TVOC concentrations measured in Belgium dwellings and their potential for DCV control

Robin De Sutter[1], Ivan Pollet[2], Anneleen Vens[2], Frederik Losfeld[2] and Jelle Laverge[1,*]

1 Building Physics, Construction and Services Research Group
Ghent University
Jozef Plateaustraat 22
9000 Ghent, Belgium
**Corresponding author: jelle.laverge@ugent.be*

2 Renson Ventilation
Maalbeekstraat 10
8790 Waregem, Belgium

ABSTRACT

Over the last decade, TVOC sensors have been touted as an interesting alternative to CO2 and RH sensors in DCV systems. Nevertheless, there is little evidence on the nature and the profile of TVOC concentrations in modern dwellings.
In this project, metal oxide TVOC sensors were installed in the local exhaust ducts in 3-4 bedroom low energy social housing dwellings equipped with a DCV exhaust ventilation system in Belgium. The TVOC and CO2 concentrations as well as RH levels were measured during operation and 2 control strategies were compared: the DCV was controlled based on the measured CO2 concentration for 2 weeks and subsequently, the same system was controlled based on the TVOC concentration.
From the observed concentrations, it is shown that, due to occupant activities such as cooking, bathing and cleaning, high, short peaks in TVOC concentrations are a typical feature of residential IAQ. This makes TVOC concentration an especially useful parameter for ‘event’ related or purge ventilation control. Nevertheless, the relative frequency of these peaks also raises the question whether it is necessary to raise ventilation rates in response to such normal instances such as eating an orange. The average ventilation flow rate during TVOC control is about 50% larger and the system operates at a higher flow rate compared to the CO2 control 40% of the time on average.
A further observation is that there is only a very weak correlation between the TVOC concentration and the CO2 concentration at lower concentrations, most likely due to faster secondary reactions of the TVOC compared to the virtually inert CO2. This limits the use of TVOC as a control parameter for non-purge related events.
In conclusion, highly peaked TVOC concentrations were observed in low energy dwellings, demonstrating the use of TVOC sensors as a control parameter for purge ventilation in DCV systems.

KEYWORDS

DCV, TVOC, CO2, sensors, control

1 INTRODUCTION

Simply reducing ventilation rates, to save energy, deteriorates IAQ, leading to undesirable effects such as productivity loss, increased respiratory problems and susceptibility to allergies (van Holsteijn, 2014). This problem creates conflicts of interest between health and good IAQ on the one hand as energy and cost savings on the other. However, two potential ventilation strategies can provide a possible solution. These energy-efficient ventilation strategies are for example Mechanical Ventilation with Heat Recovery, MHRV, and Demand Controlled Ventilation, DCV. MHRV is primarily used in countries with colder climates. The use and merit of this alternative has already been discussed extensively in literature (eg. Juodis, 2006). The other approach, DCV, possesses the ability to control the ventilation rates by using the concentration levels of pollutants in the occupied space (Haghighat, 1993). Due to well established correlations between the perceived air quality and C02 concentration, CO_2 has been generally embraced as a good indicator for ventilation demand. The continued development of C02 sensors over the last decades made this technology found its way into agricultural and industrial application. As a result of this progress, the price of these sensors has already decreased significantly. Recently CO_2 sensors are used as the main detection devices for DCV in residential buildings.

There are, however, important drawbacks with C02 sensors from an engineering point of view: they are still rather expensive and energy intensive due to the necessity to heat them for good operation of the most common, NDIR based types. Therefore, researchers are increasingly seeking alternatives to replace conventional C02 sensors used in DCV, where VOC detection appears to be promising. Metal oxide VOC sensors are a much more energy efficient and cost effective alternative to NDIR CO_2 sensors, however, their sensor value is non-compound specific and they do not pick up pure C02 (Herberger, 2012). Previous studies on the integration of such sensors in demand controlled ventilation systems in an office environment (Kolarik, 2014) and a university classroom (Szczurek, 2015) conclude that the claimed correlation exists but is far from perfect. Since a residential environment has a unique set of pollutants and microenvironments and demand controlled ventilation is widely used in residential ventilation systems in North-Western Europe, further investigations are needed into the potential of replacing traditional C02 sensors with VOC sensors for this type of DCV [6].

The aim of this paper is to compare the effect of using either the real C02 concentration or an 'equivalent' VOC concentration to control a DCV system in real, occupied dwellings. The observed VOC and CO_2 concentrations will be compared. Additionally, a transformation of the VOC signal will be proposed as a first step in the development of a new approach for control of DCV by VOC detection.

