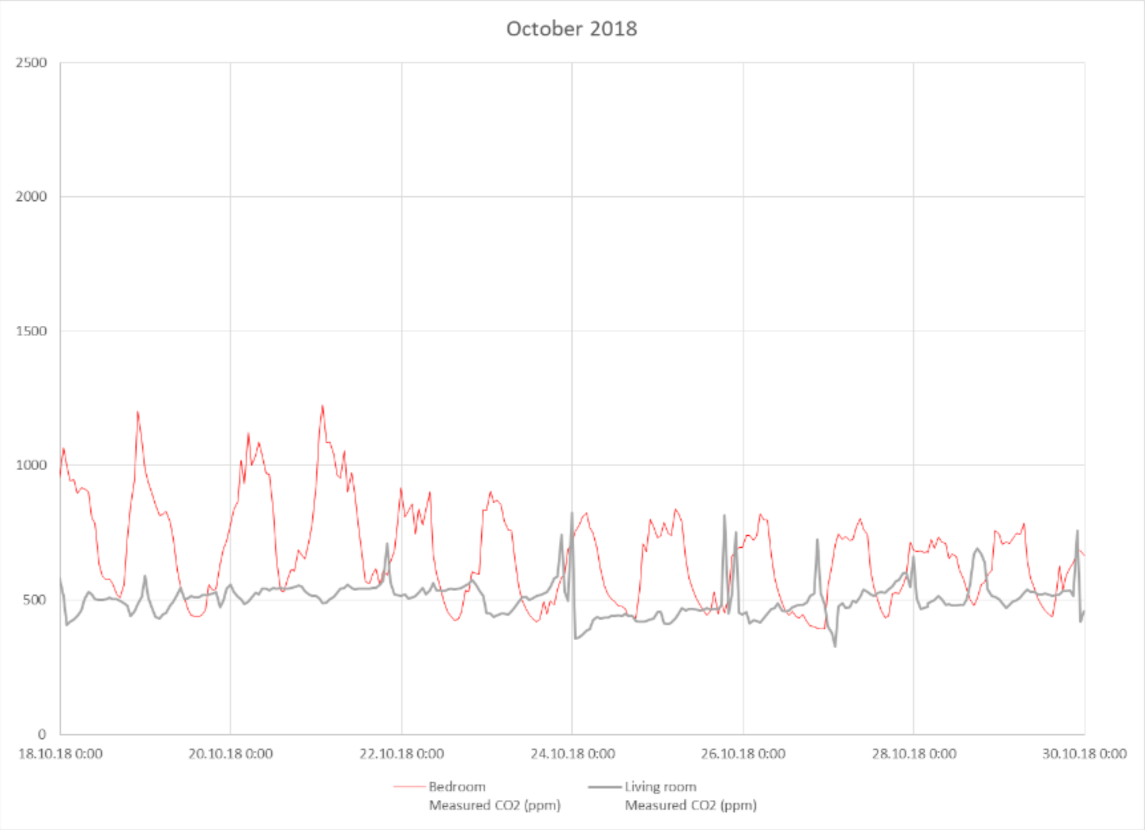


Figure 3.22. Correlation between $CO_2$ concentration in the living room and in the bedroom

Hypothesis is not confirmed – typical $CO_2$ rise pattern in the evening in the bedroom doesn't initiate $CO_2$ concentration rise in the living room simultaneously. $CO_2$ concentration in the living room after 22nd of October stays in the same range as before 22nd of October. It can be deducted that there must be another reason for $CO_2$ concentration reduction in the bedroom, for example one of the two permanent occupants in the bedroom is not staying there for some time from 22nd of October. However, since bedroom and living room are located on separate floors and there are multiple rooms in the building which are connected to different ventilation system, final deduction can't be made at this point.

### 3.3.3. Internal climate analysis in the bedroom of the Fiskars house

Based on data analyze following conclusions have been made:

- Analyzed data shows that in the bedroom $CO_2$ concentration stays in category I ja II for 33,8% of the time during occupancy period (Figure 3.18). Room does not correspond to internal climate III minimum requirements.
- 66,2% of the occupation time $CO_2$ concentration is above category II upper limit which is normal requirement for new buildings
- $CO_2$ concentration often reaches 2000 ppm which is maximum that logger is able to measure. This can be considered as unhealthy concentration which reduces life quality of a habitant
- Since this room doesn't have supply air duct nor extract air duct this is most probably the main reason for high $CO_2$ concentration
- Internal climate is considered very bad by $CO_2$ concentration

### 3.3.4. Internal climate analysis in the living room of the Fiskars house

Based on data analyze following conclusions have been made:

- Analyzed data shows that in the living room $CO_2$ concentration stays in category I ja II for 98,2% of the time during occupancy period (Figure 3.20). $CO_2$ concentration deviates 1,8% over the class II requirements. Room belongs to internal climate class II.
- Usage of internal doors between different rooms is unknown

## 3.4. Computer simulations of natural ventilation system with IDA-ICE

Logged data in Fiskars building is available only for 3-month period, bedroom is not connected directly to ventilation system, precise ventilation system solution for living room is unknown and $CO_2$ rise during the nighttime in the living room refers that internal doors are open in the house or living room is used for sleeping. For these reasons simulations for Fiskars building are neglected.

Living room in Närpiö house is ventilated with extract air ventilator and details for ventilator usage schedule are unknown. Therefor simulations for this room are neglected.

Master bedroom in Närpiö house has sufficient logged data for internal climate analyze and comparison available for whole year 2018. Information about technical solutions of ventilation system and quality of information gives a good base for comparative simulations. Further simulations and comparisons are based on the master bedroom of Närpiö building.

### 3.4.1. Simulations in Närpiö house

In order to maximize stack effect and minimize wind effect, two days with minimum wind speed and low external temperatures were chosen for calibration of simulation model.

Two nights between 11th and 12th of February and 2nd and 3rd of March had low wind speed and temperatures below 0 °C (, Figure 3.24).

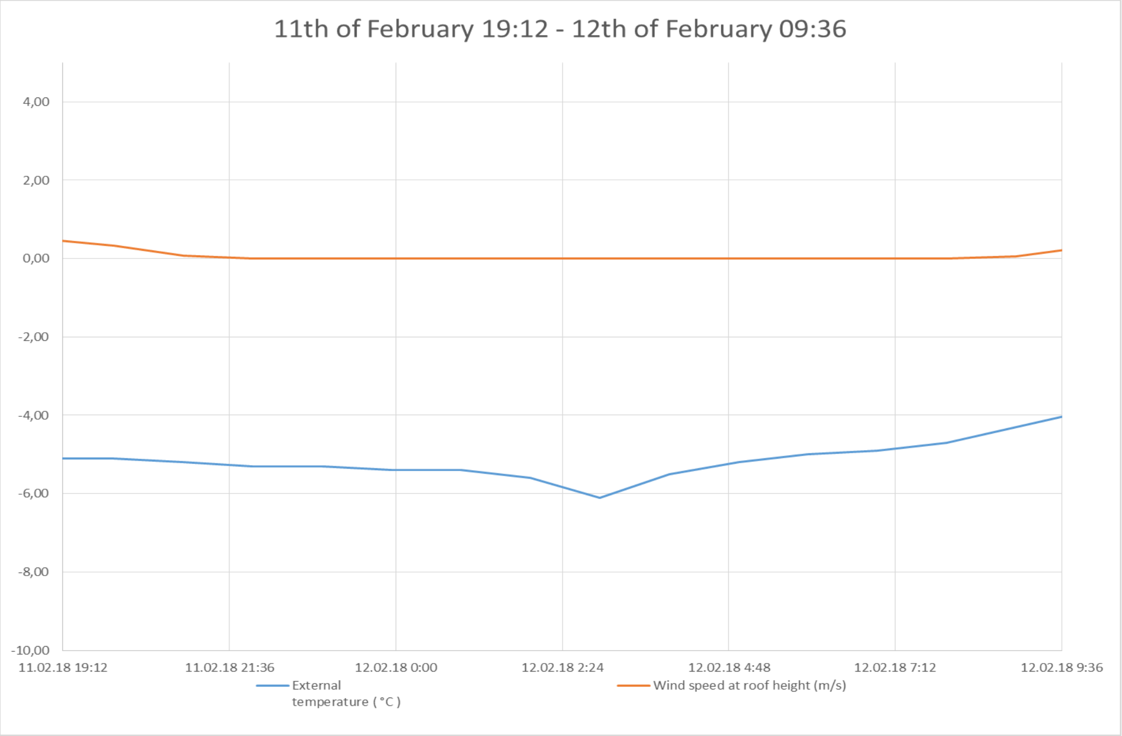


Figure 3.23 Wind and temperature between 11th of February and 12th of February

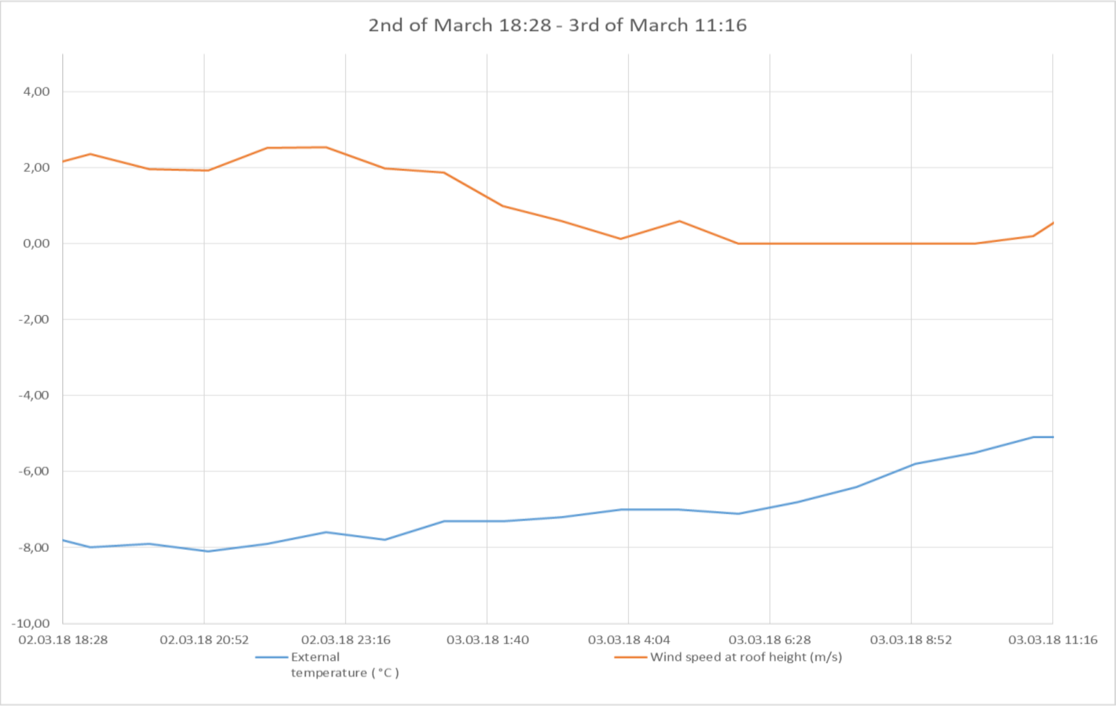


Figure 3.24. Wind and temperature between 2nd of March and 3rd of March

Pressure loss and air flow rate correlations were adjusted in simulation model to find the best correlation between simulation model and logged data in the bedroom of Närpiö building. Pressure difference 43 Pa between outdoors and indoors which gives ventilation air flow 12 l/s, characterizes master bedroom ventilation system in Närpiö house. Theoretical preliminary estimation gave an air flow 10 l/s with 43Pa pressure difference (Figure 3.26, Figure 3.25).

