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## Description of the passive air supply system based on ventilation windows supported by chimneys

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Rimante Andrasiunaite Cox  
Technical Report

Department of Civil Engineering  
Technical University of Denmark  
2015

## **Description of the passive air supply system based on ventilation windows supported by chimneys**

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## **Abstract**

Most historical buildings were originally designed with passive ventilation systems, which are often forgotten, not in-use, or are now used in a non-passive manner. In this report we investigate a passive ventilation solution for historical buildings based on a ventilation window supported by chimneys, where the air supply is provided through the ventilation window and the air is naturally extracted through the existing chimneys.

An advanced natural ventilation system in existing double skin windows has been installed in a historical case study building using the original features of the building. The passive natural ventilation is automatically controlled by internal and external top openings supported by passively extracted air through the chimneys. The building was designed as a residential building in 1920, but now used as a day care centre for children between 0.6-2.8 years. We investigated three ventilation strategies during the moderate period of the year:

- Experiment 1 – pulse ventilation
- Experiment 2 – stream ventilation
- Experiment 3 - ventilation window

The CO<sub>2</sub> produced by the occupants was chosen as the trace gas to estimate the air exchange in the building with its conduits for ventilation such as windows and chimneys. The air quality and thermal comfort of the building have been investigated based on:

- (i) Automatic recordings of CO<sub>2</sub> meters installed in every zone provided by the supplier of the system;
- (ii) External temperature, internal temperature, wind speed and wind direction around the building during the investigated periods, recorded by the supplier of the system
- (iii) CO<sub>2</sub> and temperature readings in the ventilation windows and chimneys installed during the periods of the investigation
- (iv) Air change was estimated based on the CO<sub>2</sub> readings and the number of occupants, where the occupants were recorded entering and leaving the room for longer than 15 min.

The results of our investigation showed that the proposed ventilation system “as installed” was not sufficient to provide required ventilation to the upper floor and requires modification. A modification of the system was proposed, but not tested.

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## 1 Introduction

As part of the collaboration with Gentofte Municipality, villa Bagatelle was chosen as a case study building, which is a historical building from 1920. The building was built as a residential building, but now is used as daycare center for children between 0.6 -2.8 years. The daycare center was established in 2011 and with the change of use of the building, the council required documentation that the building provides the required ventilation rates to the occupants. The municipality was planning to install a mechanical ventilation system in the building. However, due to the historical value of the building, the client (Gentofte Municipality) wanted to investigate other options that did not require the installation of central mechanical ventilation and mechanical ventilation and system, nor changing internal or external appearance of the building.

From the perspective of my research, the building was interesting as a case study building to study the alternative ways to ventilate a building by passive means. Most historical buildings have been designed with natural ventilation, which are often not in used. The building offered an opportunity to evaluate whether passive advance ventilation could be used as an option to provide fresh air to historical buildings without using electricity to move air around the building and without creating drafts for the occupants.

There are three main purposes of the study: (i) to investigate whether our solution provides sufficient fresh air to the occupants of the building without creating drafts for the occupants, (ii) whether air supply is provided through the “ventilation window” and extracted through the chimneys, as assumed, and (iii) how the system works in a real building during usage.

This report consist of following sections: section 2 describes the building before renovation and after renovation, section 3 describes the methods of analysis of the building during 3 periods with 3 different strategies, section 4 describes how the building behaves compared with proposed strategies and section 5 discusses the results and conclusion as well suggestions for future work.

## 2 Background

This section describes the building and its usage as well as the installed ventilation system.

### 2.1 Description of the building

The case study building is a 2-story building with unheated basement and unheated attic spaces. The building is heated by district heating with a heated area of 279 m<sup>2</sup> and a total area of 571m<sup>2</sup>. Before the renovation, the building was naturally ventilated, except for the bathrooms, which had mechanical extracts. In 2009 the building was upgraded by adding 300 mm of insulation between the 1<sup>st</sup> floor and the unheated attic. The U-value of such a construction is typically 0.13 W/m<sup>2</sup>K. The cavities of the external facades on the ground floor and 1<sup>st</sup> floor

were insulated with 170mm and 130mm of cavity insulation respectively. The U-values of such constructions are typically 0.16 W/m<sup>2</sup>K and 0.21 W/m<sup>2</sup>K respectively. The original wood framed windows had secondary glazing placed 120mm from the external window frames (4x120x4). The U-value of such a construction is typically 2.8W/m<sup>2</sup>K.

As the building was upgraded in 2009 with improved thermal efficiency of the external and internal wall, we first investigated the indoor thermal comfort of the building.

To be able to assess indoor air quality and thermal comfort of the building, the building was investigated by (i) measuring the internal temperature during the coldest period of the year, February 2012, (ii) determining infiltration by carrying out a blower door test and (iii) calculation of the building's ventilation requirements. Based on the measurements and the actual energy usage, the energy rating was calculated (iv) to energy performance class "F". The results of this investigation can be found in (R.A.Cox, 2012).

Even though the energy efficiency of the building was upgraded in 2009, the annual energy usage for the building was still high 83.000kWh/year or 387kWh/m<sup>2</sup>. The major problem for the building was the high infiltration rates, estimated at 1.68 ach during normal conditions (4Pa calculated) or 7.88 ach or 6.42 l/s/m<sup>2</sup> under 50 Pa pressure, which was measured with a blower door test before the renovation. The infiltration mostly occurred around the windows and doors.

Based on the measurements we proposed improving the windows' thermal efficiency to reduce leakage and to establish a passive ventilation system that would not change the appearance of the building neither internally no externally.

## **2.2 Occupancy of the building**

The building is used as daycare center for children between 0.6 -2.8 years. The building is a 2-storey building. On the ground floor there is a support daycare center occupied by up to 6 adults and a variable number of children (up to 25 children). During normal working hours from 7AM to 5PM the ground floor is occupied in zones 1-3, as shown on Figure 1. The parents arrive through the door on the east side of the building and deliver their children to the teachers in Zone 1. The arrival of the children is between 7-9AM. The children with their teachers are playing in Zone 1 and 2. Zone 3 is mostly used as an eating area, with all occupants gathering for lunch at 11-11.30AM. The other intermediate eating periods such as morning snack between 8.30-9AM and afternoon snack 14-14.30 AM vary in the number of occupants due to the nature of delivery and pick up of the children. Most children have an afternoon nap outside from 12-14AM. The parents collect their children between 14-17PM.

Zone 1, 2 and 3 have double doors between the rooms which are always open and the occupants move between these spaces, as shown in Figure 1. The children are taken to the afternoon nap through the terrace door 1, which is also

used to ventilate the space during that time. The door between zone 2 and the staircase is also partly open.

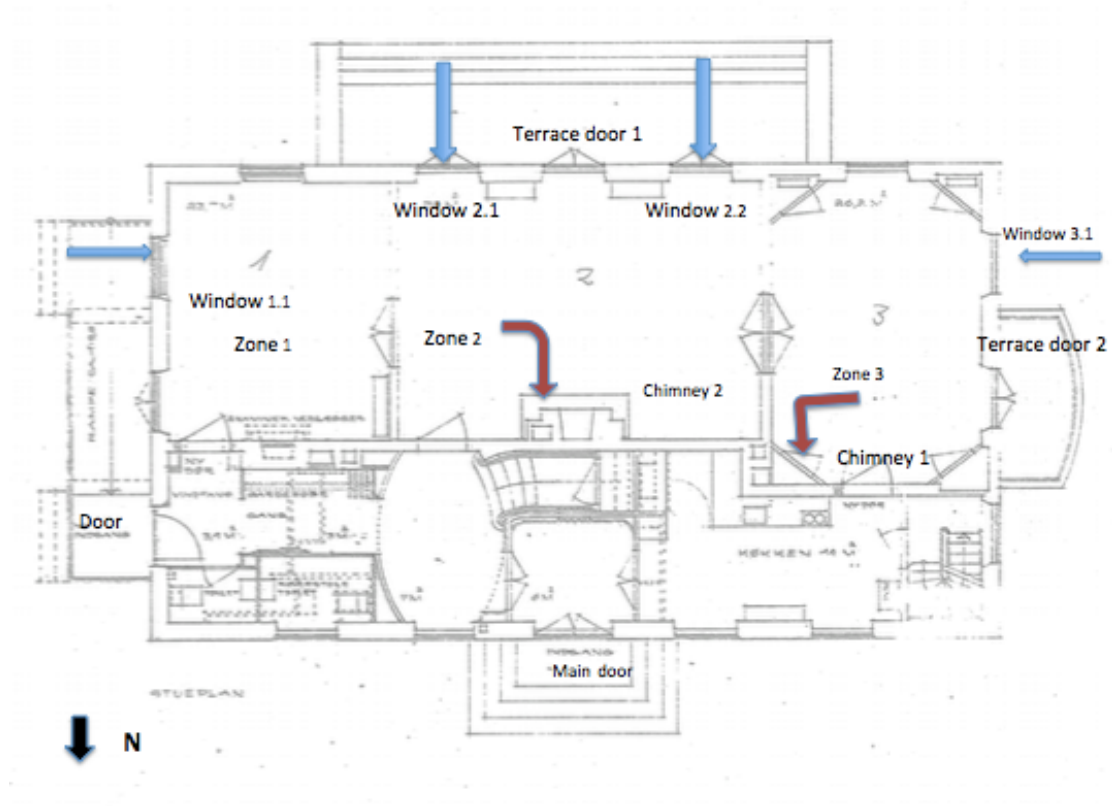


Figure 1 Diagram showing location of the windows and zones on the ground floor and assumed air movements through the window openings and chimneys.

Zone 4 and zone 5 on the 1<sup>st</sup> floor, as shown in Figure 2, are used as the daycare playroom area, where the local childminders with their children meet and spend the day together. The first floor is occupied with different adults and children nearly every weekday, with a maximum number of 5 adults and 15 children. Similar to the ground floor, the occupancy is between 7AM-5PM. Depending on the weather, the occupants spent some morning hours or afternoon hours outside on the playground. Some of the children have an afternoon nap between 12-14PM outside and some inside in Zone 5. During occupancy Zone 4 is used as a playing and eating area.

The door to the stairs is closed most of the time. Zone 6 is used as an office and a meeting room. The number of occupants in the office is mostly 1 or 2, but can be 4-5 during a meeting.



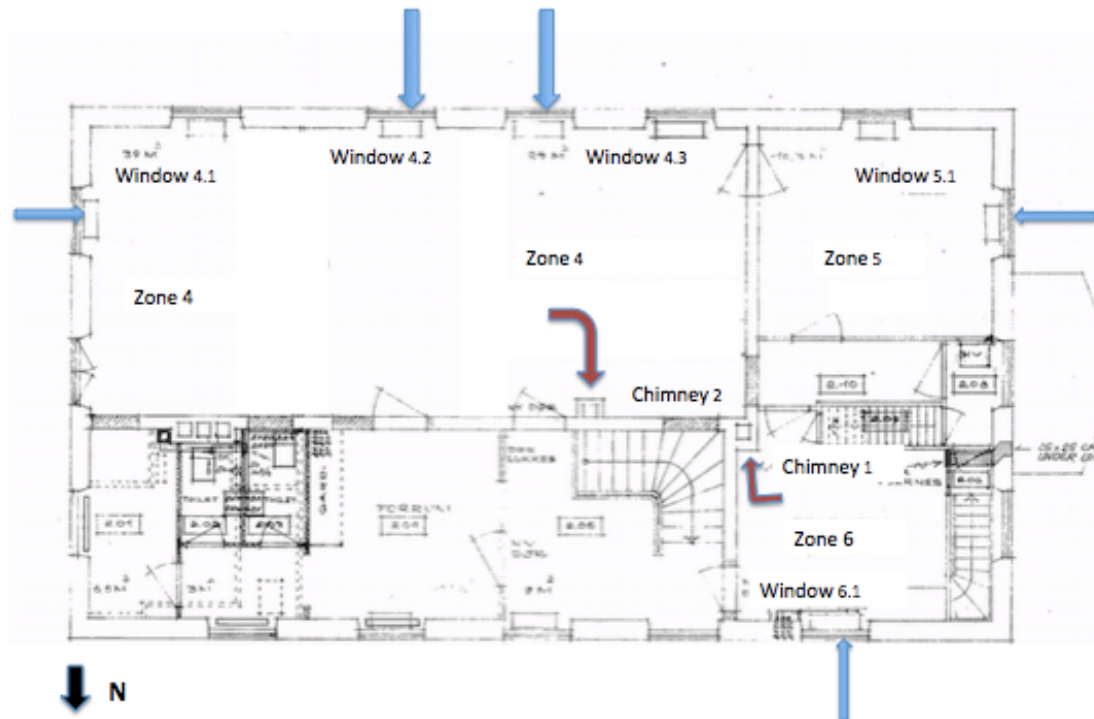


Figure 2 Diagram showing the location of the windows and zones on the 1<sup>st</sup> floor and assumed air movements through the window openings and chimneys.

### 2.3 Proposed passive ventilation system

Based on the measurements and the building construction documentation, a dynamic simulation model of the building was created in TAS, which predicted very similar results to the actual energy usage. The model was used for further investigation to evaluate possible thermal improvements to the building and to propose passive ventilation strategies for the building (R.A.Cox, 2012).

As the blower door test result showed that the air leakage around the windows provided a sufficient air amount at 1.68 ach during normal conditions (4Pa calculated) and it was higher than the calculated ventilation requirement of 1.4ach on the ground floor and 1.1 on the 1<sup>st</sup> floor, we decided to ventilate the building with “controlled” infiltration.