2 EXPERIMENTAL SETUP

For the test, 32 newly built or deep-renovated low energy dwellings with recently installed mechanical exhaust ventilation systems with demand controlled dampers in each of the individual exhaust ducts are selected. Carbon dioxide and VOC sensors are installed side by side on the extraction dampers of the kitchens and bedrooms. These are designed to be controlled by either of these sensors in a flexible demand controlled ventilation approach. The system starts with control by C02 detection but switches to control by VOC detection after two weeks. In both cases, the damper opening is linearly proportional with the measured concentration, in 7 steps from the minimal flow rate (15%) to the nominal flow rate (100%) in a 200 ppm interval around the setpoint.

The sensor values, as well as the damper position are saved with the internal logging on a 90 seconds interval. Due to the constant pressure ventilation unit, the flow rate through the damper is directly proportional to the valve position. Three such cycles were conducted in every dwelling, corresponding with 12 weeks of measuring. Eventually, due to installation errors, (power) interruptions and sensor errors, only 29 dwellings had at least 2 weeks of data in each mode to make a valid comparison.

3 RESULTS

Figure I. shows the C02 and VOC concentrations over the course of 2 weeks of measuring for dwelling W27. In the first week, the flow rate through the damper is controlled by adjusting the valve position based on the C02 concentration, with a set point of 900 ppm.
As can be seen in the figure, the set point is barely reached and the damper remains closed except one time. During the second week of the figure, the flow rate is controlled by adjusting the 'valve position' based on the VOC concentration. As can be seen the concentration is more variable and affected by higher peaks and the valve is more intensively opened when occupants are present.
When the C02 and VOC concentrations are compared (remember that they are measured at the same point in the damper), the general pattern is rather similar, but the VOC concentration has, as was mentioned above a much higher variability and is affected by higher peaks. This is consistent with the claim of the manufacturers of the sensor that it's
calibrated to represent metabolic C02 but also reacts to other sources. As has been reported in literature, these other sources may be highly instantaneous, explaining the peaks observed. Another interesting observation is that the slope of the decline in VOC concentrations also seems to be steeper. This can possibly be explained by surface chemistry and secondary reactions, which only very weakly affect the virtually inert C02.
Across all 2-week subperiods and all sensors, on average, the ‘equivalent’ VOC measured by the metal oxide sensor is 1.52 higher than the average CO2 concentration measured for the same sub period.

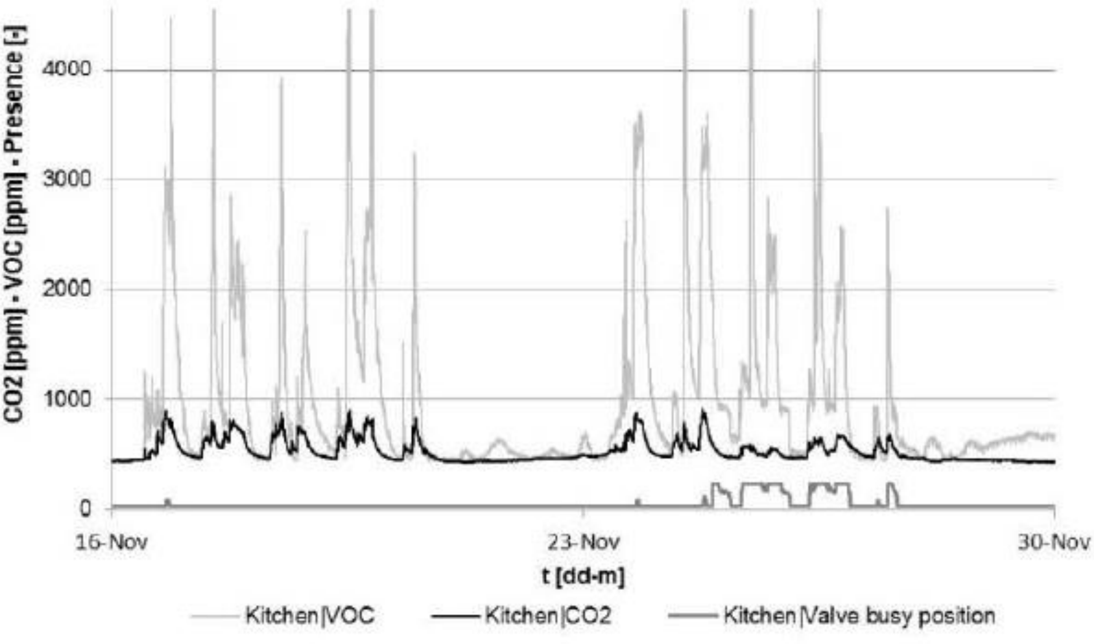

Figure 1: C02 and YOC concentrations over 2 weeks
(week l: DCV controlled by C02; week 2: DCV controlled by VOC)