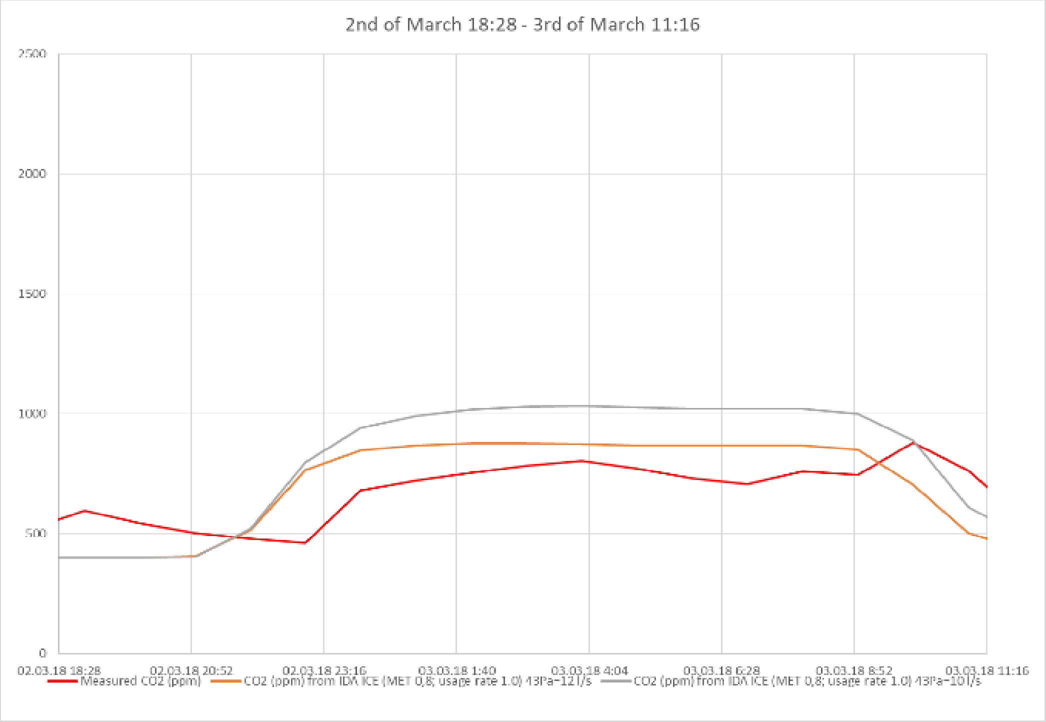


Figure 3.26. $CO_2$ calibration based on the night of 3rd of March

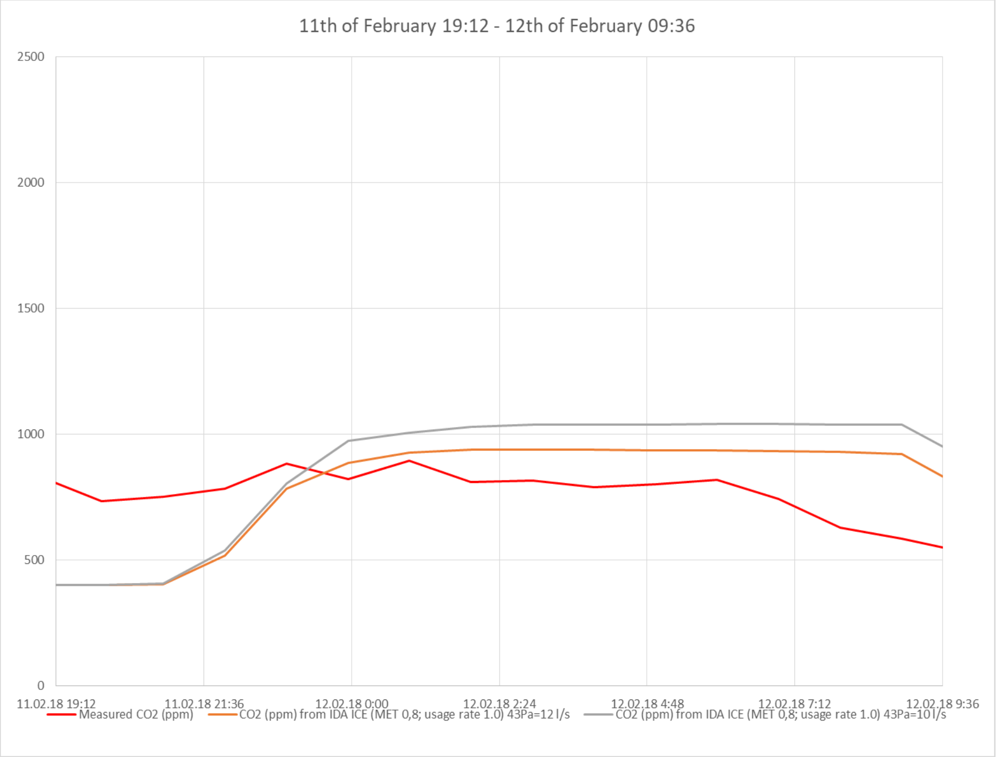


Figure 3.25 $CO_2$ calibration based on the night of 12th of February

$CO_2$ concentration the bedroom of Närpiö house was modelled with calibrated model in IDA ICE. Monthly graphs with $CO_2$ concentration were created in order to visualize modelled and measured $CO_2$ concentration comparison. Few examples are presented in Figure 3.27, Figure 3.28. All of the 12 monthly graphs are presented in Appendix 2.

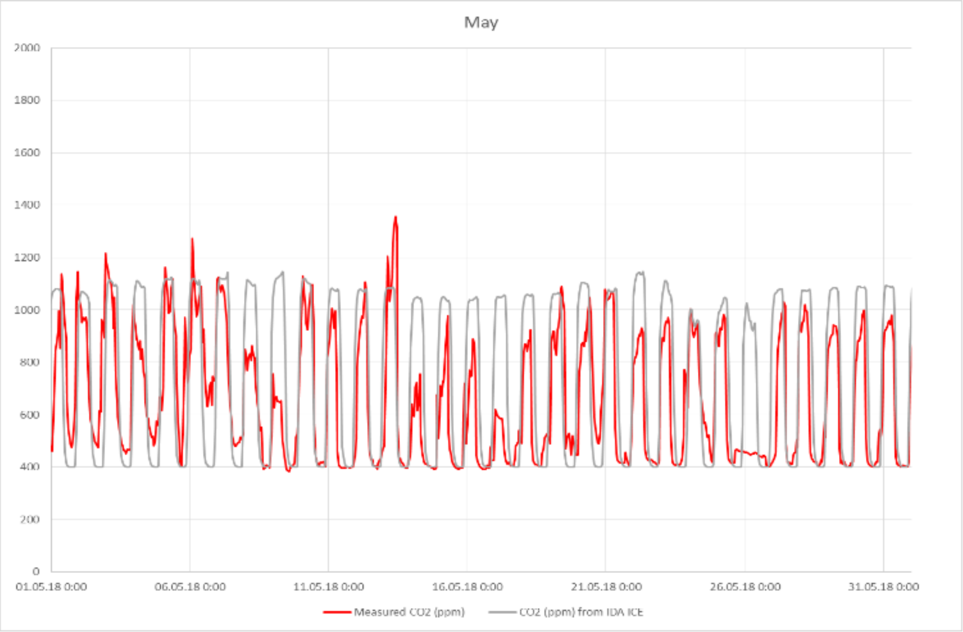


Figure 3.27. Comparison of measured and modelled CO2 concentration in May

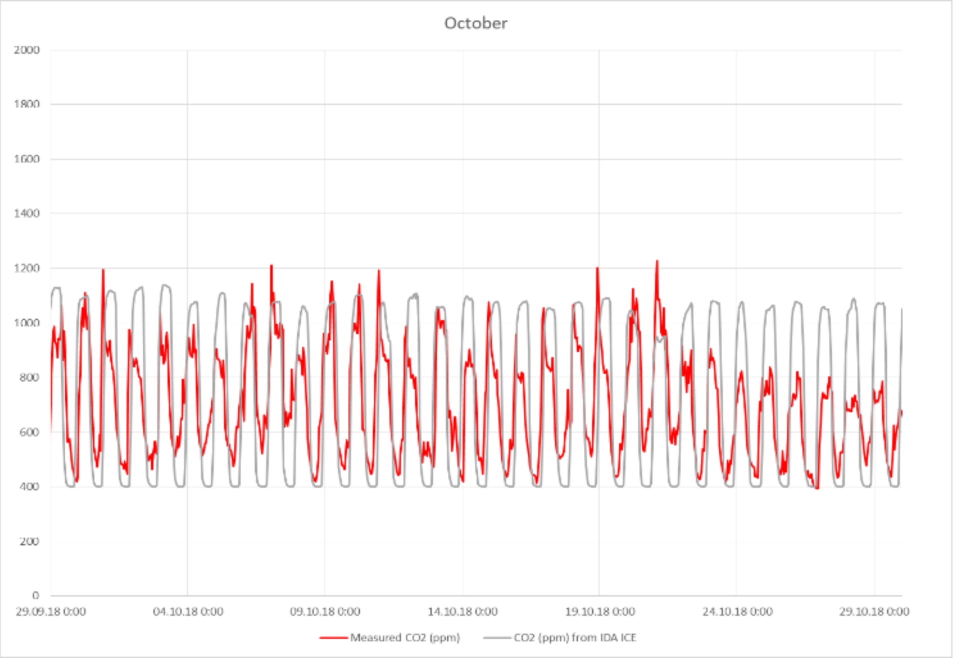


Figure 3.28 Comparison of measured and modelled CO2 concentration in October

Modelled air flows indicate that master bedroom in Närpiö house is qualified as internal climate class III by required air flow values (Figure 3.29). This is confirmed by modelled $CO_2$ concentration (Figure 3.30).