In our simulation we assumed that the air leakage of the external frame provided enough air to the gap when the external temperature was below 5°C and only internal top windows were opening during the occupancy to provide ventilation, which we assumed to be equal to the measured infiltration before the renovation. When the external temperature was above 5°C, the external windows started to open (R.A.Cox, 2012, pp. 29-30). During no occupancy all internal windows and the chimneys were closed with very little infiltration, which is the reason for calling such system a “controlled infiltration”. We assumed that the natural infiltration was reduced to 0.07 ach at 4Pa (normal conditions), when all windows were closed.

The “controlled infiltration” was achieved by improving the leakage and thermal efficiency of the windows. As the existing windows in the building were double skin windows, it was proposed to install a natural ventilation system, where the

supply air is provided through “ventilation windows” supported by the existing chimney as shown in Figure 3.

A “ventilation window” typically consists of an external and internal frame with an air gap in between. In such windows the air supply is provided through the lower part of the external frame. The air is then preheated as it moves up the gap between the external and internal glazing. This upward motion is driven by the stack effect. The preheated air then enters the building through the opening at the top of the internal frame.

The performance of ventilation window has been investigated by McEvoy et al 2003, who conducted a study investigating the effect of the cavity width, ventilation rate in the window gap as well as the position of the low –E coating on the glazing, (M.E.McEvoy, 2003), by Diomidov et al 2002 who investigated the performance of ventilation window to increase the inner pane temperature (Diomidov M.V., 2002), by Carlos et al 2010, who investigated preheating effect of ventilation window for the windows with different positions of the triple glazing, (Carlos J.S., 2010) and (Kalyanova O., 2009), who investigated how to measure air flow rate in a naturally double skin façade. All these studies have been conducted in control environment. In this report we investigate performance of ventilation window in a natural environment, in a case study building which is use.

In our case we assumed that all external frames of ventilation window are leaky (1mm around the perimeter of the window frame) and can provide the required air to the building during the cold periods of the year. Our assumption was based on the blower door test described in (R.A.Cox, 2012). During moderate periods additional air supply should be provided by opening the external windows as well.

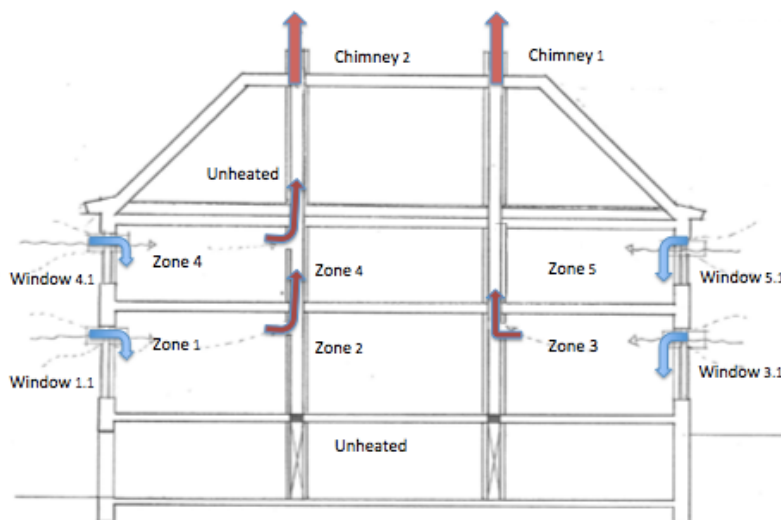


Figure 3 Diagram showing the fresh air supply through the window and extracts from the chimneys

The installed passive ventilation system is assumed to provide fresh air through 9 ventilation windows shown in Figure 1, 2 and 3, and passively extracted by the

chimneys 1 and 2. The windows located closest to the chimneys, such as windows 2.1, 2.2 and 3.1 on the ground floor and 4.2, 4.3 and 6.1 on the first floor, were assumed to work as air sources, and chimneys 1 and 2 as extractors. The window 1.1 (Figure 1) on the ground floor on the east façade, as well as window 5.1 (Figure 2) on the west façade were assumed to work both as supply and extract due to their distance from the chimneys.

As dynamic simulation programs cannot easily simulate these “ventilation windows”, we decided to investigate the air movements in the building using CO<sub>2</sub> produced by the occupants as the trace gas.

The investigation of the thermal improvements and ventilation strategies are described in the report (R.A.Cox, 2012), which was used for obtaining building permit to the natural ventilation in the property. Even though there was uncertainty as to whether the system can provide sufficient airflow to the building, the client and the building council accepted the proposal described below. The building was upgraded in 2013 based on the proposal.

#### 2.4 Installed passive ventilation system

We proposed to reduce the building’s leakage by sealing the windows and doors, and improve the thermal performance of the windows in all occupied spaces. This was achieved by adding a 3<sup>rd</sup> layer of K-coated glazing on the inner frame (Figure 4), which sealed the inner window frame and improved the U-value to 0.8 W/m<sup>2</sup>K as shown in Figure 2. Adding the 3<sup>rd</sup> layer glass did not visually changed the internal or external look of the building.

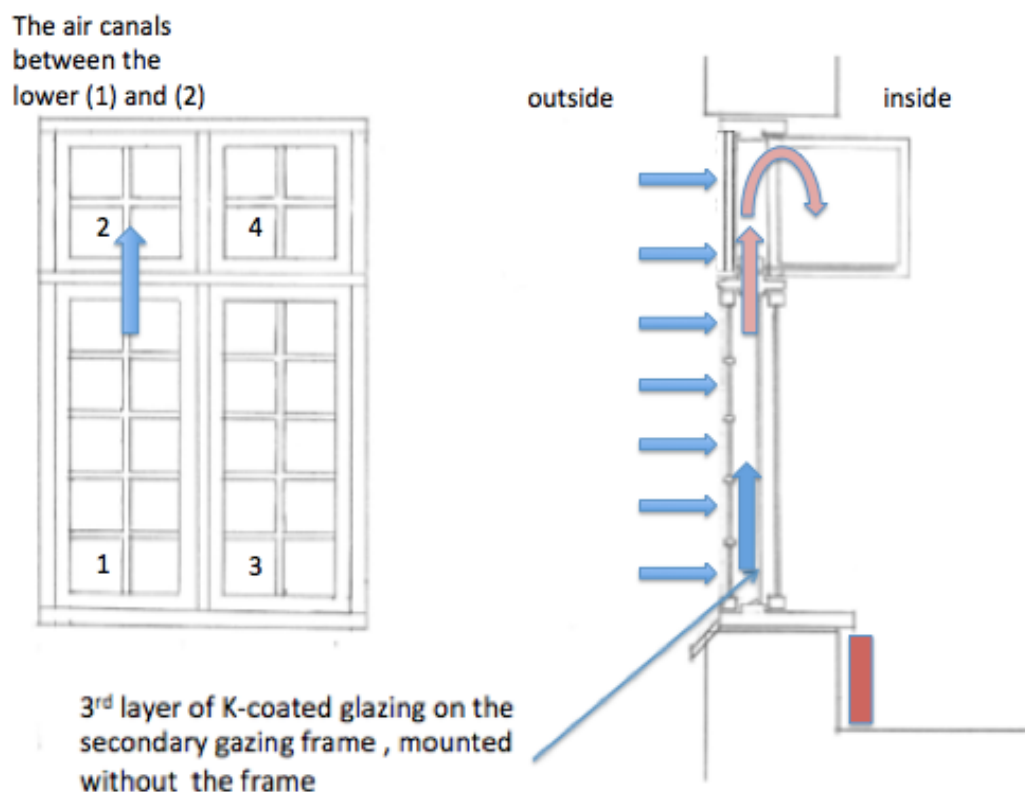


Figure 4 Diagram showing the incoming air during the coldest periods of the air (winter)

During the coldest period of the year the external frames (2) were closed and the internal frame (2) was open as shown in Figure 4. It was assumed that the external frame had leakage through a 1mm gap around the perimeter of the frame (1 and 2). The canals between the lower parts (1) and top parts (2) of the windows in the middle frames were established to ensure that the incoming fresh air through the natural leakage of the external frame of both part (1) and part (2) were working as supply air canals. The canals between part (1) and (2) also allow the air in the gap to move upwards due to the preheating effect of solar radiation or the escaping heat loss from the window, and enter the room slightly warmer than the external temperature. The parts (3) and (4) were not connected to parts (1) and (2) and are therefore not currently used for ventilation.

The openings of the windows, as well as the dampers in chimneys were controlled automatically. Even though the system was automatically controlled by opening and closing the windows, the air movements were only driven by passive means, such as buoyancy-driven or wind driven.

As the air leakage of the external frame depends on the temperature difference between inside and outside, the air to the building was proposed to be provided according to 4 strategies, depending on the external temperature:

- (i) Cold (winter), where the external temperature is below 5°C (and shown in Figure 3),
- (ii) Moderate where the external temperature is between 5-12°C and shown in the Figure 1,
- (iii) Warm (summer) where the external temperature 12-25°C,
- (iv) Hot (heat wave) when the external temperature is between 25-32°C.

During strategies (ii), (iii) and (iv), the external windows must be partly open during the occupancy and the airflow should be controlled by the degree of opening of the internal windows.

In this report we only tested the moderate period - strategy (ii), where the temperature is between 5-12°C. This period is most complicated, because of the difficulty to determine degree of the opening of the windows. If the windows will be open too much the airflow will be sufficient, but the comfort for the occupants will be compromised as well as increased heat losses. However if the windows will be open for shorter period or with limited area of the windows opening the airflow cannot be sufficient. To determine which way of opening of the windows is most sufficient we investigated three opening of the windows strategies.

### 3 Methodology

To be able to determine whether the proposed system provides enough fresh air into the building, we measured the air quality of the building during the moderate period (5-12°C) of the year with 3 different windows opening strategies:

- (i) **pulse ventilation**, - Experiment 1;

- (ii) **stream ventilation** – Experiment 2;
- (iii) **ventilation window**, –Experiment 3.

### 3.1 Measuring the air flow

Measuring passive ventilation airflow through the windows in a natural environment is complicated, because of the stochastic nature of wind, low airflow and non-uniform and dynamic flow conditions.

As the incoming air is only driven by buoyancy-driven or wind driven sources, we had a challenge not only to calculate, but also to measure the air flows in the windows or even in the chimneys, because the air flows are very low (0-0.5 m/s and were difficult to measure with equipment usually used for mechanical ventilation systems. Another challenge was to investigate the natural ventilation system in a natural environment as the measurements were taken during normal occupancy, which also restricted the choice of gases used in the experiments. The third challenge was that occupancy not only varied from hour to hour but also between the zones.

The most common ways of measuring airflow in an opening are (i) the trace gas method, or (ii) measuring the velocity profiles in an opening and calculating the airflow from these measurements (Kalyanova O., 2009).

As the airflow velocity method was not possible in the case study building, the CO<sub>2</sub> produced by the occupants was chosen as the trace gas in the experiments. We conducted a set of experiments to examine the air quality and how the air is moving in the building.

### 3.2 Air quality based on the CO<sub>2</sub> concentration in the rooms

For experiments 1-3, the air quality (CO<sub>2</sub> concentration), external temperature and internal temperature on the ground floor and the 1<sup>st</sup> floor were automatically recorded by Windows Master in 1 hour or 10 min intervals. Windows Masters is the company who provided and installed the automatically controlled windows opening system in the building. The external temperature and wind velocity as well as wind speed were recorded by the local weather station on the roof of the building. Internal temperature, relative humidity and CO<sub>2</sub> concentration were automatically recorded by the meters installed in each zone, which were also used to control the opening of the windows by the Windows Masters system. The occupants were able to overrule manually the windows opening in each zone. Figure 5 and 6 shows the location of the automatically recorded meters as well as the ventilation windows.

To investigate the air quality of the rooms, the CO<sub>2</sub> concentration was compared with the number of occupants, where the occupants were recorded entering and leaving the room for longer than 15 min.

The infiltration during no occupancy was calculated using the mass balance theory decay case, where the  $C_t$  was used as the CO<sub>2</sub> concentration at 5PM, when the occupants leave the building, and the  $C_o$  was used as the CO<sub>2</sub> concentration at 12AM.

The CO<sub>2</sub> concentration  $C(t)$  was calculated using the mass balance theory, build-up case during one hour period (11-12PM), where the number of occupants was most stable. To calculate the CO<sub>2</sub> concentration produced by the occupants, it was assumed that the average female height was 1.70m and weight 70 kg with an activity (MET) of 1.4. It was further assumed that the average child weighed 10 kg and was 0.9 m in height, with an activity of (MET) 1.4. The calculation was performed in Excel. Figure 5 shows an example of the calculation sheet.

To be able to use the balance theory the assumption was made that the air in the zones where well mixed and only had the interaction with the outside, but not with the other zones in the building.

				corrected by outdoor CO2 conc. 400pp	
$n=G/(CxV)$			C=	993.6666667	593.6666667
			G=	110.5	110499 mL/h
ACH=	0.707715339		V=	263	
			C(t)=G/nV*(1-e <sup>-nt</sup> )	599.4691905	
Occupant	Weight (kg)	Height (cm)	Activity (MET)	CO2 emission	
1	70	170	1.4	21.8	
2	70	170	1.4	21.8	
3	70	170	1.4	21.8	
4	70	170	1.4	21.8	
5	70	170	1.4	21.8	
6	10	0.9	1.4	0.2	
7	10	0.9	1.4	0.2	
8	10	0.9	1.4	0.2	
9	10	0.9	1.4	0.2	
10	10	0.9	1.4	0.2	
11	10	0.9	1.4	0.2	
12	10	0.9	1.4	0.2	
13	0	0.9	1.4	0.0	
14	0	0.9	1.4	0.0	
15	0	0.9	1.4	0.0	
16	0	0.9	1.4	0.0	
<b>Total</b>				<b>110.5</b>	
<b>Room volume</b>				<b>263</b>	

Figure 5 Calculation of the CO<sub>2</sub> production by occupants

The 3 rooms on the ground floor are connected with openings in between, and users move free between the spaces. Therefore the average of CO<sub>2</sub> was calculated of the three zones, with the common volume of the room of 263m<sup>3</sup>.