The daily concentration profiles for both CO2 and VOC across the different measurement periods for the bedroom and kitchen sensors for dwelling W33 are shown in figure 2. The occupancy pattern of the spaces is clearly better represented by the CO2 concentration. Additionally, the ventilation system is able to maintain the set point (900 ppm) quite well for CO2, but fails to do so completely for VOC.

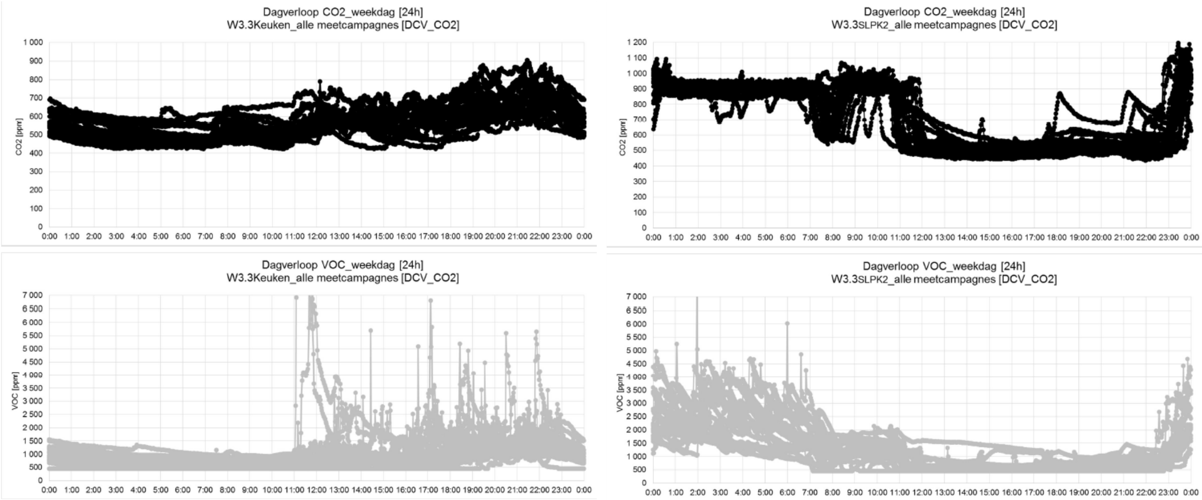

Figure 2. Day profiles of kitchen (left) and bedroom (right)
CO2 (top) and VOC (bottom) concentrations [W33]

Subsequently, to cross compare the 2 weeks of operation, the 'theoretical' valve positions are determined for each damper. This is done following the example of previous studies of Laverge et al. (2015). For each damper the valve position is calculated from the measured VOC concentrations during DCV by CO2 as if the damper would 'theoretically' be controlled by the VOC concentration. This is also done for the C02 concentration during DCV controlled by VOC. Remark that this is only an approximation, because, since the valve does not actually take this position, the subsequent concentrations are not influenced by the theoretical valve position but by the real valve position. In Figure 3, the results for dwelling W27 are given. Actually, the mismatch between the two control signals can be observed. It shows the valve position as a function of both concentrations in case the damper is controlled by the C02 concentration (bottom) or the VOC concentration (top). These results are chosen, as this is one of the few dampers that was opened repeatedly during DCV controlled by C02. Other dampers show a higher variability between the measured and calculated valve positions, with almost no opening of the damper when controlled by C02.
For all dampers the same results and conclusion, matching the results of the study of Laverge et al. (20 I 5), are seen. The damper is opened 'prematurely' and irrespective of the demand from a C02 perspective if the damper is controlled by the VOC concentration, while from a VOC perspective, lots of instances with high concentrations remain unnoticed if the damper is controlled by the C02 concentration. Again, we see that the ventilation system is not able to keep the voe concentration below or around the set point, even if the damper is fully opened. On average, the ventilation flow rate is more than 2 times higher when VOC is used as control parameter. This effect is stronger in the kitchens (average increase 176%) then in the bedrooms (average increase 69 %). This is explained by the much higher production of VOC due to occupant activities (e.g. cooking or dishwashing) in the kitchen.

