# A use case of data analysis for assessing Indoor Air Quality indicators

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## ABSTRACT

Product connectivity makes products and systems remotely controllable and possibly interoperable with other devices in the house.
The most common way to achieve this interoperability is to connect these devices locally. On the other hand, products may also be cloud-connected, which allows an easier and seamless interoperability between devices. Hence, data are collected and stored in the cloud. As soon as the measured data is sent to the cloud, large set of data are available and can be anonymously retrieved and statistically analyzed.
Whereas until recently analysis were performed on a small number but well identified and sometimes perfectly customized test sites, we have now access to large scale real life data from ordinary people living in real houses.
Thanks to the availability of miniaturized and affordable technology, we have developed and deployed low cost measurement systems embedding a limited but relevant number of sensors. Measured parameters are temperature and relative humidity, CO2, VOC and PM2.5. Data were recorded over a period of time in 2016 and from March to summer 2018.
For the purpose of the study, we retrieved the data on a sample of customers' houses equipped with dedicated indoor air quality (IAQ) connected objects and either individual exhaust or bidirectional ventilation system.
A theoretical approach by simulation was first carried out on four ventilation strategies in a four room dwelling to present the indicators before testing them on field data. The constant airflow bidirectional ventilation system appeared to be the one ensuring the best IAQ in main rooms while humidity controlled exhaust ventilation appeared to be the one ensuring the best comfort in the bathroom.
Assessing CO2 levels is relevant in periods where people are present. That is why an algorithm for the detection of people from CO2 concentration analysis was developed. Thus, it is possible to automatically calculate CO2 based IAQ indicators. We performed the calculation for four examples of IAQ field data and results were compared. The conclusion of this comparison is that ICONE is the best indicator between the three we analyzed: the scale is easy to understand, the output is independent of the length of the measurement period and it is less sensitive to threshold effect.

The availability of these easily accessible data will help to raise the awareness of all stakeholders regarding the importance of verified and guaranteed results.

The study demonstrates that this data allows a future refinement of models used for normative evaluation of systems.

Another conclusion was obtained regarding PM 2.5 pollution. The IAQ object collects outdoor air quality information computed from publicly available data, and compares it to inside measurement. In an occupied dwelling, outdoor and indoor levels are strongly correlated, which means that PM2.5 indoor concentration is mainly driven by the outside concentration. The human activity inside has no or little influence on the level.

## KEYWORDS

Ventilation, IAQ connected object, simulation, air stuffiness indicator, PM2.5.

## 1 INTRODUCTION

Indoor Air Quality (IAQ) sensor technology has evolved very quickly in the last few years, enabling low cost monitoring of IAQ thanks to sensors included in ventilation products or in dedicated IAQ connected objects. We expect a spreading of these products in the following years, which will open a new area for the ventilation industry. These sensors will be used to implement diverse demand control ventilation (DCV) strategies aiming at either lowering thermal losses due to the ventilation airflow or improving the IAQ by ventilating only the right airflow in the right place at the right time (van Holsteijn, Laverge, & Li, 2017). DCV systems have been developed for more than 30 years[1] and will see huge improvements in coming years. The advent of low cost sensors and data analysis will allow more advanced airflow control strategies based on self-learning and electronic airflow control.

Until now, it was very difficult to assess the effect of ventilation on pollutants onsite. A heavy instrumentation was necessary to monitor the IAQ as it was done in the study “Performance de la ventilation et du bâti” (air.h, 2007) which aimed at assessing onsite performance of humidity controlled ventilation systems. Because of these difficulties, residential ventilation performance has, until now, been mainly assessed by multizone indoor air quality and ventilation analysis simulation. The advent of low cost sensors makes however possible to continuously monitor the performance of systems, thus ensuring that the system delivers as expected.

The assessment of the IAQ performance is done through the calculation of IAQ indicators, but these indicators are calculated only for occupation periods. Detection of people’s presence in rooms is a challenge we will have to overcome. In this paper, we will present some stuffiness indexes and compare them for several ventilation systems, firstly through simulation results. We will then investigate a way to detect people’s presence with cheap IAQ sensors in order to learn about occupancy patterns and compute IAQ indicators from field data.

Thanks to connectivity, we are able to examine, in a second step, a huge amount of data to statistically assess the IAQ and compare it with model outputs.

We will also examine the correlation between particle concentration (PM 2.5) outside and in a dwelling.

## 2 IAQ INDICATORS

IAQ indicators are based on physical parameters and they may be used for regulatory or normative compliance purposes. Most commonly used parameters for normative IAQ assessment in a residential building are relative humidity and CO2 (carbon dioxide), relative

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[1] Humidity controlled ventilation has been used in France since the 1980’s.

humidity being the best tracer for condensation risk in bathrooms and in kitchens and CO2 the best tracer for air stuffiness due to human presence in main rooms. However, there may be a difference between the parameter used for normative IAQ assessment and parameters actually measured by sensors in demand control ventilation systems. For instance, humidity sensors are capable of tracking human presence and they have been used with success for more than 30 years in France in humidity controlled ventilation systems (Savin & Jardinier, 2009). More recently, due to sensor price drop, CO2 sensors have been directly used in demand control ventilation systems to control airflows. CO2 is a more reliable occupancy tracer than humidity since, in a dwelling, it is only emitted by human metabolism and combustion whereas humidity is affected by other factors such as various human occupancies or weather conditions.