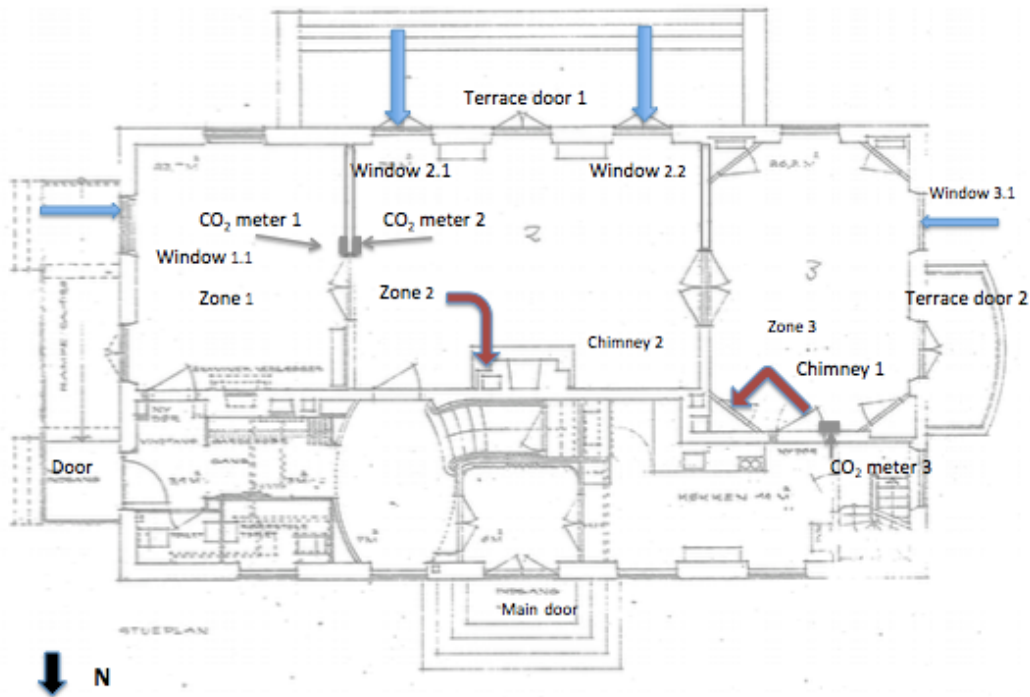


Figure 6 The grey arrows show the location of the CO2 meters, automatically recorded by Windows masters on the ground floor

On the 1<sup>st</sup> floor, zone 4 and 5 were also connected with the openings in between. However zone 5 is used mainly as a sleeping area for children during the period of 12 to 2pm, and therefore the air change was calculated for the each zone separately. The volume of zone 4 was 145m<sup>3</sup> and for zone 5 was 36 m<sup>3</sup>.

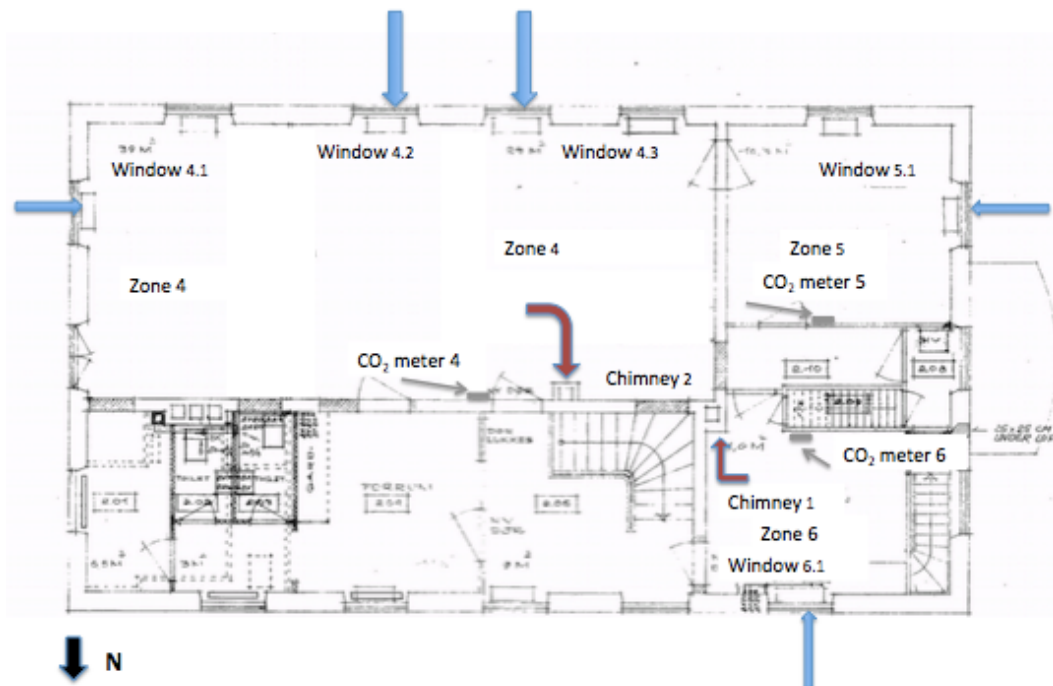


Figure 7 The grey arrows show the location of the CO2 meters, automatically recorded by Windows masters on the first floor

The air quality of the room was considered (i) **good** if the CO<sub>2</sub> concentration did not increase above 1000ppm, (ii) **moderate** when the CO<sub>2</sub> concentration was between 1000-1500ppm, and **bad** if the CO<sub>2</sub> concentration was above 1500ppm.

### 3.3 Analysis of air movements based on additional meters located in the chimneys and ventilation windows

To verify whether the ventilation in the building behaves as predicted using the simplified calculation model described earlier, a set of experiments was carried out in the spring and autumn of 2013.

Automatic recordings of CO<sub>2</sub> levels and internal temperature were not sufficient to show whether the air was coming in through the windows and extracted by the chimneys. Therefore, additional CO<sub>2</sub>, temperature and relative humidity meters were installed in all 9 ventilation windows and chimneys. The locations of the additional meters are shown in Figure 8. On the ground floor two meters were used per window: (i) in the gap of the top of the window where both internal and external openings of the window were located, and (ii) in the gap at the bottom of the window, where there were no openings except from the additionally added holes in the window frame between upper and lower part of the window, as shown earlier in Figure 4 and in Figure 9.

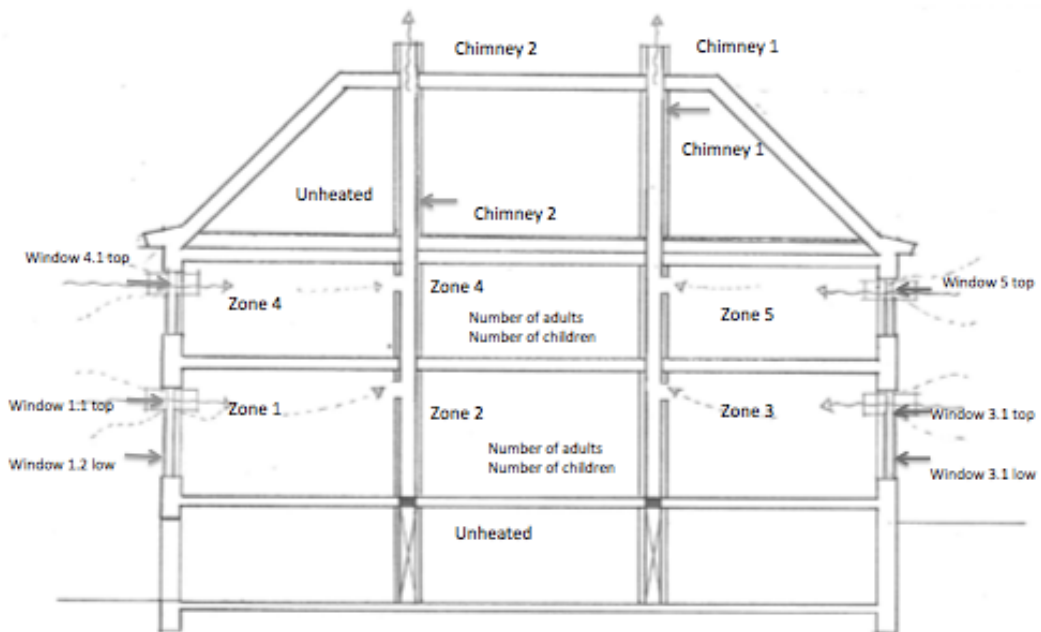


Figure 8 Location of the additional meters installed in all ventilation windows and chimneys during experiments 2 and 3.





Figure 9 Location of the additional meters in the gap between external and internal frame: on the left is the meter located in the top of the window and on the right the meter is located in the bottom of the window.

On the 1<sup>st</sup> floor only one meter was installed in the top of the windows.

### 3.4 Ventilation strategies tested in experiments 1-3

To be able to determine whether the proposed system provides enough fresh air into the building, we measured the air quality of the building during the moderate period of the year with 3 different ventilation strategies:

- (i) where fresh air was provided by **pulse ventilation**, (every hour both external and internal windows are open 30 cm (100% ) for a 6 min period) during the occupancy and closed during no occupancy - Experiment 1;
- (ii) where fresh air was provided by **stream ventilation** through the external windows, which were constantly open 3cm (10%) and the internal windows were open 30 cm (100%) during the occupant hours and closed during no occupancy – Experiment 2;
- (iii) where fresh air was provided by the **ventilation window**, (the external windows are closed and only the leakage of the external windows frames provides the fresh air and the internal windows are open 30 cm (100%) –Experiment 3. During experiment 3 the external windows were open each hour for a 3 min period.

## 4 Results

This chapter describes the set up and results of experiments 1-3.

#### 4.1 Pulse ventilation strategy - Experiment 1

Experiment 1 investigated the pulse ventilation strategy and was conducted during 27 April - 14 May 2013.

##### 4.1.0 Ventilation set up for experiment 1

During the period of the experiment the natural ventilation was automatically controlled by the Windows Masters program. Both top windows (internal and external) in our ventilation windows were opened 30cm, which is determined by the max length of the motor (100%) for 3 minutes every hour.

The measurements were collected at an hourly rate by Windows Masters.

The number of occupants in the building was only counted on the ground floor.

##### 4.1.1 Results of experiment 1

The experiment showed that the air quality on ground floor was good most of the time. During the 16 day period, the CO<sub>2</sub> levels on the ground floor exceeded 1000ppm for a total of 5 hours, on as shown in Figure 10. The CO<sub>2</sub> levels on the first floor exceeded 1000ppm for a total of 14 as shown in Figure 11.

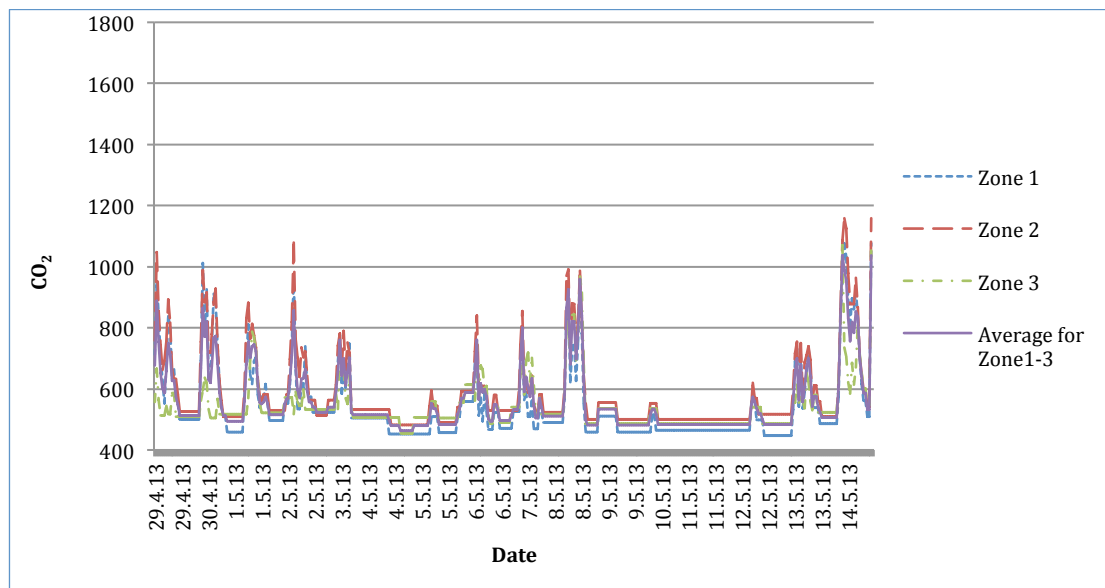


Figure 10 CO<sub>2</sub> concentration on the ground floor during the experiment 1, (27 April - 14 May 2013)

The max CO<sub>2</sub> level on the ground floor were recorded at 1159 ppm in the Zone 2 on the 14 of May 2013 between 10-13.