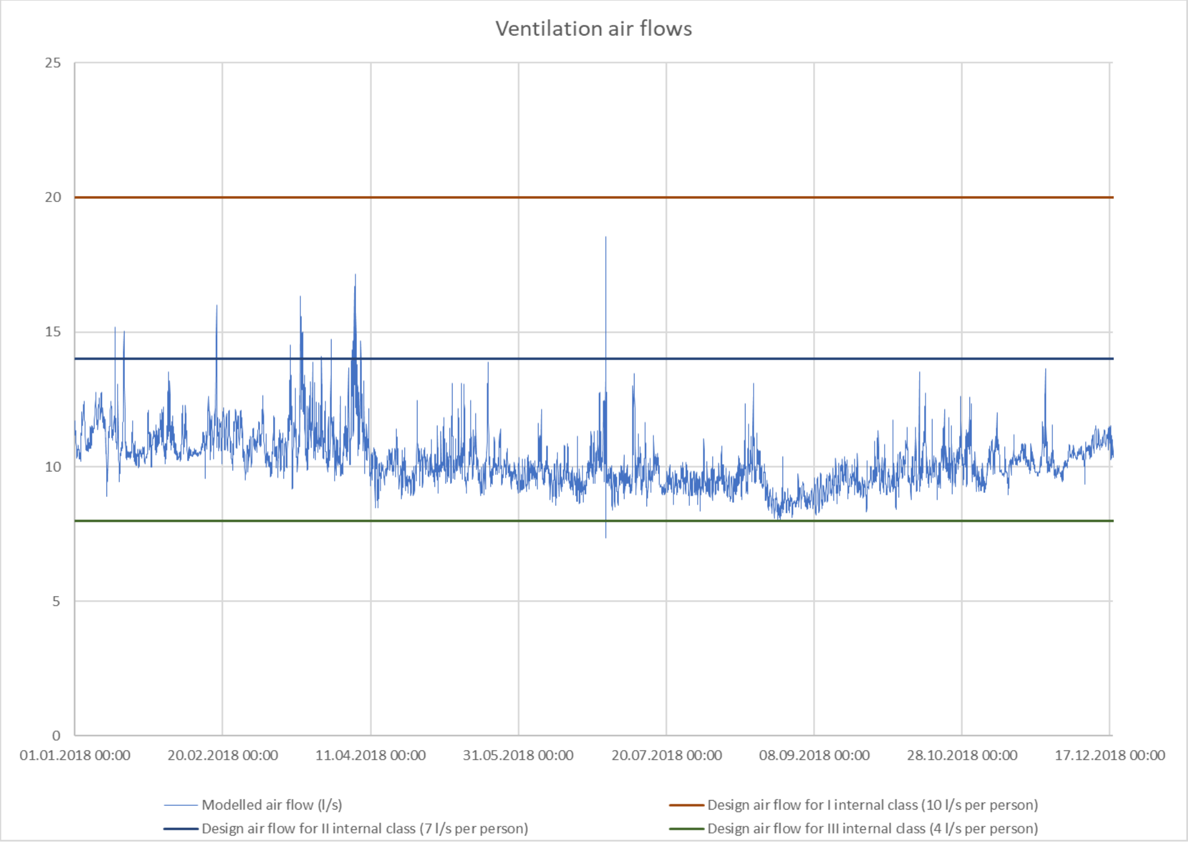


Figure 3.29. Modelled airflows with comparison of required design air flows for internal climate class I, II, III

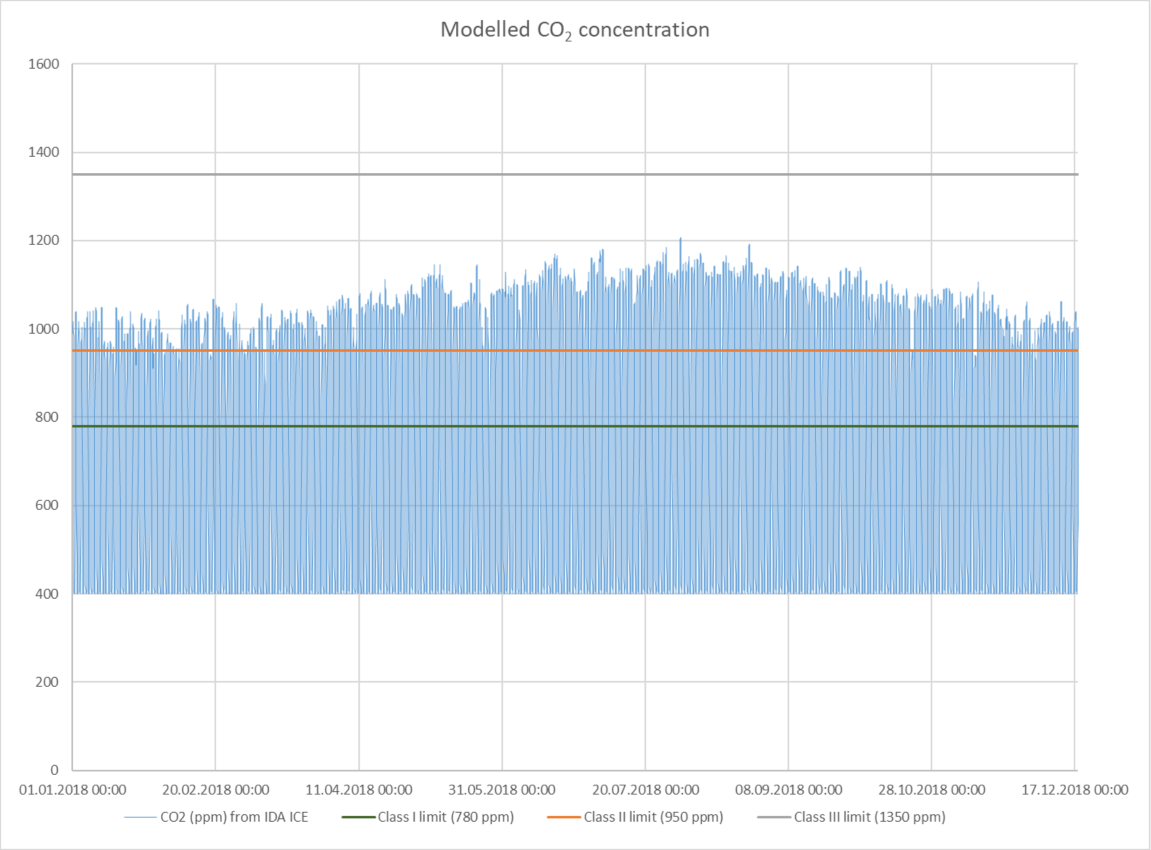


Figure 3.30. Modelled CO2 level with comparison of internal climate class I, II, III limits

### 3.4.2. Key findings and discussions

Based on simulations following conclusions have been made:

- Calibrated simulation model gives good correlation between measured $CO_2$ concentration and modelled $CO_2$ concentration
- Since precise conditions in Närpiö house regarding opened windows, ventilator use, opened internal doors etc. are unknown, deviation between measured and modelled data is expected.
- Based on comparison between modelled and measured data holiday periods, visitors, opened windows, temporary absence of one or both occupant of the bedroom can be assumed but not verified. Days while occupants have been absent can be pointed out by data observation by weekly and daily interval (Figure 3.31).
- Solar chimney has not been modelled since this functionality is currently not available in IDA ICE 5.0 version

- Bedroom of Närpiö house belongs to III category of internal climate classification by simulation model results. This corresponds to classification based on measured data.

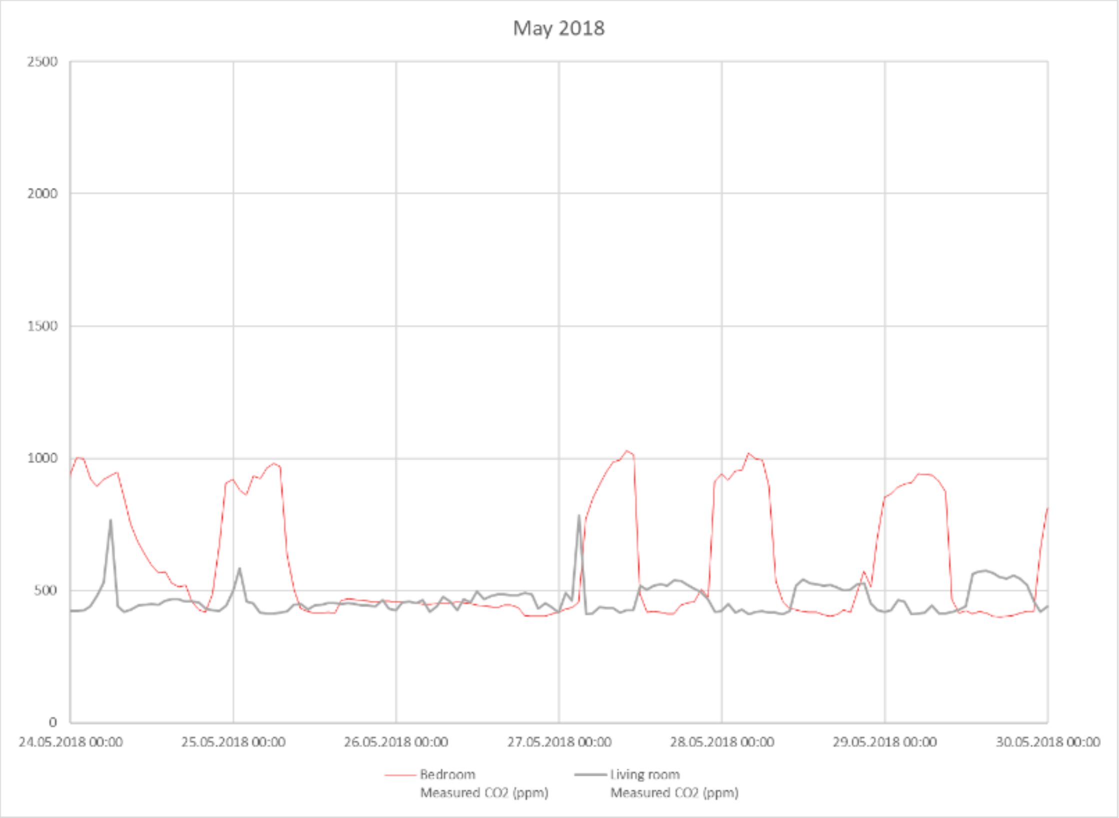
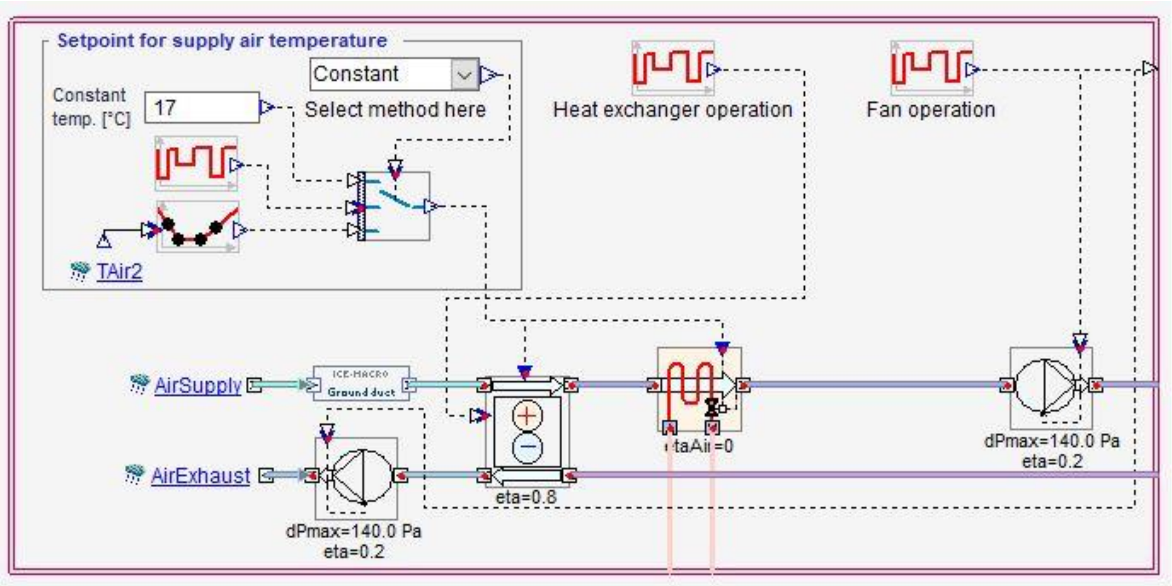