This is also shown in the typical day profiles of the concentrations for both rooms shown in figure 3, where substantially more pronounced peaks that do not match a rise in CO2 can be seen in the VOC concentration in the kitchen.

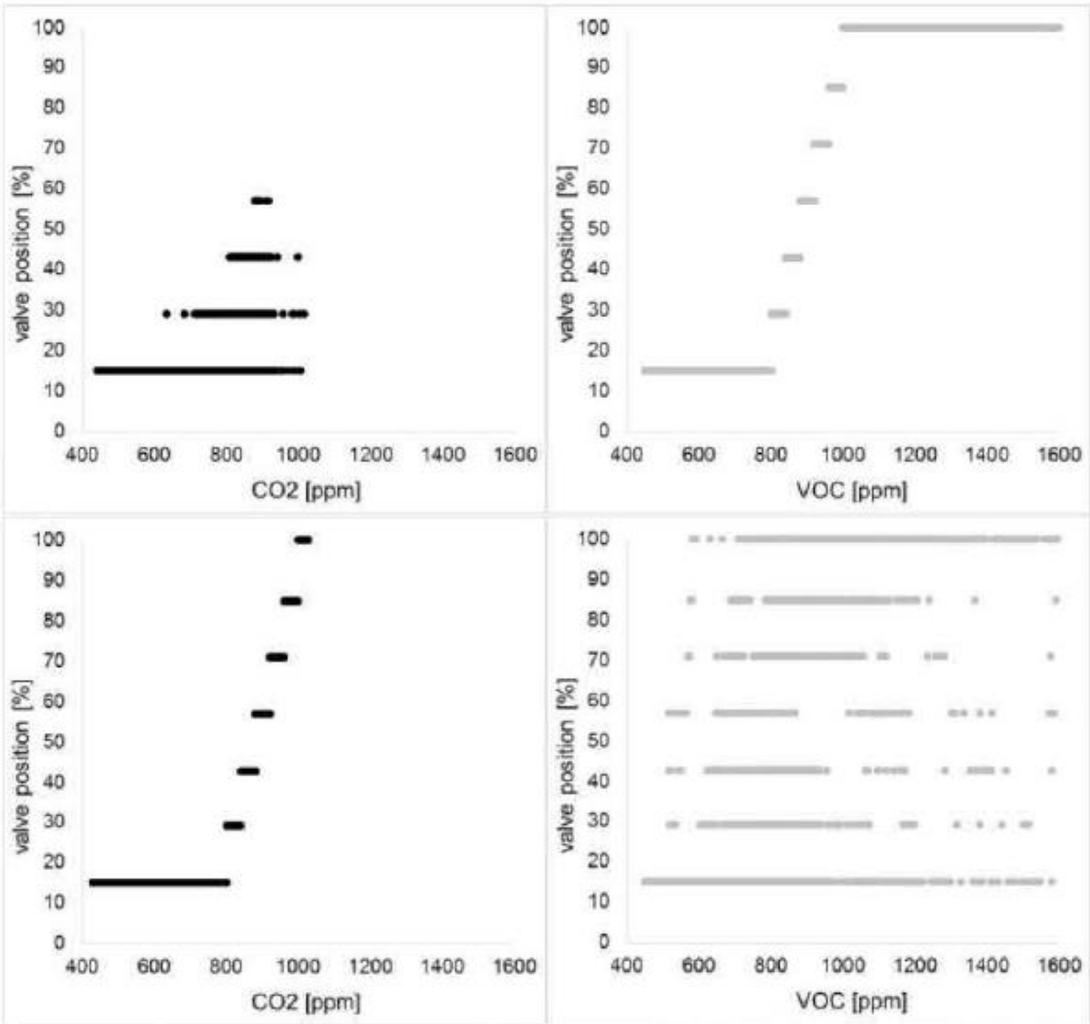

Figure 3: Correlation between the measured C0 2 (left_top) and VOC (right_bottom) and the calculated valve position based on measuredC02 (left_bottom) and VOC (right_ top) [W2.7Kitchen_campaign 3]

4 ALTERNATIVE FOR VOC SIGNAL PROCESSING

Considering the results that have been presented above, a new approach to handle the VOC concentration as a DCV control parameter is introduced. The high variability of the VOC concentration is something that can' t be left untouched. It's decided to "manipulate" the VOCs signals in such a way the new corresponding valve positions approach the original valve positions that are accessed by DCV c02. The original step control (7 steps, 15 - 100%) and set points (900 or 800ppm +/- l00 ppm) of the considered ventilation system remain the same. This new approach consists of three so-called "manipulations" and is presented below.