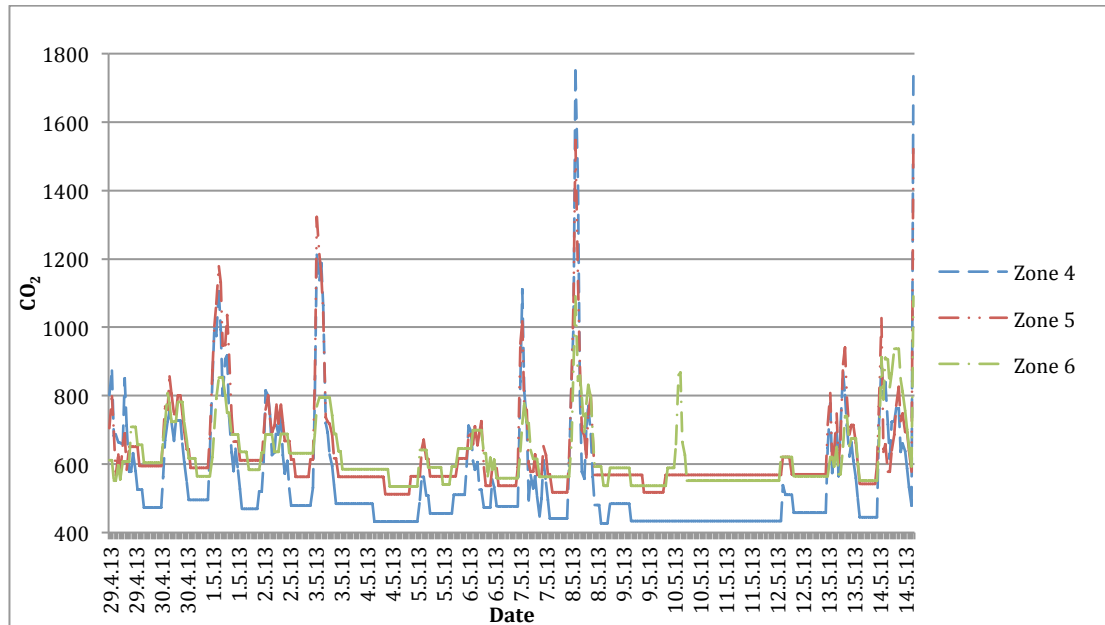


Figure 11 CO<sub>2</sub> concentration on the first floor during the experiment 1 (27April - 14 May 2013)

The max CO<sub>2</sub> level on the 1<sup>st</sup> was recorded at 1751ppm on the 8 of May 2013.

The highest CO<sub>2</sub> levels on the ground floor was recorded on the 14 of May 2013. We therefore investigated in detail the air change per hour during that day.

#### 4.1.1.1 External conditions for experiment 1

The average external temperature on 14 of May between 10-12 am was 10.5°C with the wind speed of 3m/s and an internal temperature of 21.5°C.

The infiltration was calculated during the 7pm-12am on 14 of May. The external temperature was 15-12°C higher in the afternoon and cooling down during the evening, and the wind speed 3-2m/s changing from south west to south east during the evening. The infiltration was calculated using the decay method to be 0.0029 ach/h.

#### 4.1.1.2 Analysis of the concentration of CO<sub>2</sub> in the occupied rooms

The most stable number of the occupants is usually between 11-12am. During this two-hour period there were 7 children and 5 adults in zones 1-3, on the ground floor. It was calculated that the occupants produced a total of 110.5 CO<sub>2</sub> emissions in an hour.

Figure 12 shows the CO<sub>2</sub> concentration on the ground floor during 14 of May 2013.

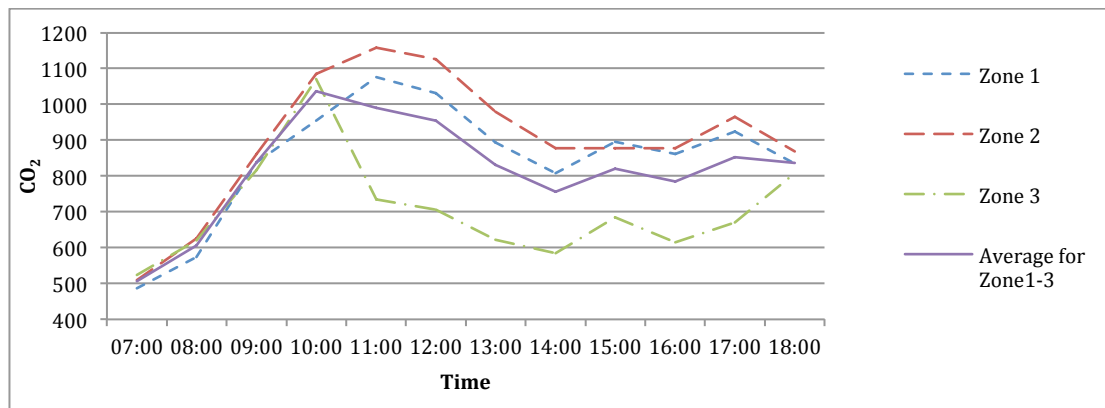


Figure 12 Hourly CO<sub>2</sub> levels on the ground floor 14 May 2013

To be able to keep the CO<sub>2</sub> levels below 1000ppm, the air change should be 0.7 ach. The measured average CO<sub>2</sub> concentration for 1-3 zones was 1103 ppm, which is considered moderate. Using the actual concentration, it was calculated that the actual air change was 0.6 ach, which is lower than required.

#### 4.1.1.3 Summary of the results of Experiment 1

Experiment 1 recorded the average hourly CO<sub>2</sub> concentration in the room and the number of occupants and provided a rough estimate of the air quality in the room.

##### Summary of experiment 1

- (i) Experiment 1 confirmed that the air quality in the room was good most of the time on the ground floor and moderate on the 1<sup>st</sup> floor. However we were not able to estimate whether the ventilation strategy used during experiment 1 had reduced thermal comfort for the occupants by increasing draughts. There was insufficient data to calculate the air change on the 1<sup>st</sup> floor, as the number of occupants was not recorded.
- (ii) The data collected from Windows Masters during experiment 1 were hourly recordings, (an average of CO<sub>2</sub> concentration during 1 hour period). It means that CO<sub>2</sub> concentration could be higher for a shorter period of the time say 10 min, but not recorded and therefore was not sufficient to provide accurate air quality in the rooms.
- (iii) We used a simplified assumption that the room has well mixed air and the air exchange was only to the outside. However, our measurements showed that the air in the three zones is not well mixed as the CO<sub>2</sub> concentration differed from 100 to 250ppm from room to room.
- (iv) In experiment 1 the “ventilation windows” worked as simple windows, where the fresh air passed through the external frame and directly through the secondary frame to the room.

- (v) During experiment 1 we were not able to estimate how the air moved in the room and whether the air was entering from the windows and extracted from the chimneys as predicted.
- (vi) Experiment 1 did not show whether the gap between the windows internal and external frame had any influence on the air quality or the temperature of the incoming air.

## 4.2 Stream ventilation – Experiment 2

To analyze whether the air in the building was indeed entering the room through the top of the ventilation windows and extracted through the chimneys, as shown in Figure 1-3, the **stream ventilation** strategy was investigated in Experiment 2 conducted during the 7 day period of 17 - 25 October 2013.

### 4.2.1 Ventilation set up for experiment 2

During the period of experiment 2 the natural ventilation was set up such that all external ventilation windows were constantly open 3cm (10%) and the internal windows were open 30cm (100%) during occupancy. Only internal windows were manually regulated by occupants. The CO<sub>2</sub> concentration in 10 min intervals was collected from Windows Masters data. The air change was calculated the same way as in experiment 1.

In addition to the CO<sub>2</sub> concentration, temperature and relative humidity in ventilation windows and chimneys were recorded at 1 min intervals.

### 4.2.2 Results of experiment 2

Experiment 2 revealed that the air quality in the building was partly unsatisfactory (above 1000ppm) during the occupancy on the ground floor and worse on the 1<sup>st</sup> floor. During the 4 occupied days the CO<sub>2</sub> levels on both floors exceeded 1000ppm, for 9 hours on the ground floor and for 14 hours on the 1<sup>st</sup> floor. The max CO<sub>2</sub> level on the ground floor was 1409 ppm (for 10 min) and around 1300ppm on the 22 of October between 12-14, as shown in Figure 13.

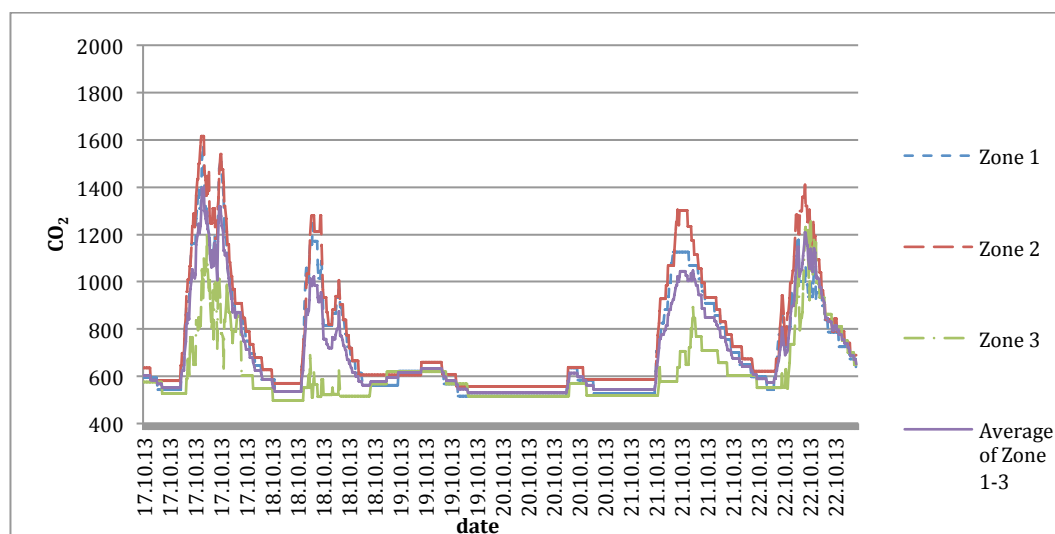


Figure 13 CO<sub>2</sub> concentration on the ground floor during experiment 2 (17 -22 October 2013)

The max CO<sub>2</sub> level on the first floor was 2275 ppm in zone 6 (office) and around 2000ppm for nearly an hour on the 21 of October between 10.30-11.30, as shown in Figure 14. We did not analyse data from the office (zone 6) because the occupants overruled the automatic settings of the ventilation system. The window was closed most of the time during the occupancy.

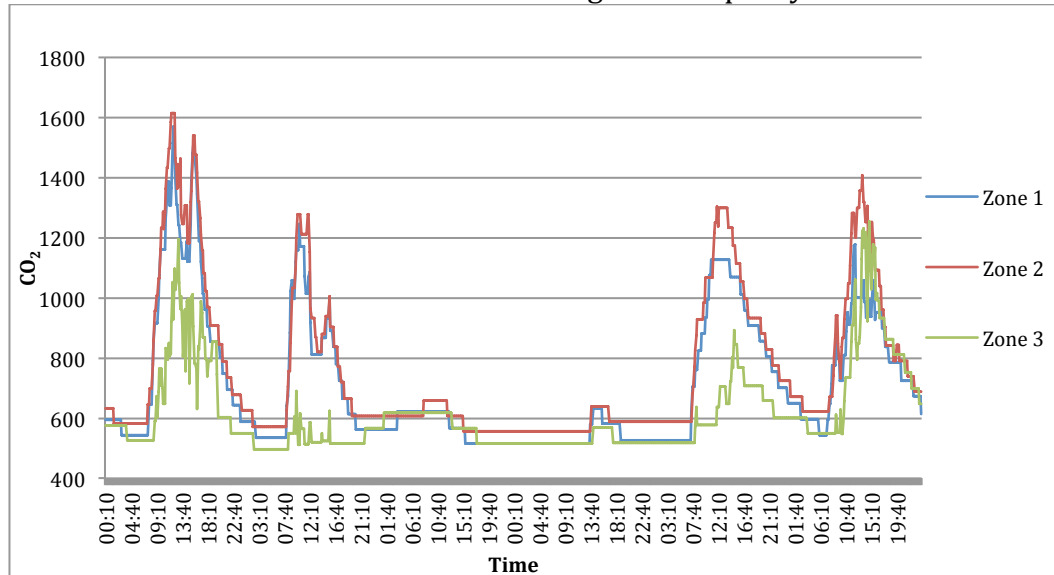


Figure 14 CO<sub>2</sub> concentration on the first floor during experiment 2 (17 -22 October 2013)

The highest recorded CO<sub>2</sub> levels in Zone 4 and 5 were 1852 and 1862 respectively.

#### 4.2.2.1 Analysis of the concentration of CO<sub>2</sub> in the occupied rooms

Only one day, the 21<sup>th</sup> of October, was analysed, because the other days were missing some of the key measurements. For example, the meters in the chimneys were using batteries, which went flat and were not able to record data from the 22<sup>nd</sup> of October 2013. By accident some of the meters were turned off by the occupants. The number of occupants was only recorded from the 21<sup>th</sup> of October 2013.

The measurement results showed that the average quality of the air in the rooms was moderate, where the average of the CO<sub>2</sub> concentration was below 1000 ppm most of the time, as shown in the Figure 15. The highest concentration was recorded in Zone 2, where the extraction to the chimney is placed.