Figure 3.31. Missing occupants on the 26th of May

## 3.5. Energy efficiency

Energy efficiency is one of the default requirements to be demanded by modern ventilation systems. In order to compare different modifications and solutions, comparison simulations have been conducted by multiple different setups based on the bedroom of Närpiö house. Comparison of ventilation system configurations 1-6 are presented in Table 10 and on Figure 3.33. Configuration 1 is currently in use in the bedroom of Närpiö house, rest of the versions are hypothetical. Schematic setup of air handling unit with  heat recovery and ground duct is presented on Figure 3.32.

Parameters for energy calculation simulation are listed in paragraph 2.4 IDA-ICE simulation layout and setup (page 25). Exception is infiltration, value q50=1,5 m3/h·m2.



Constant temp. [°C]: 17

Select method here: Constant

Figure 3.32. Air handling unit with ground duct

Table 10. Comparison of annual energy efficiency by different ventilation system setup

| **Parameter** | **V.01** | **V.02** | **V.03** | **V.04** | **V.05** | **V.06** |
|---|---|---|---|---|---|---|
| Mechanically controlled air flow (YES/NO) | NO | NO | YES | YES | YES | YES |
| Controlled air flow (l/s) | - | - | 14 | 14 | 14 | 14 |
| *Air flow controlled by schedule (YES/NO) | NO | NO | YES | YES | YES | YES |
| Ground duct 10m, d=160mm (YES/NO) | YES | NO | YES | NO | NO | YES |
| Heater for incoming air (YES/NO) | YES | YES | NO | NO | YES | YES |
| **Heat recovery (YES/NO) | NO | NO | NO | NO | YES | YES |
| Annual net energy for air heater (kWh/m$^2$) | 44,0 | 44,5 | 0 | 0 | 2,96 | 0 |
| Annual net energy for room heater (kWh/m$^2$) | 102,4 | 113,5 | 89,11 | 104,2 | 40,7 | 37,7 |
| Count of hours while $CO_2$ value 950PPM exceeded | 3162 | 3005 | 16 | 8 | 4 | 11 |
| ***Additional electric energy consumption by ventilators (kWh/m$^2$) | 0 | 0 | 8,03 | 8,03 | 8,03 | 8,03 |
| Total annual net energy consumption (kWh/m$^2$) | 146,4 | 158,0 | 97,14 | 112,2 | 51,7 | 45,7 |
| $CO_2$ concentration meets internal climate category II (YES/NO) | NO | NO | YES | YES | YES | YES |

*Schedule is 1,0 from 8PM to 10AM, 0,15 for rest of the time

**Heat recovery 80%, minimum exhaust air temperature 0 °C

***SFP=1,4kW/m$^3$·s

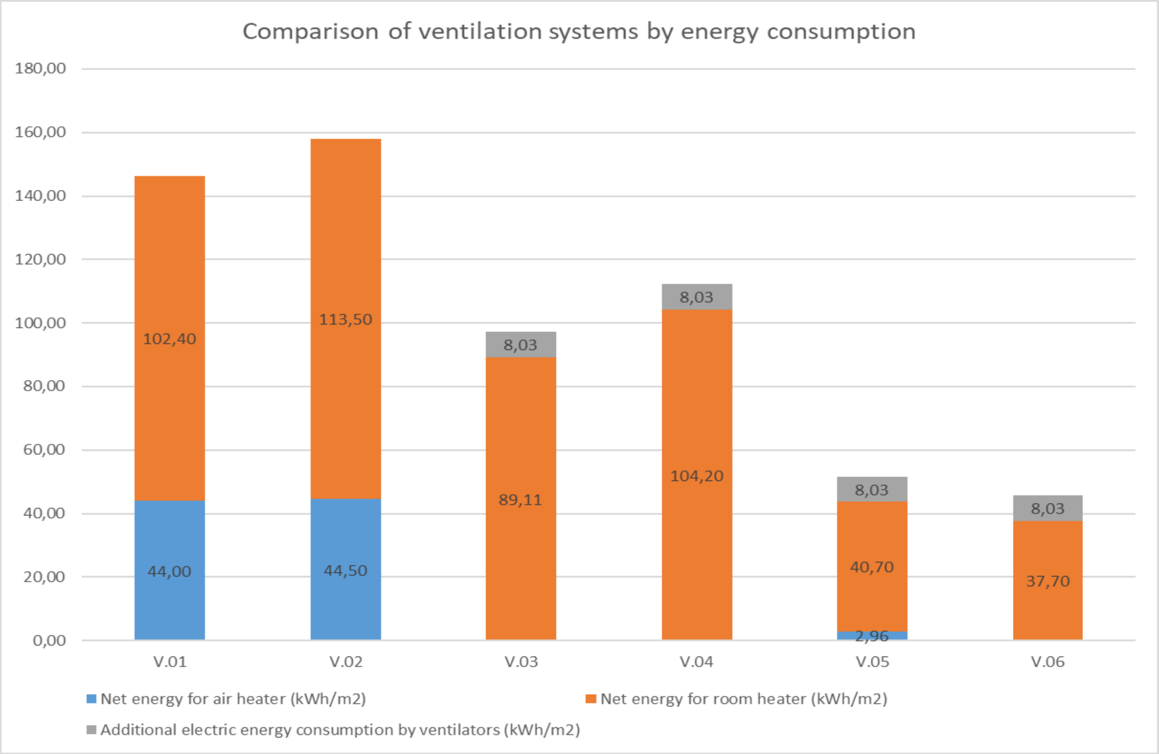


Figure 3.33. Comparison of ventilation systems by energy consumption

Ventilation system versions without mechanical ventilation doesn’t follow the criteria for internal climate category II. All modelled solutions will provide at least category III internal climate by CO2 concentration (Figure 3.34).

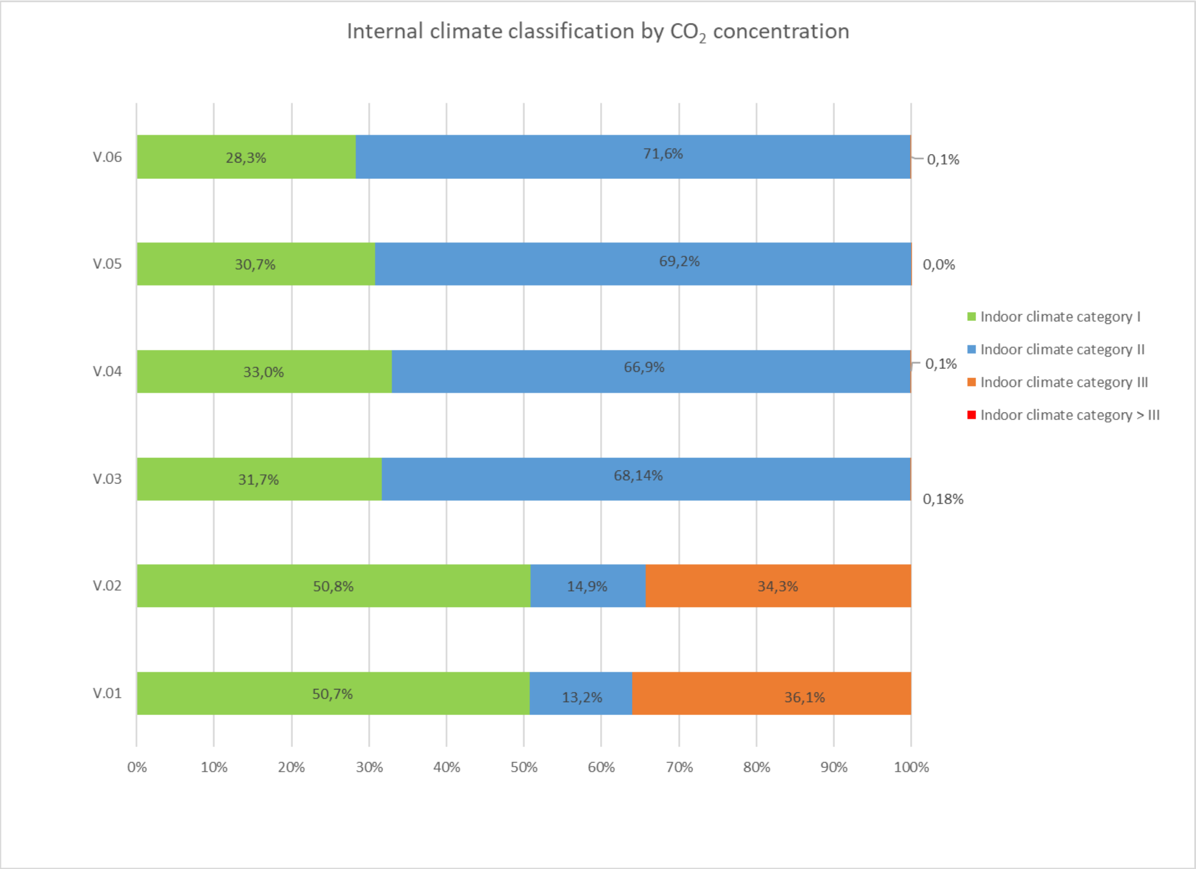


Figure 3.34. Comparison of ventilation systems by $CO_2$ concentration

Based on simulation modelling results following conclusions have been made:

- Ventilation system without controlled airflow does not provide sufficient air exchange rate to meet requirements of internal climate category II parameters which are demanded by new residential buildings
- Ground duct can reduce energy need for heating incoming air by 15%. However, influence for ground duct length and effective cross-section area dimensioning have not been calculated in this case
- Additional ground duct for intake air in air handling unit with heat recovery can eliminate the need for additional heating coil in the ventilation system (version V.06, Figure 3.33).
- Simulations showed that compared to existing stack ventilation solution in Närpiö house, net energy consumption would be reduced 2,83 times when by using common air handling unit with ventilators and heat recovery or even 3,2 times when using common air handling unit with ventilators and heat recovery with additional ground duct for inlet air.