The three adjustments that are made to the VOC control signals are: (1) a horizontal stretching of the VOC concentration; (2) a vertical concentration shift; (3) constrain the increases and declines of the VOC-peak concentrations.

4.1 Horizontal stretching

The step control, as described for the determination of the valve position, does not operate using the instantaneous concentration values. It however uses a weighted average. This weighted average, which takes into account the concentration that is previously registered, ensures a constant sequence of control signals. Depending on a constant k-value, the current weighted average can be affected more or less by the previously determined weighted average. There is a larger horizontal stretching of the VOC control signal as the k-value is higher.
The original formula uses, for the control of DCV by C02, a k-value which is equal to 20. Using the VOC concentration, similar behaviour is obtained for the comparison of the valve positions if one assumes a higher k-value for the determination of the weighted averages. The best results and increasing correlations are received when k=50. Nevertheless, the k-value is considered at 30, as this is the best chosen value when taking the following operations into account.

4.2 Vertical shift

The second manipulation is a vertical concentration offset of the VOC signal which is equal to the third quartile, 75th percentile, of the observed concentration differences between C02 and VOC for each damper. Each damper will be manipulated by a different offset. The universality of this step to obtain an universal control algorithm for DCV by VOC can be questioned since it requires both a startup period (2 weeks of data) and CO2 concentrations to be measured. The best results are found when using these concentration shifts because they indirectly take into account the user profiles and variability between the dwellings. To avoid that the system becomes insensitive to continuously high concentrations, a maximum value of 600 ppm is allowed for the shift.

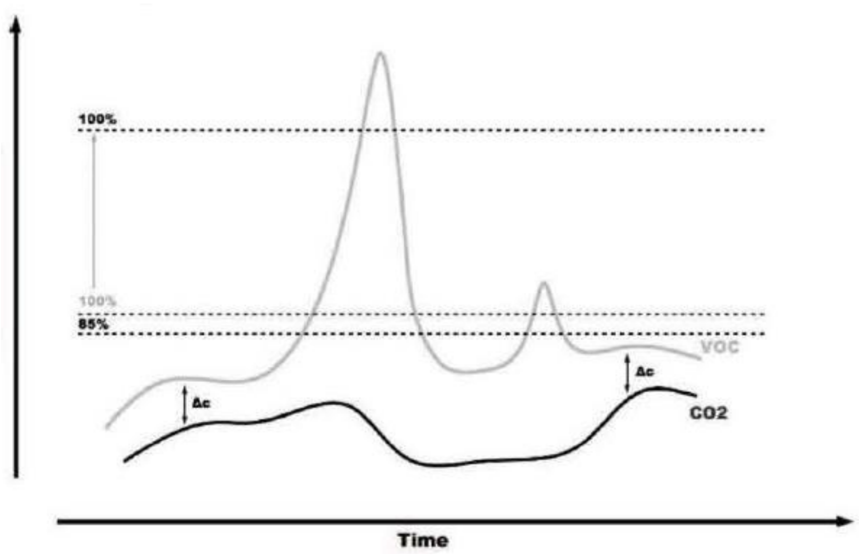

Figure 4: Strategy outline of new approach

4.3 Peak shaving

The last manipulation on the VOC concentration is the constraint of so-called "gray areas" . These areas represent the slopes of the existing VOC-peaks. This manipulation is shown in the strategy outline in figure 45 below by the dotted lines. In comparison with C02, VOC-peaks show very steep slopes, for which a direct increase in ventilation is not always necessary from

a health and comfort perspective. Nevertheless, these sometimes extremely high and damaging VOC-peaks can't be neglected.
VOC concentrations above 2000 - 3000 ppm may have adverse effects on human health. Consequently, an additional requirement is provided. Merely when the average VOC concentration, expressed in C02 equivalents, over a period of 5min. exceeds the value of 3000 ppm, the damper will be fully opened. Therefore the range of the second to last valve position is expanded in such a way the damper will react more economically, but will be fully opened when the VOC signal reaches values above 3000 ppm regarding comfort and health issues.