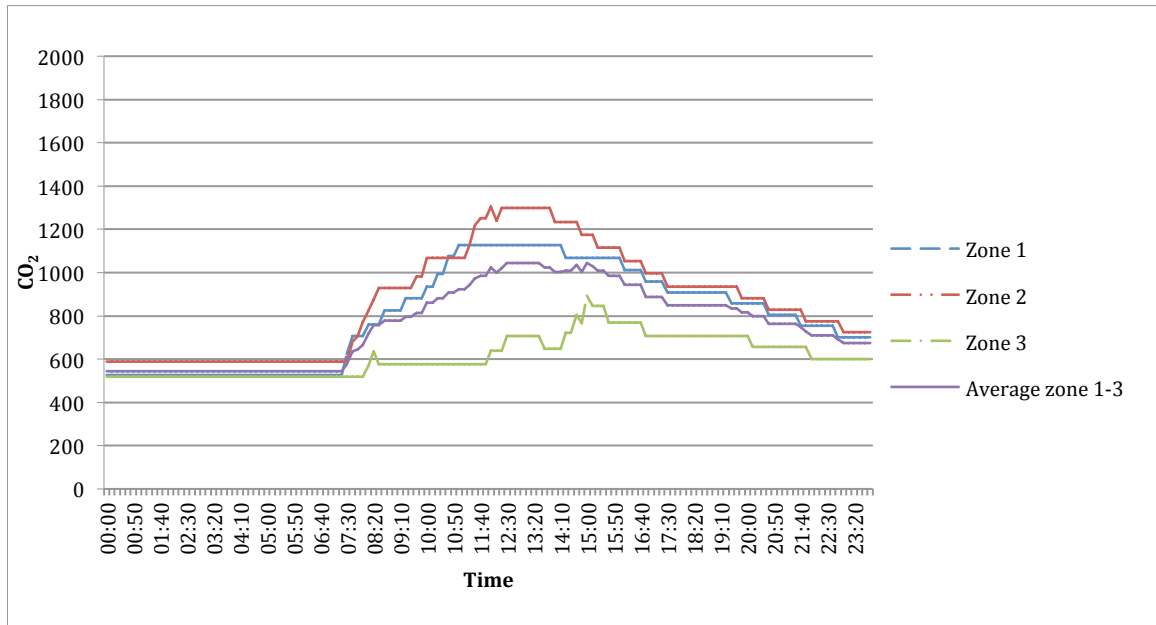


Figure 15 CO<sub>2</sub> concentration on the ground floor during October 21 2013

The room on the 1<sup>st</sup> floor was not occupied during 21th of October. However, the CO<sub>2</sub> concentration was still slightly higher during the occupant period as shown in Figure 16.

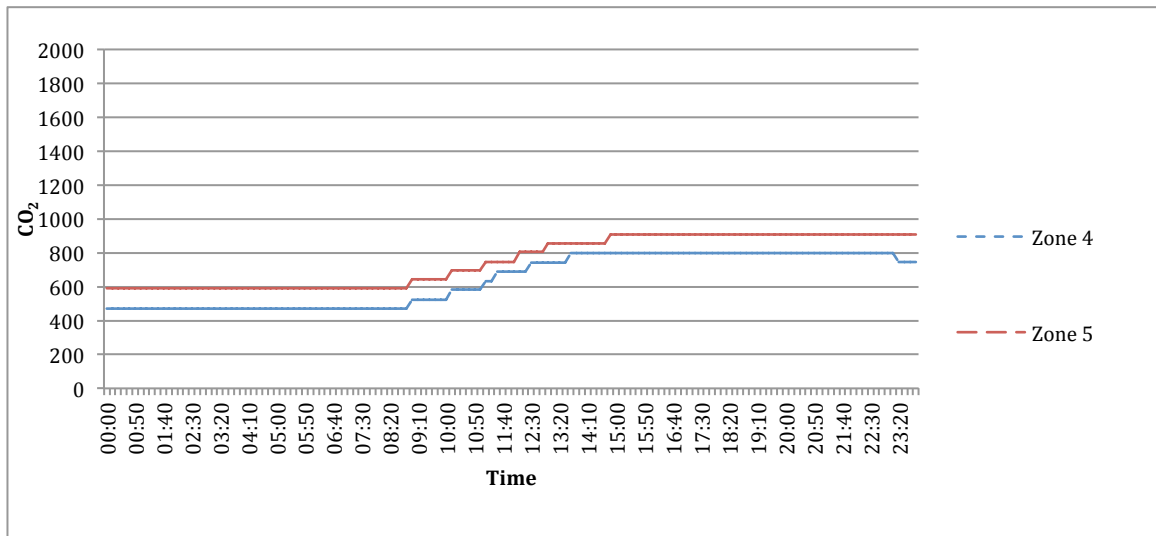


Figure 16 CO<sub>2</sub> concentration on 1st floor on the 21 October 2013

The reason for that could be that the chimney 2 supports both floors and the polluted air from the ground floor escapes not only through the chimney 2 but also entered the 1<sup>st</sup> floor. We noticed a similar case during one visit to the building, where the 1<sup>st</sup> floor was unoccupied and the internal windows were closed. By opening internal windows the CO<sub>2</sub> levels dropped, indicating that the air flow was directed back to the chimney.

The air change per hour is calculated only during October 21, as the data is incomplete for other days. The 1<sup>st</sup> floor was not occupied during that day.

The number of occupants in the building was counted on the ground floor.

During the 1-hour period (11-12PM) there were 2 children and 8 adults in the zone 1-3, on the ground floor. It was calculated that the occupants produce 175 CO<sub>2</sub> emissions in an hour.

To be able to keep the CO<sub>2</sub> levels below 1000ppm, the air change should be a 1.1 ach. The measured average CO<sub>2</sub> concentration for 1-3 zones was 1304 ppm, which is considered moderate. Knowing the actual concentration, I estimated that actual air change is 0.74 ach.

#### ***4.2.2.2 External conditions during experiment 2***

The average external temperature on the 21th of October between 10-12 am was 13.5°C with the wind speed of 1.5 m/s from the south-west direction. The internal temperature was on average 21.5°C during the occupied hours.

The average infiltration  $n$  was calculated to be 0.0013 ach and estimated based on the weather conditions between 17.00 to 24.00 on the 21 of October.

#### ***4.2.2.3 Measurements of the concentration of CO<sub>2</sub> from windows and chimneys***

In this section we present the results of measuring the concentration of CO<sub>2</sub>, and temperature recorded by the additional meters described in section 3.3

The meters installed in the windows and chimneys showed (Figure 17) that the concentration of CO<sub>2</sub> in the chimneys was higher than in the rooms, which indicated that the chimneys were working as extractors. Furthermore, the experiment showed that the windows, which were located closes to the chimney were working constantly as air supply windows, such as in windows 2.1 and 2.2 in zone 2 on the ground floor and 4.3 in zone 4 on the 1<sup>st</sup> floor, as shown in Figure 17 and 18.

The CO<sub>2</sub> concentration at the bottom of the windows on the ground floor hardly varied and was lower than in the top of the window, which indicated that the incoming air did not mixed with the incoming air.



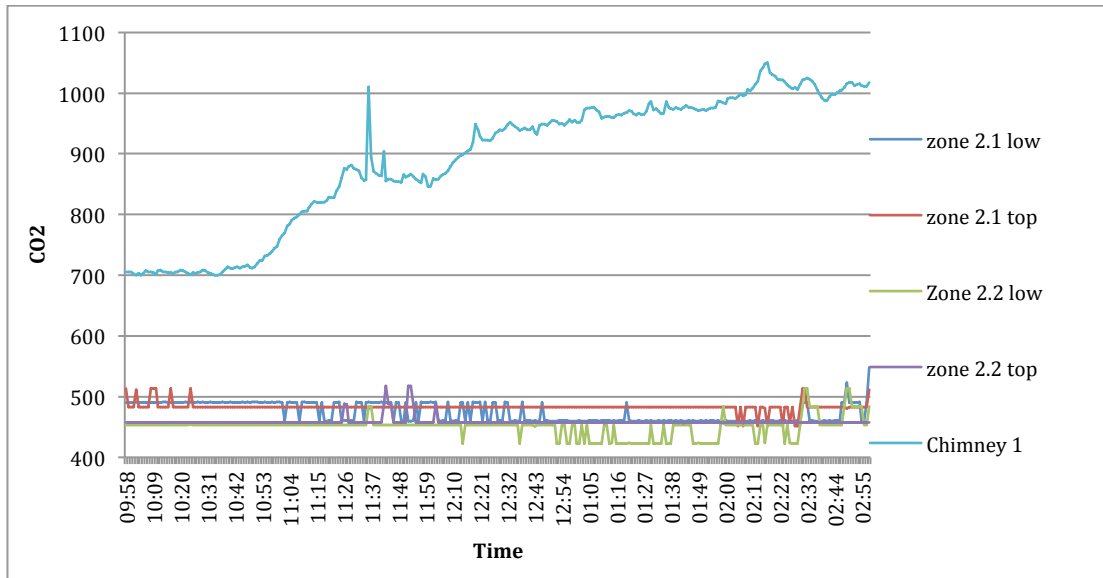


Figure 17 The levels of CO<sub>2</sub> concentration in windows in Zone 2 and in the Chimney 2, which is the closest to the windows openings.

Other windows, which had a longer distance to the chimneys, such as window 1.1 in Zone 1 on the ground floor, window 4.2 in Zone 4 and window 5.1 in Zone 5, (Figure 18), worked as both supply and extract.

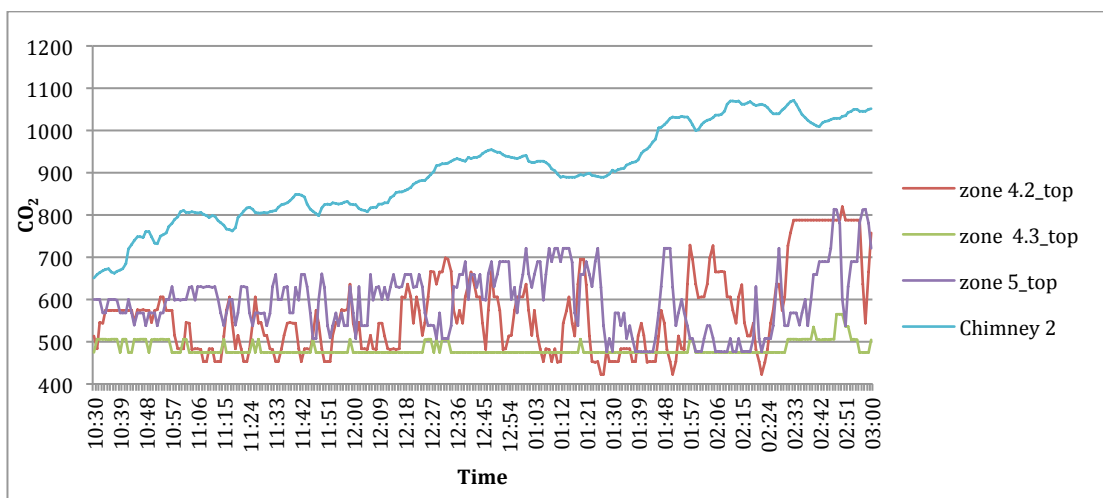


Figure 18 The levels of CO<sub>2</sub> concentration in windows in Zone 4 on the 1<sup>st</sup> floor and in the Chimney 2, which is the closest to the windows openings.

#### 4.2.2.4 Measurements of temperature in windows

The incoming temperature through the ventilation windows was stable and varied from 13 -16°C at the top of the window and was at least 2-3°C warmer at the bottom of the windows (Figure 19). As the temperature difference was so small between the top and the bottom of the window it was not clear whether the incoming air mixed with the air in the gap.

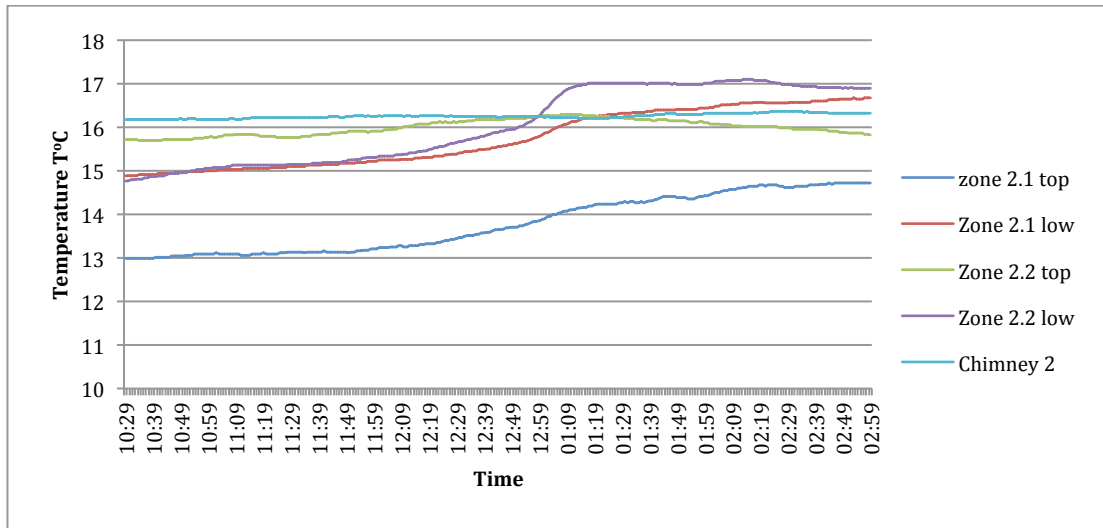
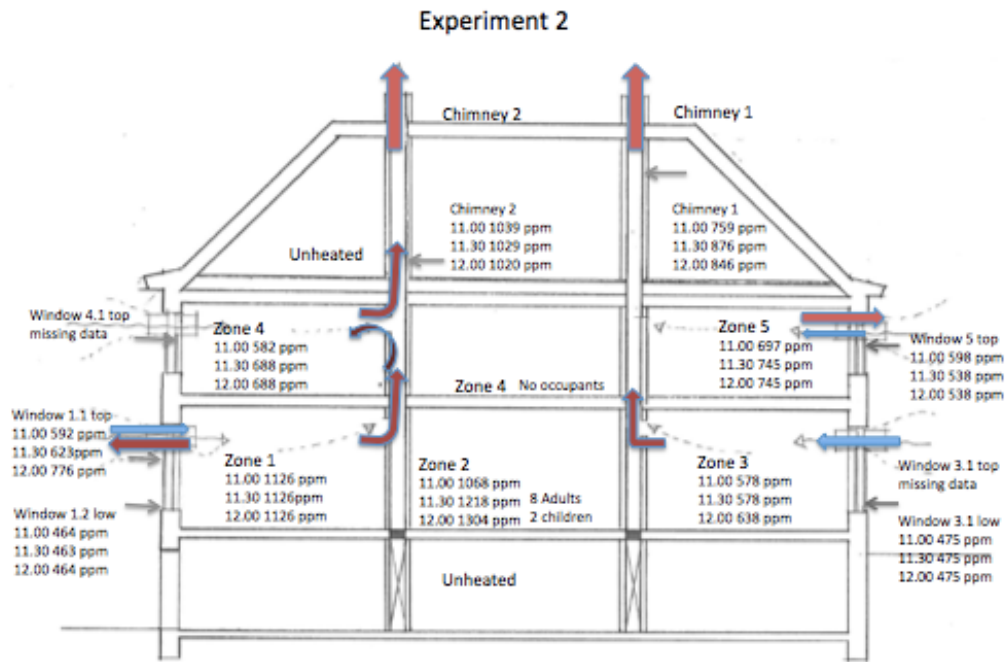


Figure 19 The temperatures in the top and the bottom of the windows in Zone 2, which were working as inlets.