# 4. SUMMARY

Aim of the thesis was to analyze internal climate in two naturally ventilated detached houses in Finland. It was done by two methods – analysis of logged data and theoretical simulations with IDA ICE software. Goal of the analyze and simulations was to confirm if designed ventilation solution could provide sufficient air exchange rate which corresponds currently valid requirements by national building codes and standards.

Observed research articles confirmed that solar chimney and ground duct as components of ventilation system, have been separately researched before. Ground duct for air intake in ventilation systems can be perspective in hot climate with low relative humidity of outdoor air. Focus on energy efficiency of the building along with the quality of internal climate in the buildings has been in focus by the European Union for more than 10 years and considering new policy "European Green Deal", it will stay in focus for next decades.

Both of the houses that were observed had stack ventilation system combined with ground duct for intake air and fan in extract air duct for ventilating some rooms of the building. At least one of the houses, in Närpiö, had additional solar chimney for boosting the ventilation during sunshine hours. House in Fiskars had analyzable logged data only for 3-month period and data analyze showed that internal climate in the bedroom was very poor. Measured data in the house in Närpio covered full year of 2018 and therefore it provided good basis for analyze and modelling.

Measured $CO_2$ concentration values place bedroom in Närpiö building to internal climate category III, living room to category I. Bedroom in Fiskars is placed into category IV and living room into category II.

According to measured $CO_2$ concentration values neither of the building qualify to requirements which are demanded by new residential buildings.

Dynamic simulation model was created for master bedroom in Närpiö house and calibrated by comparison of measured data. Good correlation appeared between measured $CO_2$ values and modelled $CO_2$ values. Results from simulation model and measured data, both place master bedroom in Närpiö house to internal climate class III.

Annual energy consumption comparison was calculated by modelling annual net energy consumption per $m^2$ for room heating, supply air heating and ventilators if applicable. Calculations showed that compared to existing stack ventilation solution in Närpiö house, net energy consumption would be reduced by 2,83 times when using common air handling unit with ventilators and heat recovery unit or even 3,2 times when using common air handling unit with ventilators and heat recovery unit with additional ground duct instead of currently built solution. It’s also very important to acknowledge that simulated solutions with heat recovery unit would ensure $CO_2$ concentration which corresponds to internal climate class II while stack ventilation solution would provide only III class internal climate which does not correspond to requirements for new residential buildings.

Wet and humid environment due to the condensate from intake air to the duct will impose remarkable risk for mold and bacteria growth. If this can be avoided, then ground duct would be good addition to conventional mechanical ventilation system with heat recovery but would not substitute this.

# EESTIKEELNE KOKKUVÕTE

Käesoleva magistritöö eesmärk oli analüüsida sisekliimat kahes loomuliku ventilatsiooniga ventileeritavas Soome eramus. Analüüs toimus kahes osas – hoonetes mõõdetud andmete analüüs ning simulatsioonarvutused IDA ICE tarkvaraga. Analüüsi eesmärk oli kontrollida, kas ehitatud ventilatsioonilahendused suudaksid tagada piisava õhuvahetuse, mis vastaks tänapäevastele ehitusseadustikus ning standardites kehtestatud nõuetele.

Teadusartiklite ning kirjanduse analüüs kinnitas, et päikesekorstnat ja pinnasesse paigutatud ventilatsioonisüsteemi õhuvõtutoru on ka varasemalt eraldi uuritud. Pinnasesse paigaldatud õhuvõtutoru ventilatsioonisüsteemis võib olla perspektiivne kuumas kliimas, kus on välisõhu madal õhuniiskus. Hoonete energiatõhusus koos hoonete sisekliima temaatikaga on olnud Euroopa liidus fookuses juba rohkem kui 10 aastat. Arvestades hetkel käimasolevat „Rohepööret" jääb see veel oluliseks teemaks aastakümneteks.

Mõlemas uuritavas majas on loomuliku ventilatsiooni süsteem kombineerituna pinnasesse paigaldatud õhuvõtutoruga ning lisaks kanaliventilaatorid õhu mehaaniliseks väljatõmbeks mõnest hoone osast. Vähemalt ühes majades, Närpiö majal, on ka päikesekorsten, mis peaks suurendama hoone õhuvahetust, kui päike paistab.
Fiskarsi majas oli analüüsitavaid andmeid ainult kolme kuu kohta ning analüüsitud mõõtmisandmed näitasid, et siseõhu kvaliteet magamistoas oli väga halb.
Närpiö maja mõõtmistulemused olid olemas terve 2018. aasta kohta ning see pakkus head ainet andmetel põhinevaks analüüsiks ning võrdlevateks simulatsioonarvutusteks.

Mõõdetud $CO_2$ kontsentratsiooni järgi paigutus Närpiö maja magamistuba III sisekliima klassi ning magamistuba I sisekliima klassi. Fiskarsi majas olev magamistuba paigutus IV sisekliima klassi ning elutuba II sisekliima klassi.

Kumbki hoonetest ei vasta mõõdetud $CO_2$ konsentratsiooni järgi nõuetele, mida esitatakse uutele eluhoonetele.

Dünaamilise simulatsioonarvutuse mudel koostati Närpiö majas asuva magamistoa kohta ning kalibreeriti mõõdetud andmete järgi. Mõõdetud ja simulatsioonarvutusega saadud $CO_2$ kontsentratsiooni andmed korreleerusid hästi. Nii mõõtmisandmete kui simulatsioonarvutuste järgi paigutus Närpiö maja magamistuba sisekliima III klassi.

Simulatsioonarvutustega leiti hoone netoenergiakulu $m^2$ kohta kütmiseks, ventilatsiooniõhu eelsoojendamiseks ning ventilaatorite töös hoidmiseks, selle põhjal võrreldi vastavate lahenduste aastast energiakulu.

Arvutused näitasid, et võrreldes Närpiös majas hetkel välja ehitatud ventilatsioonisüsteemiga väheneks energiakulu 2,83 korda kui kasutataks tavalist sundventilatsioonisüsteemi soojustagastusega ning 3,2 korda kui soojustagastusega sundventilatsioonisüsteemile lisataks pinnasetoru hoonesse juhitava välisõhu eelsoojendamiseks enne soojustagastit.

Väga oluline on välja tuua, et sundventilatsioonisüsteem tagaks ruumides $CO_2$ taseme, mis vastab II-le sisekliima klassile, samal ajal kui olemasolev süsteem tagab vaid III klassi sisekliima. III klass ei vasta hetkel kehtivatele nõuetele uusehitiste kohta.

Pinnasesse paigaldatud õhuvõtutorus tekkiv kondents põhjustab niisket ja märga keskkonda, mis tekitab arvestatavat riski hallituse ning bakterite kasvule torus. Kui seda saaks vältida siis võiks pinnasesse paigaldatud toru olla heaks täienduseks tavalisele mehaanilisele soojustagastusega ventilatsioonisüsteemile, aga ei asenda tavalist ventilatsiooniseadmesse paigaldatud soojusvahetit.

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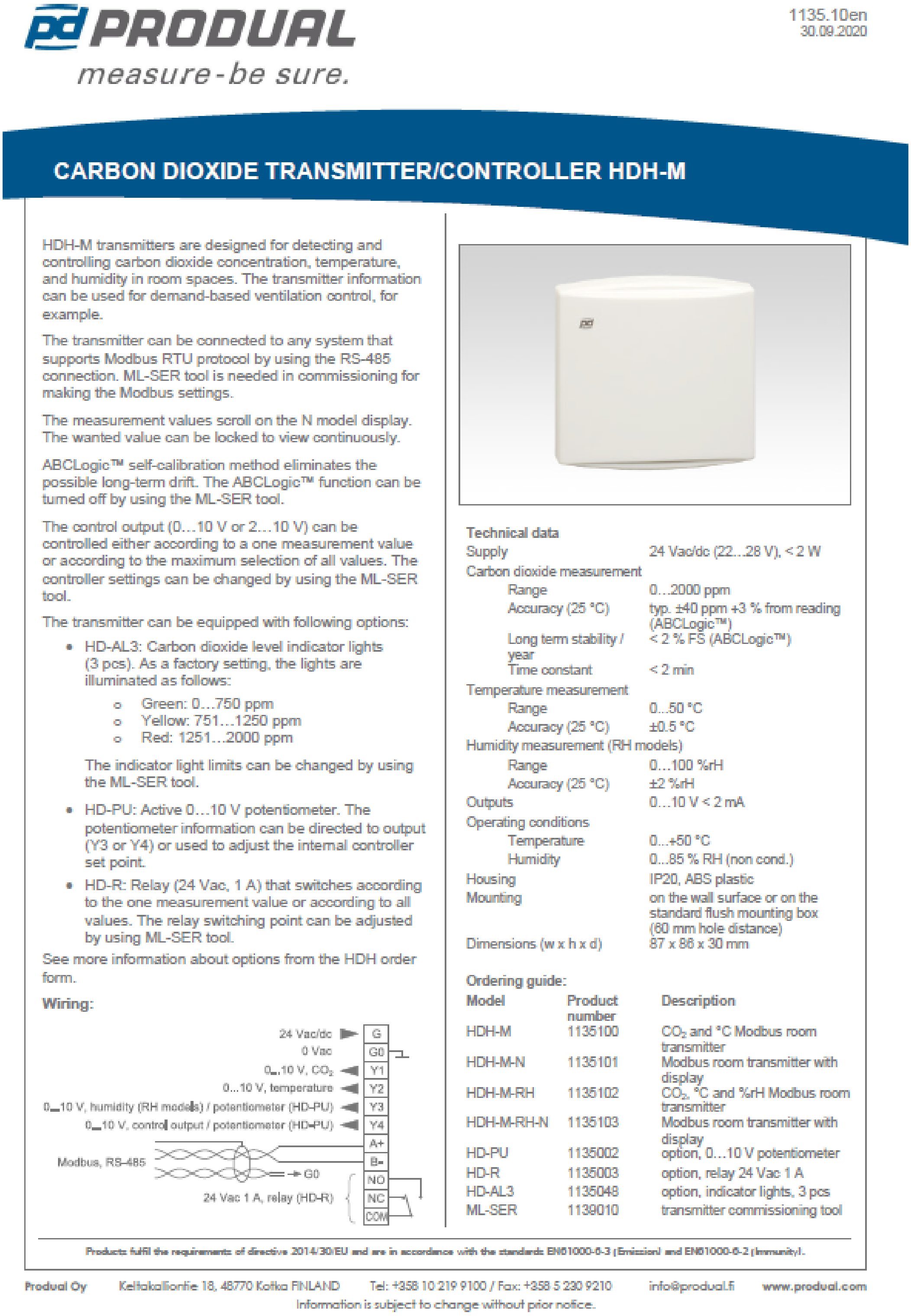
# APPENDICIES

## Appendix 1. Produal HDH-M-RH room sensor



PRODUAL
measure - be sure.