Finally, the latter manipulations are performed on the four test cases (8 dampers). The results of this new 'control algorithm' seem to be very promising, as is shown in figure 5. below.
Based on these latest results, an alternative demand controlled ventilation controlled by VOC sensors seems certainly attainable, if one manipulates the VOC signal. However, the dwelling and activity dependency, e.g. the use of different concentration shifts for each dwelling, pose a problem as these make it difficult to assign a universal character to this new approach.
Consequently, one can conclude that the possible replacement of C02 sensors by VOC-sensors is 'theoretically' possible. Future research should not focus on achieving similar conducts or correlations between the concentrations, but rather on the way how the VOC signals, and consequently the operation of the system, can be manipulated during DCV controlled by VOC in order to avoid possible over-ventilation and prematurely opening of the damper.

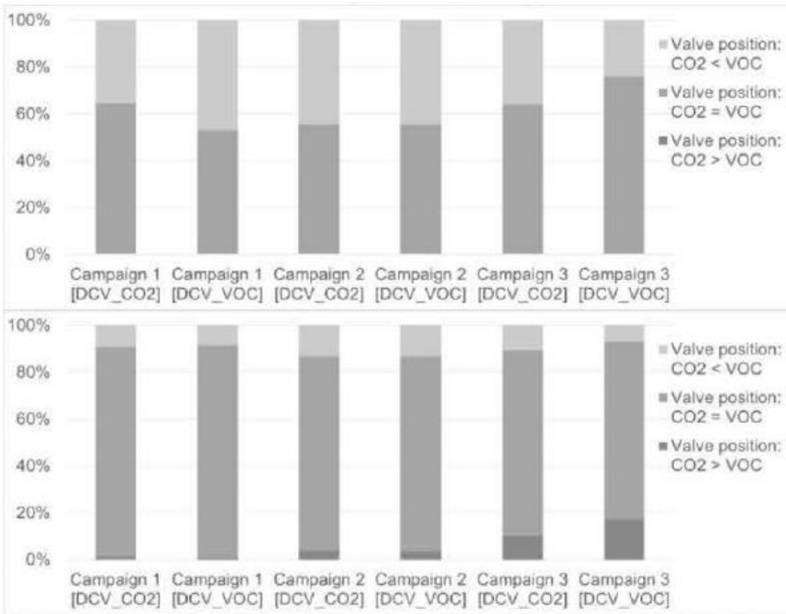

Figure 5: Comparison C02 I VOC valve positions after manipulation of VOC [W2.2Kitchen (top)_ W2.7Kitchen (bottom)_ all campaigns]

5 CONCLUSIONS

The aim of this paper was to compare the effect of using either the real C02 concentration or an 'equivalent' VOC concentration to control a DCV system in real, occupied dwellings. CO2 and ‘equivalent’ VOC concentrations were measured simultaneously in 29 dwellings. The observed VOC and CO2 concentrations were compared and showed that, on average, the VOC concentration was more than 50% higher than the CO2 concentration and displayed a much more peaked behaviour.

As C02 detection is used as the common standard for demand controlled ventilation it seems that the manipulations on the VOC concentration are necessary to avoid over-ventilation when using DCV by VOC. In the observed dwelling, the average ventilation flow rate under VOC based control was double that of CO2 based control.
Additionally, a transformation of the VOC signal was proposed as a first step in the development of a new approach for control of DCV by VOC detection. The new approach is mainly based on the comparison of valve positions for CO2 and VOC based control. The results show that achieving similar control behaviour through a manipulation of the VOC signal is possible, but nevertheless, the dependency on dwelling and activity specific data make it difficult to generalise this approach as a control strategy. When using an "overall" value for the concentration shifts acceptable results are recorded, but they appear not always consistent.
In conclusion, a general, obvious choice of C02 or VOC detection appears to be difficult, since the different approaches do not always provide straightforward results. Secondary technical and economic interests, as well as health aspects, could possibly be more conclusive in this CO2 vs VOC debate. DCV controlled by C02 detection has repeatedly proven its benefits in various studies. The results obtained in this study also show that CO2 is a good occupancy related parameter and controls the DCV system quite well if the occupant is the main pollutant of interest, while VOC based DCV will offer better protection against exposure to activity related pollutants. Nevertheless, the highly peaked nature of the exposure to these pollutants severely limits the possibility of the ventilation system to keep the concentrations below the chosen setpoint.

6 ACKNOWLEDGEMENTS

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