The temperature in the rooms was between 21-23°C during the occupied hours, therefore the incoming air at 13-16°C could possibly create a feeling of draft for the occupants. From the experiment we were not able to determine the temperature of the incoming air.

**4.2.2.5 Summary of the results of experiment 2**

The results are summarised in Figure 20 for the 21<sup>st</sup> of October between 11-12am. During this period the occupants on the ground floor were usually in zone 3 on the ground floor preparing and eating lunch.



**Figure 20 Summary of the experiment 2**

**Summary of the results of experiment 2**

- (i) Experiment 2 recorded CO<sub>2</sub> levels in the rooms at 10 minute time intervals. It provided more detail about the air quality in the room than in experiment 1. The recorded CO<sub>2</sub> levels in the room were moderate or high during the short periods of the time (10min) on the ground floor and bad on the first floor.
- (ii) Knowing the occupancy in the room, it was possible to estimate the air change in the rooms, which was lower than required. The air quality was moderate during the analysed day, 21th of October, but was worse during other days, e.g. Friday the 18<sup>th</sup> of October or Tuesday the 22<sup>nd</sup> of October, but the data to analyse these was partially missing.
- (iii) We used a simplified assumption that the room has well mixed air and the air exchange was only to the outside. However, our measurements showed that the air in 1-3 zones was not well mixed as the CO<sub>2</sub> concentration differed by 100 - 600ppm from room to room. We also noticed that the polluted air from the ground floor was moving through the chimney to unoccupied zone 4 and 5, showing that the air in the building was also mixing with the air between the zones and not only with outside.
- (iv) As the external windows were constantly open, the airflow was sufficient to create a flow through the windows located close to the

chimneys, such as 2.1 and 2.2 (south façade) on the ground floor and 4.2. (south façade) on the 1<sup>st</sup> floor which worked as air supplies, and chimneys 1 and 2 which worked as air extractors. The windows on the east facades 1.1 and west 5.1 worked as both supply and extractor. Although the data was not complete, it was possible to estimate how the air moved in the room and confirm the air was incoming from the windows and was extracted from the chimneys as predicted.

- (v) In experiment 2 the “ventilation windows” worked as simple windows, where the fresh air passed through the external frame and directly through the secondary frame to the room, as the incoming temperature of the air was close to the external temperature (the preheating affect was less then 2-3°C.
- (vi) Due to missing data from the key measurements on other days, we were only able to investigate one single day, which is not sufficient to confirm our model.

### **4.3 Ventilation window strategy - Experiment 3**

Experiment 3 was conducted to investigate the performance of the “ventilation window” when the windows are function as ventilation windows.

Experiment 3 was carried out during a 7-day period in November from the 1<sup>st</sup> to 8<sup>th</sup> in 2013 to investigate the ventilation window strategy.

#### **4.3.1 Set up of ventilation strategy for Experiment 3**

During the period of the experiment 3, the natural ventilation was automatically controlled by the Windows Masters program. All external ventilation windows were closed most of the time except for a 3 min period each hour. The internal windows were constantly open 30cm (100%) during occupancy and were manually regulated by occupants if it was too cold. During Experiment 3, the windows worked as “ventilation windows” except for the 3 min period of each hour, where the windows worked as normal windows. The idea was that the leaky external frames should provide the required ventilation supplemented by 3 min of normal ventilation. During no occupancy all internal and external windows were closed.

The CO<sub>2</sub> meters were installed in all 9 ventilation windows and both chimneys for the same purposes as in experiment 2, which was to investigate how the air is moving through the building.

#### **4.3.2 Results of Experiment 3**

The highest CO<sub>2</sub> levels were recorded on the 4<sup>th</sup> of November 2013 in Zone 5 on the 1<sup>st</sup> floor and in Zone 4 on the 1<sup>st</sup> floor on the 7<sup>th</sup> of November 2013. During the 4<sup>th</sup> of November, Windows Masters forgot to set the automatic control of windows. Therefore, the fully functional system was only available from the 5<sup>th</sup> of November as shown in Figure 21.

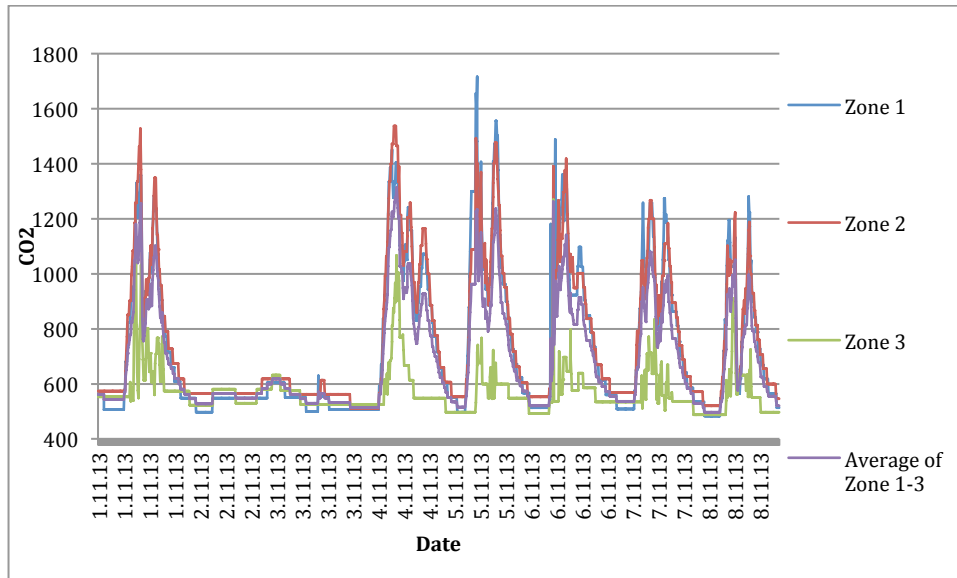


Figure 21 CO<sub>2</sub> concentrations in the rooms during Experiment 3

We investigated in detail the day of 7<sup>th</sup> of November 2013 between 11 and 12pm, because we had most complete data from the day.

#### 4.3.2.1 External conditions during experiment 3

The average external temperature between 7-17 on the 7<sup>th</sup> of November was 9.8°C and the wind velocity varied between 1-4 with an average wind velocity of 2.4m/s with the direction of south west. The average internal temperature during the occupied hours was 22°C in Zone 1 and 2 and 24°C in Zone 3 on the ground floor and 21°C in Zone 4 and 20°C in Zone 5.

The infiltration  $n$  during no occupancy was calculated to be 0.003 ach and estimated based on the weather conditions between 17.00 to 24.00 on the 7<sup>th</sup> of November 2013. The external temperature during that period was, on average 8.3°C and the wind velocity varied between 1.5-3 with an average wind velocity of 2.2m/s with the direction of south west.

#### 4.3.2.2 Analysis of the concentration of CO<sub>2</sub> in the occupied rooms

During the occupancy on the 7<sup>th</sup> of November 2013, in hours before midday the number of occupants was stable on the ground floor with 7 adult females and 10 children between age 0.6-2.8 years. It was calculated that the occupants produce 154.7 CO<sub>2</sub> emissions in an hour.

To be able to keep the CO<sub>2</sub> levels below 1000ppm, the air change needed to be a 0.98 ach. The measured average CO<sub>2</sub> concentration for 1-3 zones was 1079 ppm, which is considered good, however in Zone 1 and Zone 2 the CO<sub>2</sub> concentration was 1258 and 1266 respectively, as shown in Figure 22. The average low CO<sub>2</sub> concentration is due to the low concentration in Zone 3. Knowing the actual concentration, I estimated that actual air change for the average of zone 1-3 to be 0.87 ach.

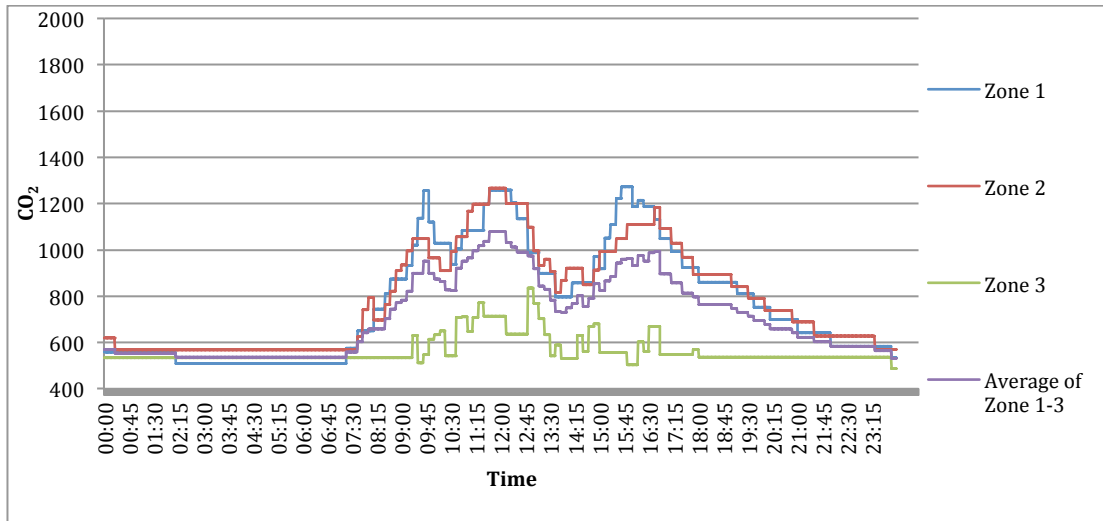


Figure 22 CO<sub>2</sub> concentration on the ground floor in zone 1-3 during occupancy on the 7<sup>th</sup> of November 2013

In the room on the 1<sup>st</sup> floor, CO<sub>2</sub> concentration was higher, reaching 1934ppm during a 10 min period in Zone 4 and varying between 1200 and 1700ppm during the occupancy, as shown in Figure 23. The high CO<sub>2</sub> concentration also appears in Zone 6, which is the separate office with one occupant. We did not investigate Zone 6 because the occupant was feeling a draught from the window and had the window closed most of the time.

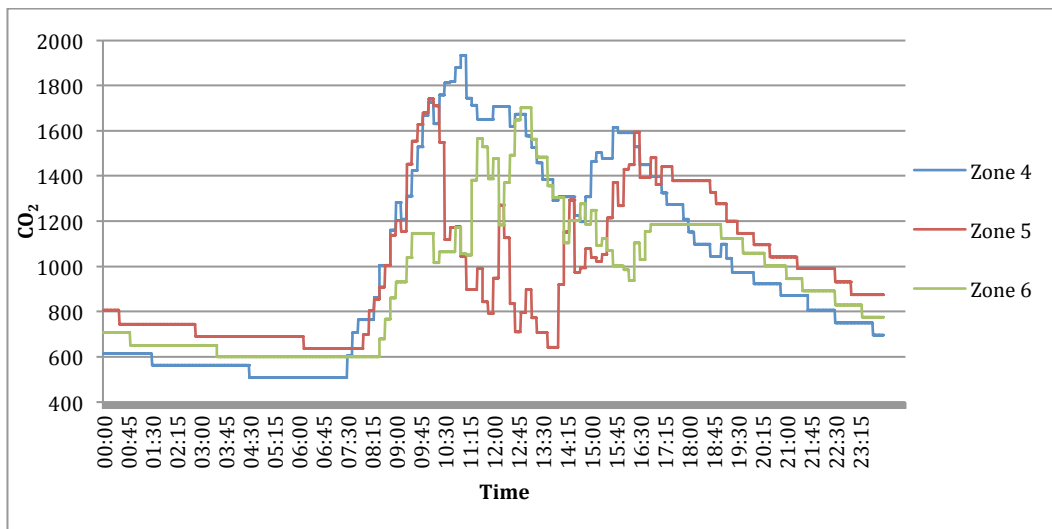


Figure 23 CO<sub>2</sub> concentrations on the 1<sup>st</sup> floor during November 7<sup>th</sup> 2013.