1135.10en
30.09.2020

### CARBON DIOXIDE TRANSMITTER/CONTROLLER HDH-M

HDH-M transmitters are designed for detecting and controlling carbon dioxide concentration, temperature, and humidity in room spaces. The transmitter information can be used for demand-based ventilation control, for example.

The transmitter can be connected to any system that supports Modbus RTU protocol by using the RS-485 connection. ML-SER tool is needed in commissioning for making the Modbus settings.

The measurement values scroll on the N model display. The wanted value can be locked to view continuously.

ABCLogic™ self-calibration method eliminates the possible long-term drift. The ABCLogic™ function can be turned off by using the ML-SER tool.

The control output (0…10 V or 2…10 V) can be controlled either according to a one measurement value or according to the maximum selection of all values. The controller settings can be changed by using the ML-SER tool.

The transmitter can be equipped with following options:

- HD-AL3: Carbon dioxide level indicator lights (3 pcs). As a factory setting, the lights are illuminated as follows:
    - Green: 0…750 ppm
    - Yellow: 751…1250 ppm
    - Red: 1251…2000 ppm

  The indicator light limits can be changed by using the ML-SER tool.
- HD-PU: Active 0…10 V potentiometer. The potentiometer information can be directed to output (Y3 or Y4) or used to adjust the internal controller set point.
- HD-R: Relay (24 Vac, 1 A) that switches according to the one measurement value or according to all values. The relay switching point can be adjusted by using ML-SER tool.

See more information about options from the HDH order form.

**Wiring:**

**Technical data**

| | |
|---|---|
| Supply | 24 Vac/dc (22…28 V), < 2 W |
| Carbon dioxide measurement | |
| Range | 0…2000 ppm |
| Accuracy (25 °C) | typ. ±40 ppm +3 % from reading (ABCLogic™) |
| Long term stability / year | < 2 % FS (ABCLogic™) |
| Time constant | < 2 min |
| Temperature measurement | |
| Range | 0…50 °C |
| Accuracy (25 °C) | ±0.5 °C |
| Humidity measurement (RH models) | |
| Range | 0…100 %rH |
| Accuracy (25 °C) | ±2 %rH |
| Outputs | 0…10 V < 2 mA |
| Operating conditions | |
| Temperature | 0…+50 °C |
| Humidity | 0…85 % RH (non cond.) |
| Housing | IP20, ABS plastic |
| Mounting | on the wall surface or on the standard flush mounting box (60 mm hole distance) |
| Dimensions (w x h x d) | 87 x 86 x 30 mm |

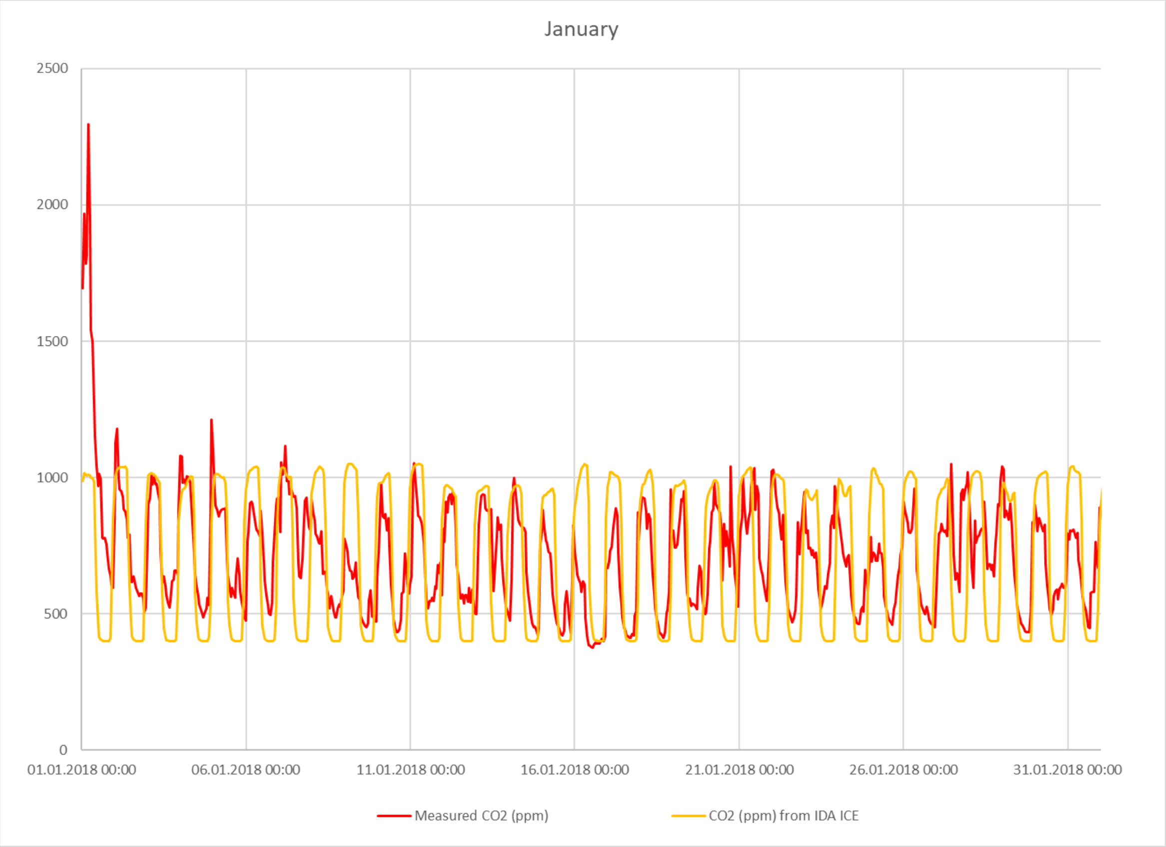
**Ordering guide:**

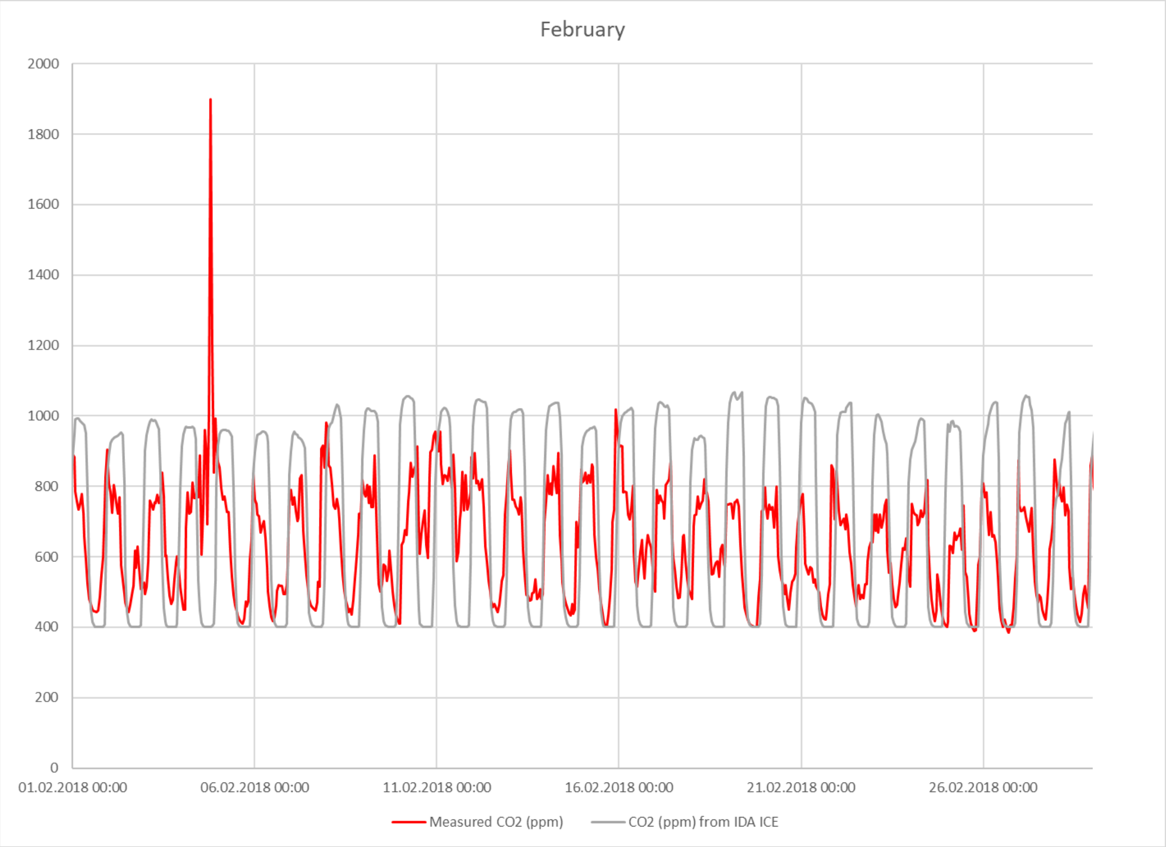
| Model | Product number | Description |
|---|---|---|
| HDH-M | 1135100 | CO$_2$ and °C Modbus room transmitter |
| HDH-M-N | 1135101 | Modbus room transmitter with display |
| HDH-M-RH | 1135102 | CO$_2$, °C and %rH Modbus room transmitter |
| HDH-M-RH-N | 1135103 | Modbus room transmitter with display |
| HD-PU | 1135002 | option, 0…10 V potentiometer |
| HD-R | 1135003 | option, relay 24 Vac 1 A |
| HD-AL3 | 1135048 | option, indicator lights, 3 pcs |
| ML-SER | 1139010 | transmitter commissioning tool |

Products fulfil the requirements of directive 2014/30/EU and are in accordance with the standards EN61000-6-3 (Emission) and EN61000-6-2 (Immunity).