During a 1-hour period before midday, the number of occupants was also stable on the 1<sup>st</sup> floor with 4 adult females and 11 children between age 0.6-2.8 years. It was calculated that the occupants produce 89.6 CO<sub>2</sub> emissions in an hour. The volume of the zone 4 is 143m<sup>3</sup>.

To be able to keep the CO<sub>2</sub> levels below 1000ppm, the air change needs to be 1.04 ach. The measured CO<sub>2</sub> concentration for zone 4 was 1934 ppm, which is considered bad. The actual concentration was estimated to be 0.4ach.

#### 4.3.2.3 Measurements of the concentration of CO<sub>2</sub> from windows and chimneys

The meters installed in the windows and chimneys showed that the concentration of CO<sub>2</sub> in the chimneys was higher than in the rooms on the ground floor, as shown in the Figure 24. It indicated, that even though the air flow in the chimneys were fluctuating, the chimney 2 was still working as an extractor most of the time, and the windows 2.1 and 2.2 in Zone 2 were working as air supply. During a 3 min period each hour, when the external windows opened, the CO<sub>2</sub> levels dropped in the windows on the south façade as well as in the chimney 2. It is not clear whether the opening of the external windows increased the air exchange in the rooms by increasing the air velocity, or it disturbed the airflow and reversed the airflow in the chimney 2.

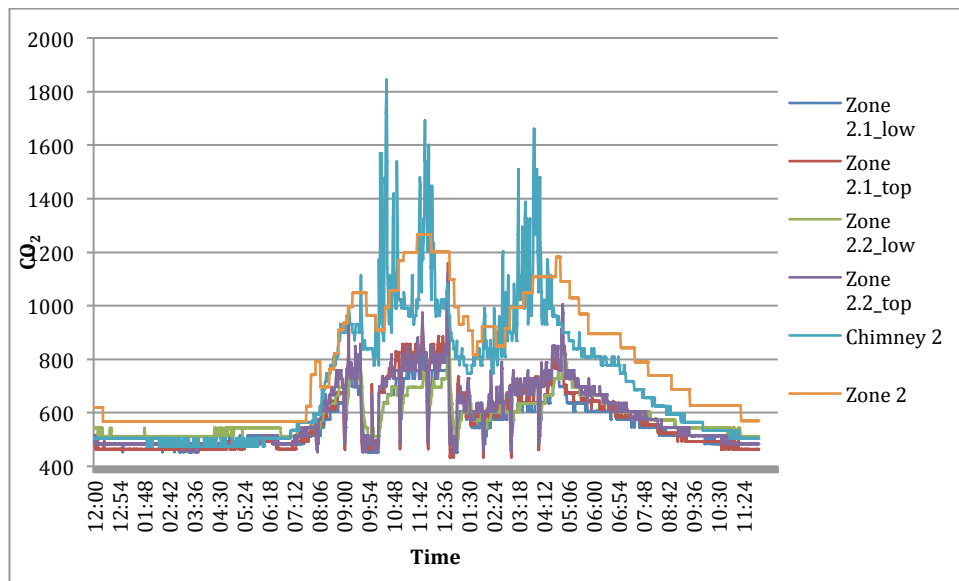


Figure 24 CO<sub>2</sub> concentration in the zone 2(south façade) on the 7<sup>th</sup> of November.

The CO<sub>2</sub> concentration at the bottom of the windows in Zone 2 had the lowest variations and was only slightly lower (100ppm) than at the top of the window, which indicated that the incoming air probably did mixed with the air in the gap of the window.

As the wind direction was from the south-west, the window on the east facing façade 1.1 on the ground floor worked both as an extractor and supply, as shown in Figure 24. The window 4.1 on the 1<sup>st</sup> floor worked mostly as an extractor, as the CO<sub>2</sub> concentration was highest, as shown in Figure 25.

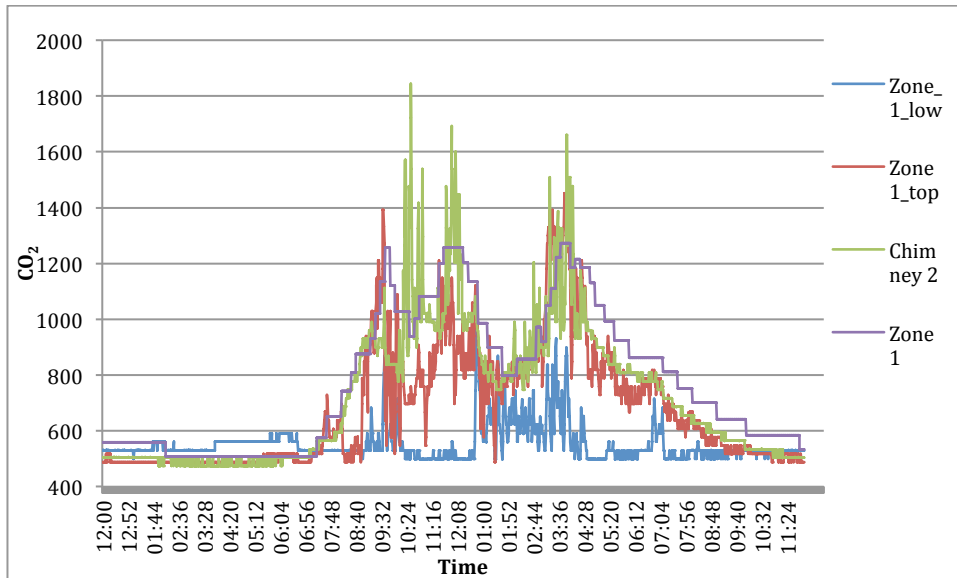


Figure 25 CO<sub>2</sub> concentration in Zone 1 (east facing façade) on the 7<sup>th</sup> of November 2013.

The window 3.1 on the west facing façade on the ground floor worked as an air supply with the lowest CO<sub>2</sub> concentration recorded in Zone 3 (Figure 26). Chimney 1 is located in the same room and worked mostly as an extractor. Zone 3 had the best air quality in the building, which was possible influenced by the wind direction as the wind direction was south west.

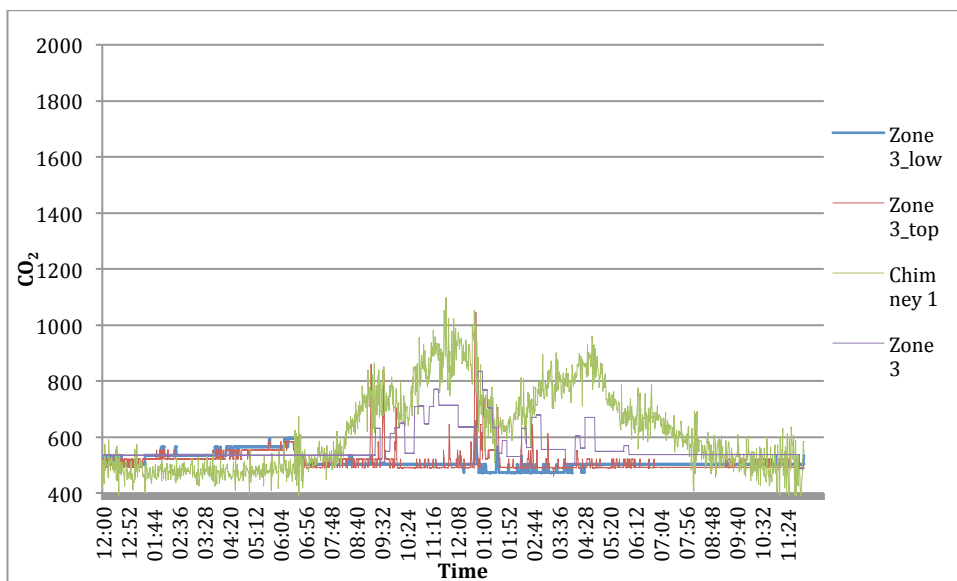


Figure 26 CO<sub>2</sub> concentration in Zone 3 on the ground floor during the 7<sup>th</sup> of November 2013

As chimney 2 was working as the air extractor for both floors, the high CO<sub>2</sub> concentration in chimney 2 could also be caused by the average higher CO<sub>2</sub> concentration on the 1<sup>st</sup> floor, as shown in Figure 27.





Figure 27 CO<sub>2</sub> concentration in the zone 4 (south façade) on the 1<sup>st</sup> floor during 7<sup>th</sup> of November 2013.

The CO<sub>2</sub> concentration in chimney 2 was lower than the average room concentration on the 1<sup>st</sup> floor, as shown on the Figure 27. The highest CO<sub>2</sub> concentration was recorded at the top of window 4.1 on the east facing façade, which worked as an air extractor and was influenced by the south-west wind. The CO<sub>2</sub> concentration at south facing windows 4.2 and 4.3 and chimney 2 was slightly lower, with high fluctuation, indicating that the air was moving both ways.

The relatively lower CO<sub>2</sub> concentration, with high fluctuation was also recorded in window 5.1 in Zone 5 on the 1<sup>st</sup> floor (Figure 28). Note that Zone 5 has no direct connection to chimney and is connected to chimney 2 through an opening between zone 4 and 5. Therefore window 5.1 works both as a supply and extractor.

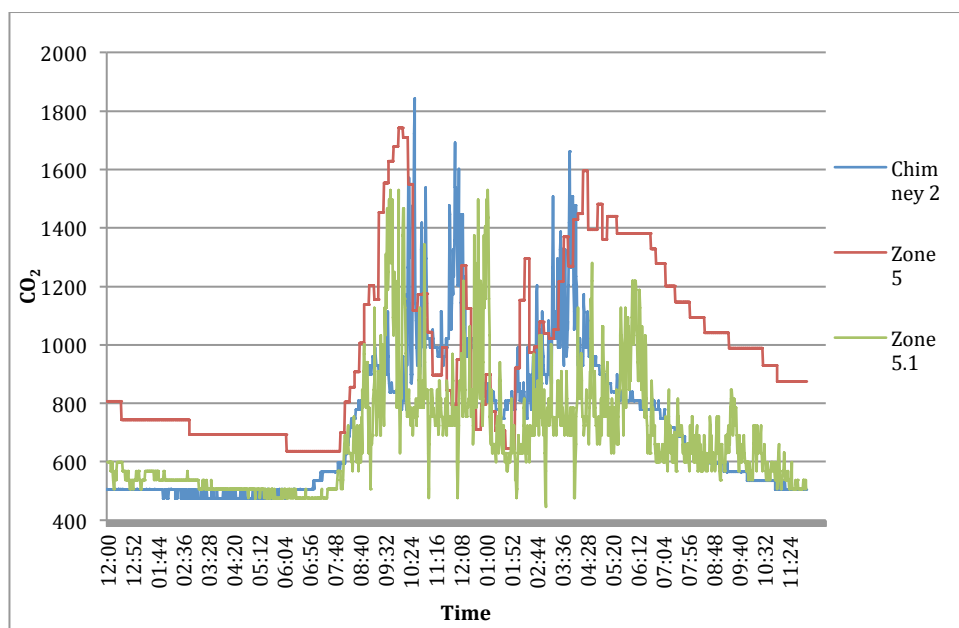


Figure 28 CO<sub>2</sub> concentration in Zone 5 on the 1<sup>st</sup> floor during the 7<sup>th</sup> of November 2013

#### 4.3.2.4 Measurements of temperature in windows

The incoming temperature through the ventilation windows was stable for the top part of the windows and varied from 14 -16°C, as shown in Figure 29. The temperature at the bottom of the windows was at least 3-5°C cooler during the unoccupied hours and increased during the day, reaching the temperature of the incoming air in the top of the window. The drop in the temperature at the top of the windows apparently occurred due to opening of the external doors by the occupants. The smaller drops in the temperature occur every hour due to the automatic opening of the windows controlled by Windows Masters.

The temperature difference between the top and the bottom of the windows was changing during the occupied hours, indicating that there was probably some kind of mixing of the air in the gap of the window. Note, that the temperature in the lower part of the window was cooler than in the top, which indicated that the air was coming in through the leakage in the external frame, as predicted, and was different from experiment 2 where the temperature in the top was cooler.