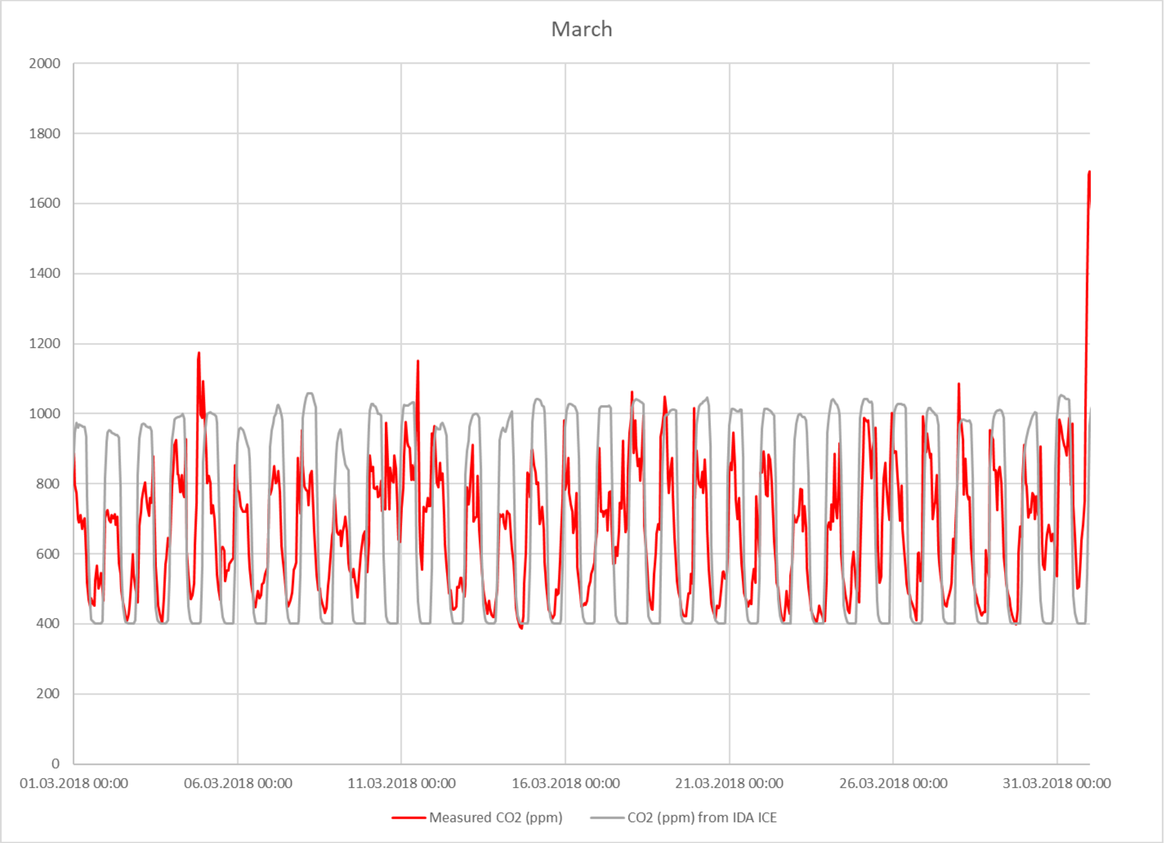
Produal Oy Keltakalliontie 18, 48770 Kotka FINLAND Tel: +358 10 219 9100 / Fax: +358 5 230 9210 info@produal.fi www.produal.com
Information is subject to change without prior notice.

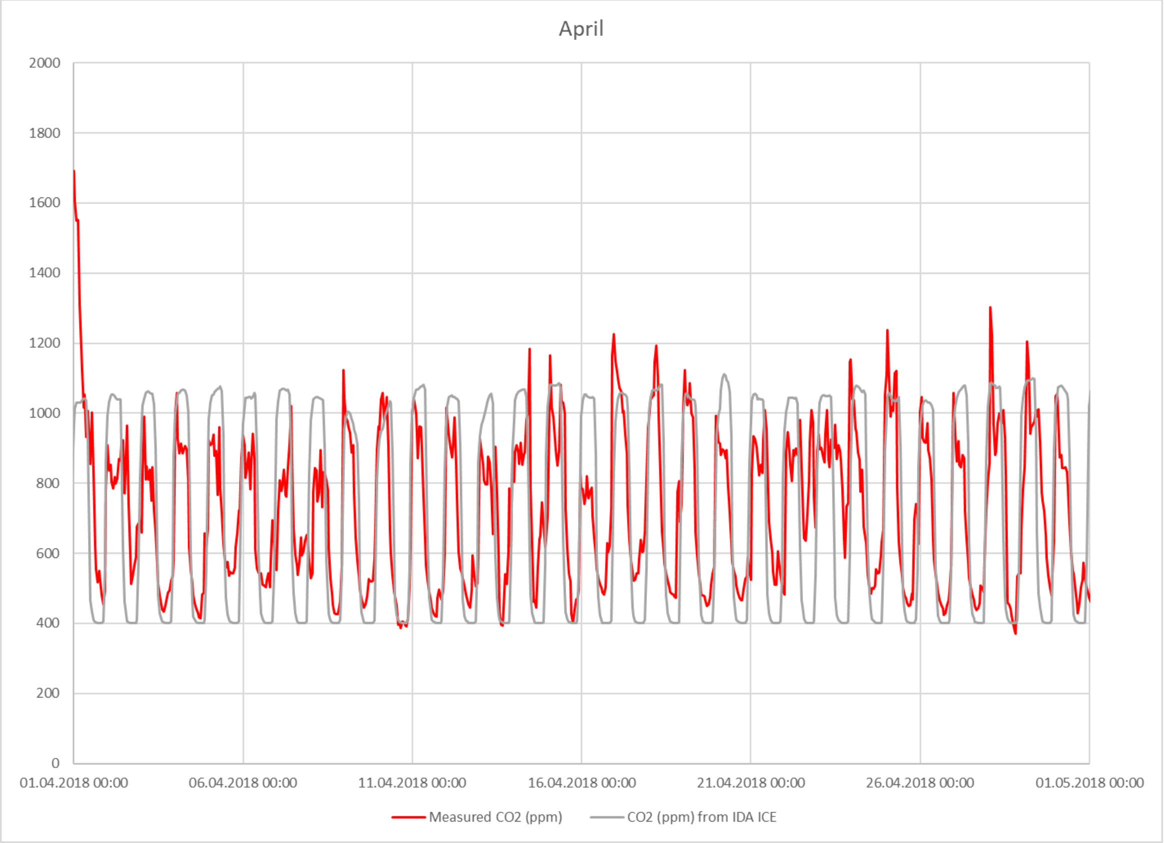
# Appendix 2. Measured and modelled CO2 concentration in Närpio house January 2018 and February 2018