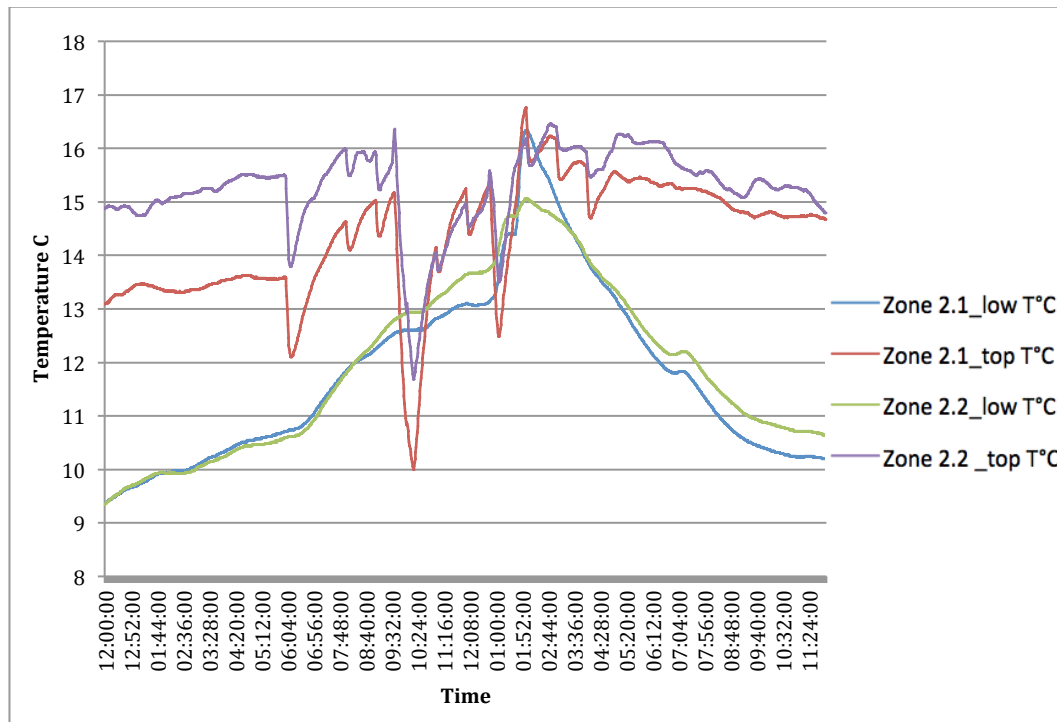
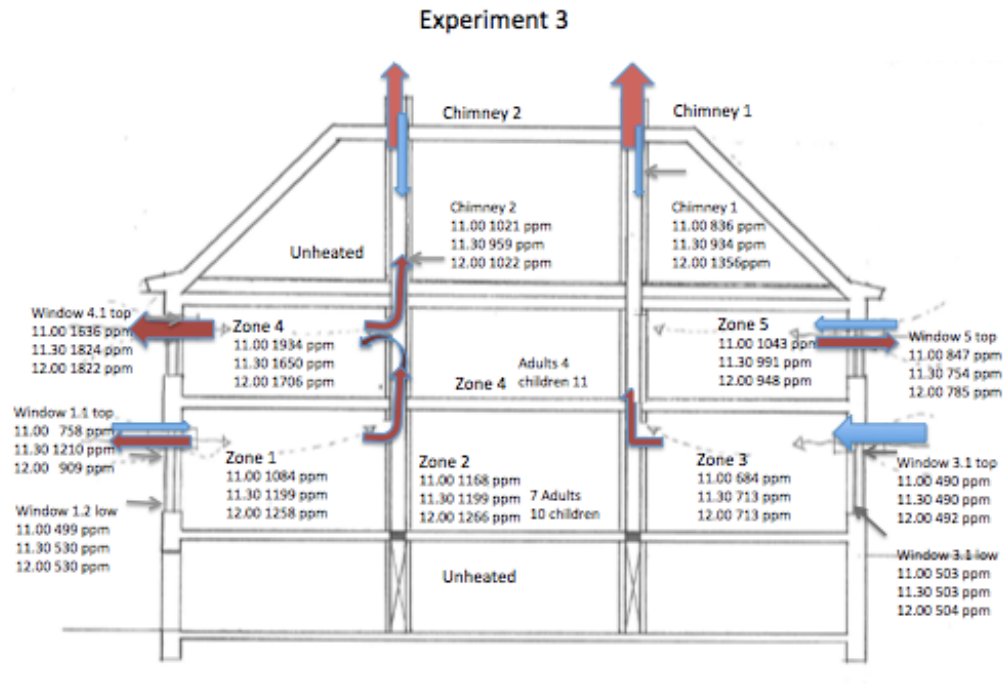


Figure 29 Temperature in the gaps in windows 2.1 and 2.2 in Zone 2 on the 7th of November 2013

#### 4.3.2.5 Summary of the results of experiment 3

The results are summarised in Figure 30 during the 7<sup>st</sup> of November 2013 between 11-12am. During this period, the occupants on the ground floor were in zone 3 on the ground floor and in Zone 4 at the 1<sup>st</sup> floor preparing and eating lunch.



**Figure 30 Summary of Experiment 3**

Summary of the results:

- (i) Experiment 3 recorded CO<sub>2</sub> levels in the rooms at 10 min time intervals and showed more detailed air quality in the rooms than in experiment 1.
- (ii) In experiment 3 the “ventilation windows” worked as predicted, where the fresh air passed through the external frame, was preheated and mixed with the escaping air from the room (the preheating affect was around 5°C)
- (iii) Even with closed external windows and a low wind velocity, the wind had an influence on the pressure difference inside the house and dominated the airflow through the building from the west Zone 3 on the ground floor and Zone 5 on the 1<sup>st</sup> floor to the east window 1.1 in Zone 1 on the ground floor and window 4.1 in Zone 4 on the 1<sup>st</sup> floor.
- (iv) Chimneys 1 and 2 had similar CO<sub>2</sub> concentrations as in Experiment 2. The windows located close to the chimneys, such as 2.1 and 2.2 (south façade) on the ground floor and 4.3. (south façade) on the 1<sup>st</sup> floor, worked as air supplies and chimneys 1 and 2 worked as air extractors. However, the airflow fluctuated and indicated that there was not sufficient airflow through the system.

- (v) There were more fluctuations recorded in supply windows and chimneys and the opening of a window or door was more visible on the CO<sub>2</sub> concentration recordings or the temperature in the windows.
- (vi) The CO<sub>2</sub> levels were moderate on the ground floor but too high on the 1<sup>st</sup> floor during the occupancy, which indicated that the system could not provide sufficient airflow to the 1<sup>st</sup> floor. Knowing the occupancy in the room, it was possible to estimate the air change in the rooms, which was lower than required.
- (vii) The external windows were closed most of the time, except for 3 min periods every hour, and therefore did not provide sufficient airflow through system especially for the 1<sup>st</sup> floor. The reason for this could be that the external frames were tighter than predicted, and the external temperature was higher than estimated in the dynamic simulation model, which predicted that the windows should additionally open when the external temperature was above 5°C.
- (viii) As in experiment 1 and 2, we used a simplified assumption that the room has well mixed air and the air exchange was only to the outside. However, our measurements showed that the air in 1-3 zones was not well mixed as the CO<sub>2</sub> concentration differed by up to 600ppm from zone 1 and 3.

Due to many uncontrolled parameters, such as (i) always changing number of occupants and their exact position, (ii) the air movements between the rooms, as well as (iii) opening and closing the doors not only to the rooms but also to outside etc., created a great challenge in estimating, measuring and calculating the actual air flows in the windows or even in the chimneys. The air change calculation could only provide the rough estimate of the air change in the room,

## 5 Discussion

The purpose of the study was: (i) to investigate whether our solution provides sufficient fresh air to the occupants of the building without creating drafts for the occupants, (ii) whether air supply is provided through the “ventilation window” and extracted through the chimneys, as assumed, and (iii) how the system works in a real building during usage.

We investigated three strategies:

- (i) where fresh air was provided by **pulse ventilation**, Experiment 1;
- (ii) where fresh air was provided by **stream ventilation**, Experiment 2;
- (iii) where fresh air was provided by **ventilation window**, Experiment 3.

## 5.1 Does the system provide sufficient fresh air

Neither of the three window opening strategies **could provide the required air change of 1.4 ach.** .

As the occupancy in the building during all 3 experiments was lower than designed, all three strategies provided nearly sufficient fresh air to the ground floor:

- Experiment 1 –according to the actual number of the occupants the system should provide minimum of 0.7ach, however the system provided only 0.6 ach.
- Experiment 2 - according to the actual number of the occupants the system should provide minimum of 1.1 ach, however the system provided only 0.74 ach
- Experiment 3 - according to the actual number of the occupants the system should provide minimum of 0.98 ach, however the system provided only 0.87 ach

None of the three window opening strategies provided sufficient air change to the 1<sup>st</sup> floor. The reason for this may be that the pressure difference due to the stack effect was sufficient for the ground floor and not sufficient to the 1<sup>st</sup> floor.

- Experiment 1 –the actual number of the occupants was not available, and therefore we could not estimate the air change
- Experiment 2 – there were no occupants on 1<sup>st</sup> floor during the analysed day
- Experiment 3 - according to the actual number of the occupants the system should provide a minimum of 1.04 ach, however the system provided only 0.4 ach

## 5.2 Did the system worked as predicted?

The idea of the installed system was to use the existing windows as “ventilation windows”, where the air in the building is provided by the natural leakage of the external frames. Only in Experiment 3 did the 9 windows with the automatic control from Windows Masters work as “ventilation windows”. During Experiment 3 the air supply was additionally added by the “pulse ventilation” in a similar way as in the experiment 1.

During experiment 2, a stable flow in the chimneys and the windows close to the chimneys was observed. However, as the internal and external window were open in the same side, the window worked as a simple opened window and not as a “ventilation window” and no preheating effect was observed. Even with constantly open external windows there was not sufficient air for the 1<sup>st</sup> floor.

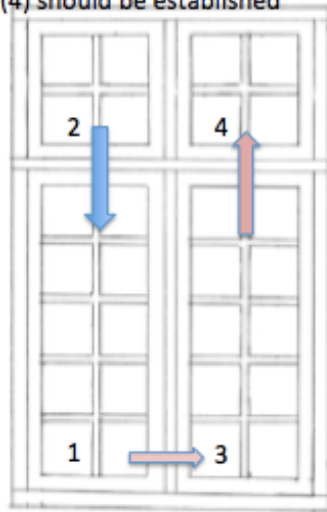
During experiment 3 the system worked as predicted and the CO<sub>2</sub> concentration was lower in the windows close to the chimney, which we interpreted as an indication that the windows worked as an air supply, even with some fluctuation. The preheating effect was observed in the windows, which could be due to the solar radiation in the window gap as well escaping air from the room.

### 5.3 Options for improvement

Experiments 1-3 showed that the leakage of the external frame was not able to provide sufficient airflow during the occupied hours. Experiment 2 showed that if the external windows were slightly open during the occupied hours, the flow in the chimney and in the windows close to the chimneys is stable. However no preheating effect was then observed. To achieve the preheating effect and to provide the required airflow the system should be improved:

- (i) The whole window frame should be used for ventilation purposes. In this case, the external window opening can stay as it was during the Experiment 1-3 (the top window (2) as shown on the Figure 31 is automatically controlled by Windows Masters) and the internal window should be closed on the top window. The internal window on the opposite side (4) as show in Figure 31 should be open. In the bottom of the frame the air passage must be established between (1) and (3) as well as the air passage between (4) and (3) as shown on the Figure 33. The fresh air is then expected to come in through the open external window (2) and be forced to travel down to box (1) and through the passage to box (3) and extracted into the room by the internal open box (4). It is hoped that the chimney will then have a stable flow and the windows close to the chimney will work as the air supply. By having opening external windows wider on the 1<sup>st</sup> floor than on the ground floor (4:1) the pressure difference might be equalised.
- (ii) To connect zone 5 to chimney 1, as zone 5 has to low air circulation.

The air canals between the lower (1) and (2) ,(1) and (3) as well as (3) and (4) should be established



3<sup>rd</sup> layer of K-coated glazing on the secondary gazing frame , mounted without the frame

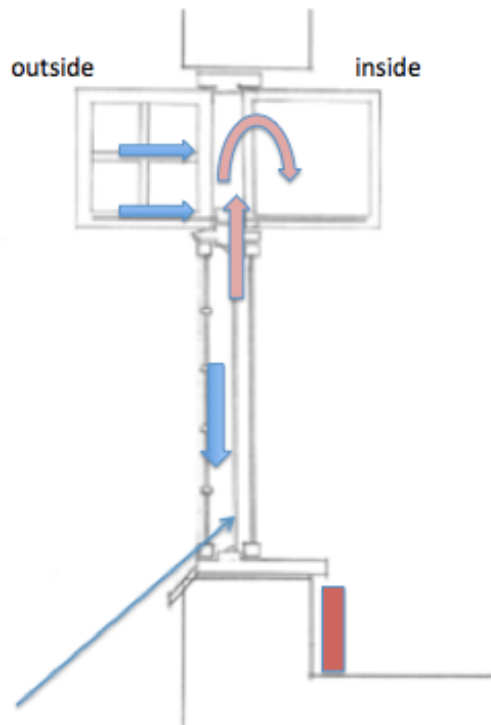


Figure 31 Suggestion for improving the system

An experiment confirming that the improved system works as predicted should be conducted.

## 6 Conclusion

In the natural ventilated building the driving force for the ventilation is the pressure difference between inside and outside. The pressure difference can be due to the temperature difference or the wind forces around the building. As we were investigating the performance of the ventilation window, we ignored the wind forces around the building. This assumption was based on the fact that as long the external windows were closed, the influence of the wind would be reduced and the leakage of the external window frame provides the airflow, driven only by the temperature difference. We also assumed that the opening and closing of the internal top ventilation window could control the airflow not only through the window, but also through the chimney, which in this case works as the extractor.

Experiment 1-3 investigated the system with 3 different ventilation strategies. The system as installed did not provide sufficient airflow to the ground floor or to the 1<sup>st</sup> floor. During the investigated period the building did not reach the full occupancy and therefore the air supply was nearly acceptable for the ground floor but insufficient for the 1<sup>st</sup> floor.

The assumption that the external wind can be ignored using ventilation window system was incorrect. The wind influence was mostly visible during experiment 3 where the system was configured to work as predicted.

The installation of the internal and external automatically controlled windows on the same side was also incorrect. When both external and internal windows were open, the window worked as a simple window. To be able to make the window work as a “ventilation window” the automatically controlled openings should be installed on the opposite side of the window and the air passages should be established between the boxes so the air is forced to move down to the lower part of the window and extract through the top part of the opposite box.

This investigation of a natural ventilation system in a natural environment reveals how difficult it is to estimate, measure and calculate the air flow in the building, where the zones are connected and people are moving constantly between the spaces. During the project we used simplified estimates to calculate the measured CO<sub>2</sub> levels in the building. The system could be better modelled using a dynamic calculation model and more detailed readings of the airflow in the building and more detailed registration of the movements of the occupants.