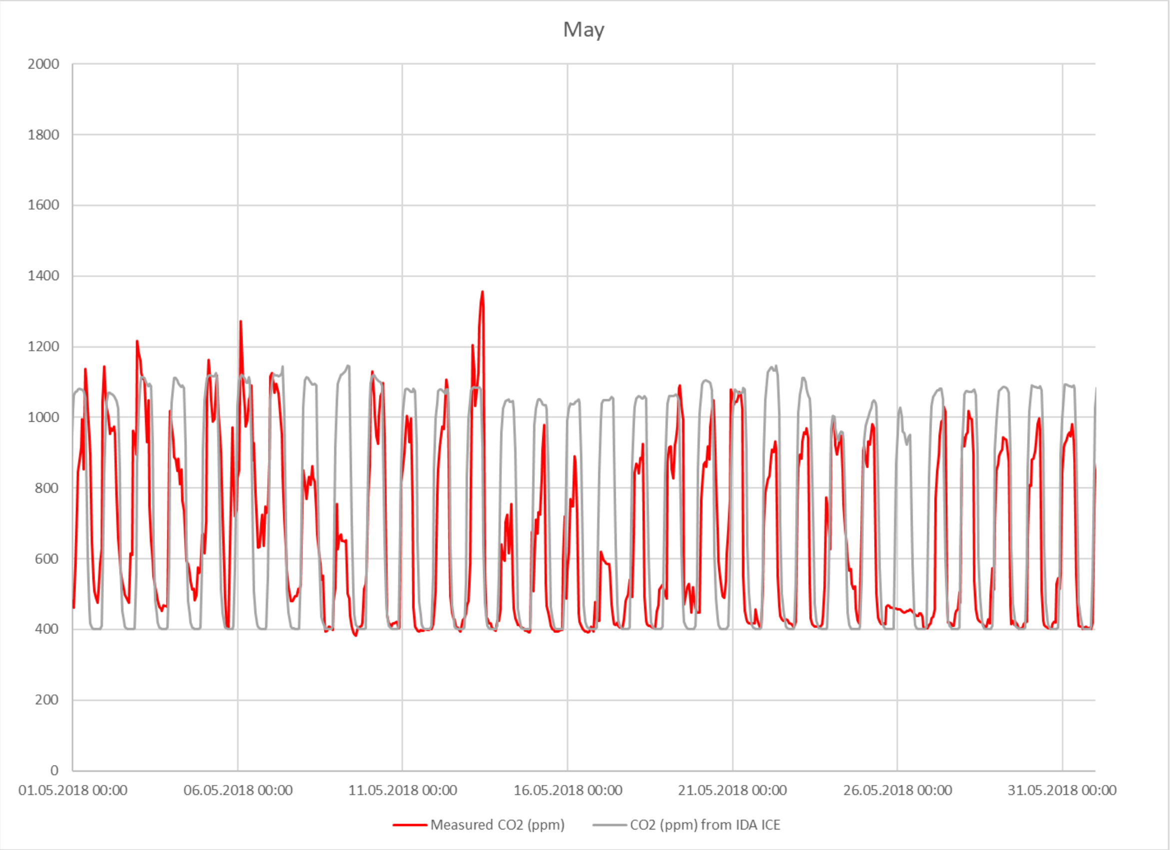


## Appendix 2. Measured and modelled CO2 concentration in Närpio house March 2018 and April 2018

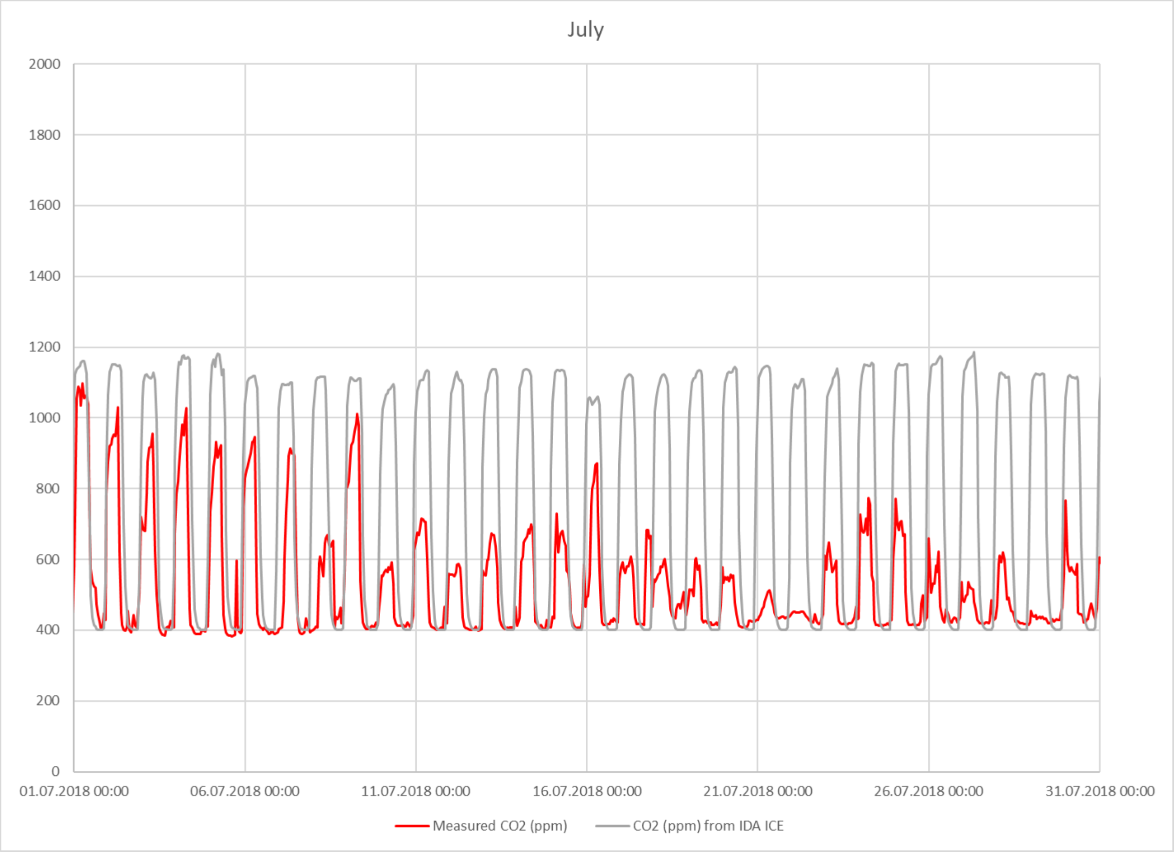


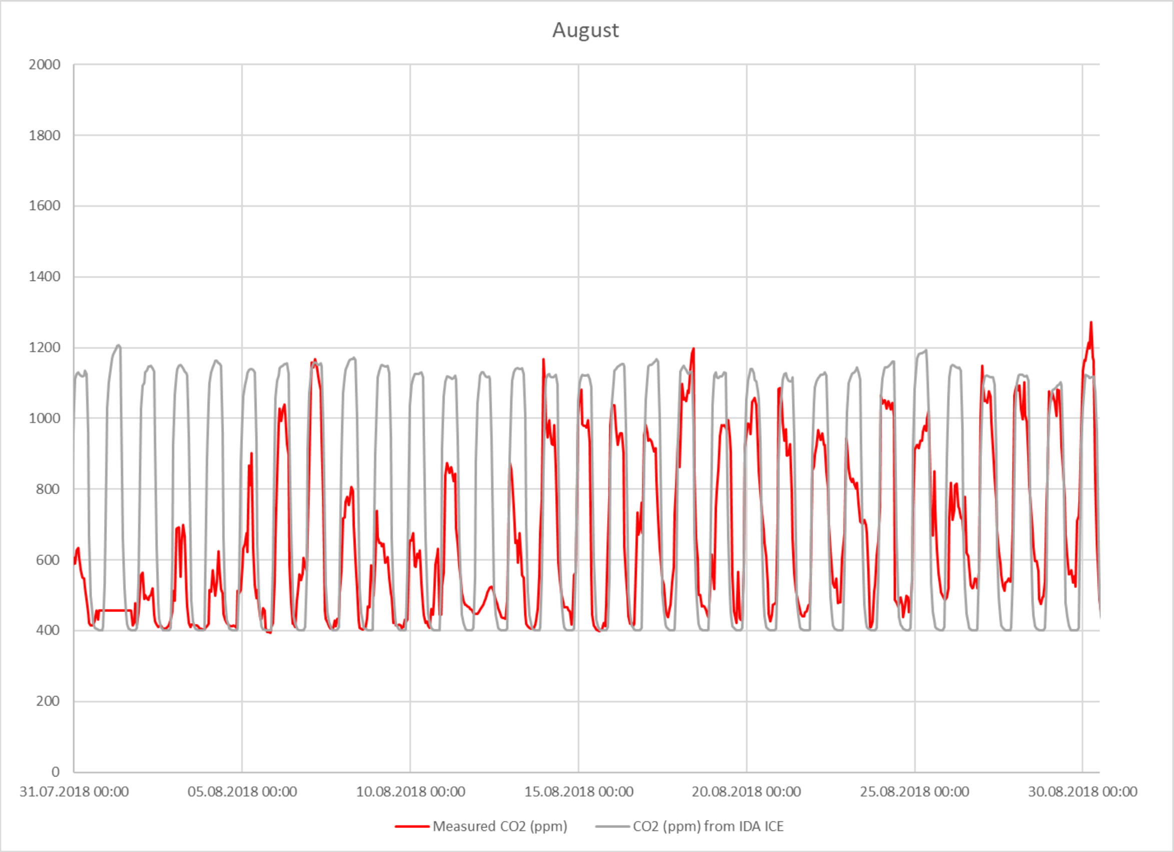


# Appendix 2. Measured and modelled CO2 concentration in Närpio house May 2018 and June 2018

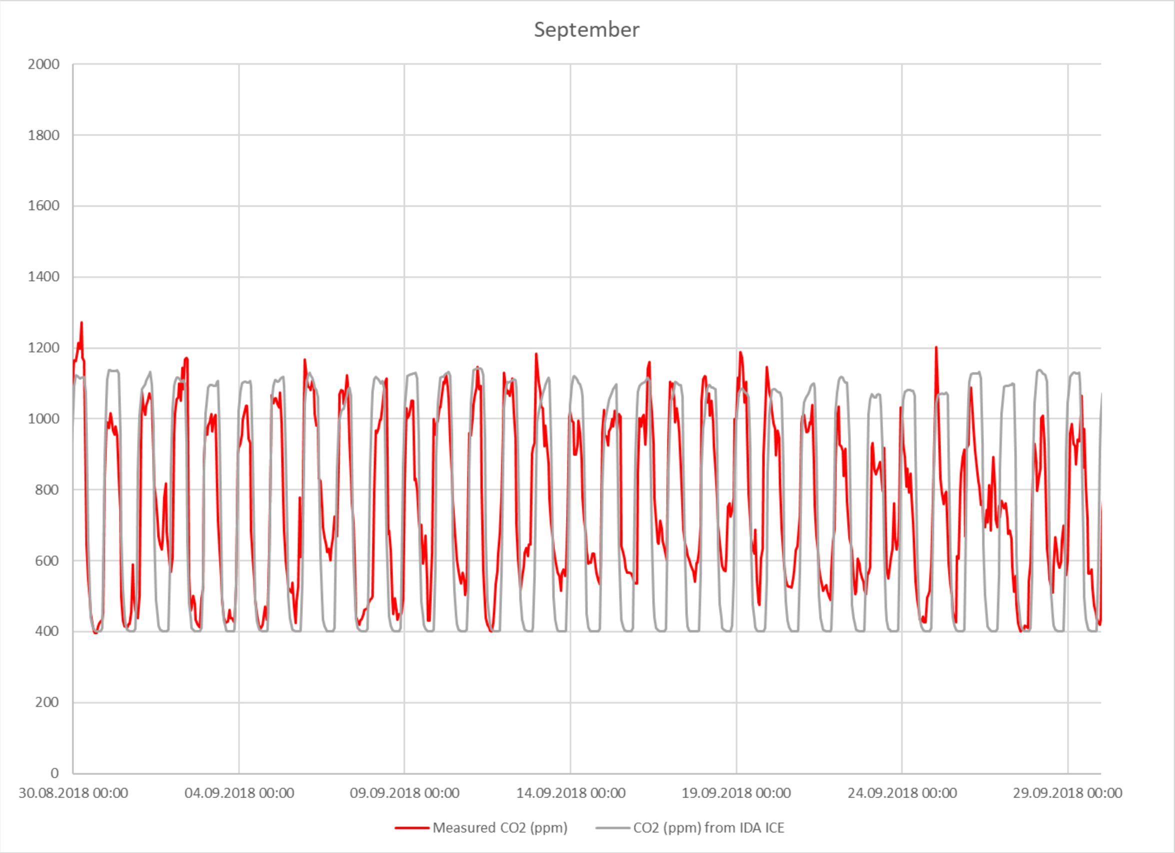


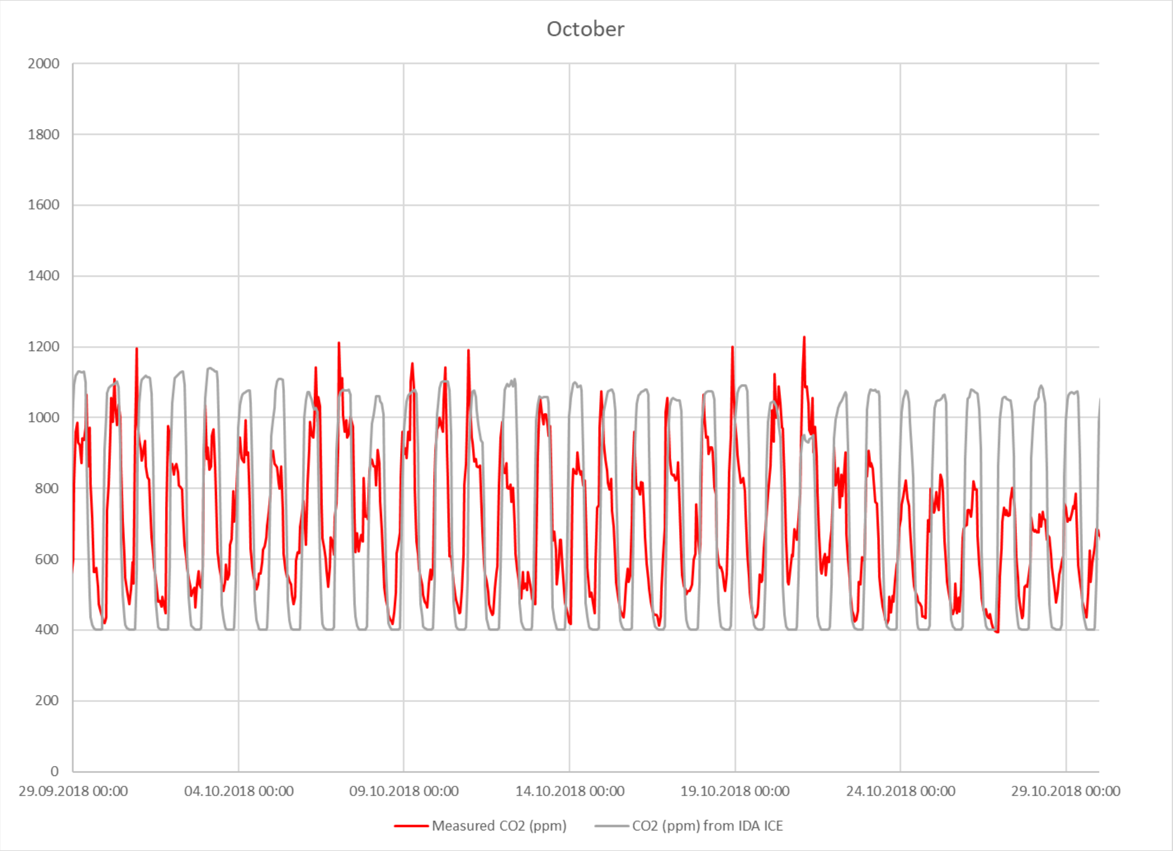
# Appendix 2. Measured and modelled CO2 concentration in Närpio house July 2018 and August 2018





# Appendix 2. Measured and modelled CO2 concentration in Närpio house September 2018 and October 2018





## Appendix 2. Measured and modelled CO2 concentration in Närpio house November 2018 and December 2018