VOC (Volatile Organic Compound) sensors are also more and more included on board of ventilation products or IAQ monitoring devices. But, despite their cheapness, they have not been used for a normative or regulatory purpose, except to detect human presence in toilets, because of their lack of discrimination capacity between the many types of VOCs. Devices to measure specific and harmful VOCs, like formaldehyde and benzene, are still expensive and not available for continuous monitoring.

Moreover, affordable and miniaturized particles matter (PM) sensors have also been developed in recent years and have raised interest due to the massive negative impact of PM pollution on human health. According to European Energy Agency estimates, 428 000 premature deaths originated from long‑term exposure to PM2.5 concentrations in Europe in 2014 (European Environment Agency, 2017). And, in China, the issue of PM2.5 is even more critical and concentrations regularly reaches levels as high as 600 µg/m3[2].

When we assess a ventilation system according to those parameters, we rarely use the raw concentration itself as it varies during the day according to human activities. Indicators integrate the concentration over the time and thus take into account the level and the duration of the exposure.

We will now present a sample of indicators based on CO2 and humidity.

## 2.1 Cumulated CO2 values in ppm.h – threshold 2000.

This indicator has been developed for the assessment of humidity controlled systems by the Expert Group in charge of assessing Demand Control Ventilation Systems in France (n°14.5, 2015). It is calculated in each sleeping or living room, during occupancy time and from 1st of October to the 20th of May, this part of the year being considered as representative of the heating period. Each hour, if the CO2 concentration exceeds 2000 ppm, the concentration is added to the indicator result (see Figure 1).

The advantages of this index is that it is discriminative and thus there are large differences in cumulated CO2 values in ppm.h from the different systems assessed. However, the threshold is very high and that indicator is not suitable for instance for control strategies based on CO2 sensors where the set point could be 1950 ppm, which is rather high, and nevertheless sallows to keep the cumulated ppm.h to zero. Another drawback of this indicator is that the value obtained is dependent on the duration of the simulation or measurement: the longer the period, the higher the value.

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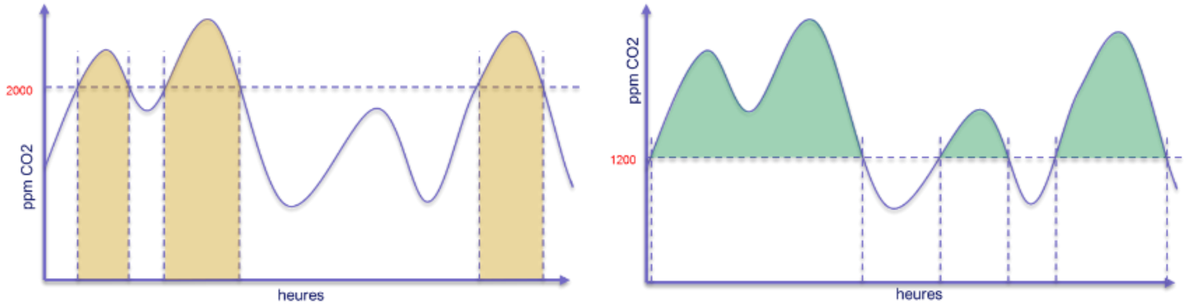
[2] Measured in April 2017 at the US ambassady. http://www.stateair.net/web/historical/1/1.html

## 2.2 Cumulated CO2 values in ppm.h – threshold 1200

In the Netherlands, a cumulative ppm CO2 indicator is also often used. The threshold is set at 1200 ppm and is consistent with the standard NEN 1087 setting 1200 ppm as the maximum concentration value acceptable in individual rooms (Itard, Ioannou, Meijer, Rasooli, & Kornaat, 2016). Only the CO2 concentrations in excess of the threshold are considered. This indicator is slightly less discriminative than the previous one.

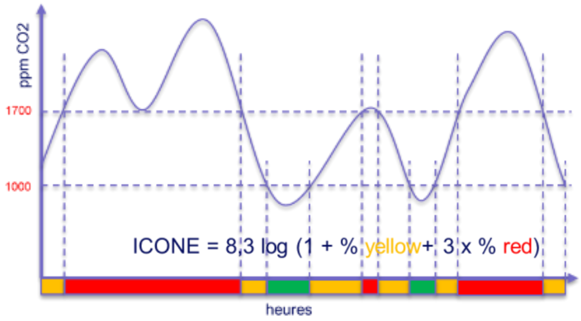
## 2.3 ICONE Air stuffiness index (CO2)

More recently, a new stuffiness indicator called ICONE has been introduced in France by the CSTB (Centre Scientifique et Technique du Bâtiment) in 2007 for IAQ assessment in schools. Ribéron (Ribéron, et al., 2016) presented this indicator and discussed its possible use for residential buildings.



a) Cumulated ppmh CO2 > 2000 ppm

b) Cumulated ppmh CO2 > 1200 ppm



c) ICONE

Figure 1: Illustration of the determination of 3 stuffiness indicators

The founding principles of ICONE are:

- a logarithmic law, similarly to olfactive perception,
- a scale from 0 to 5, 0 being the best score and 5 the worst,
- if all CO2 concentrations are below 1000 ppm, the ICONE indicator value is 0,
- if all CO2 concentrations are above 1700 ppm, the ICONE indicator value is 5,
- if all CO2 concentrations are in the range of 1000 to 1700 ppm, the ICONE indicator value is 2.5.

The 0 to 5 scale is very easy to understand for a non-expert and the value is independent of the duration.

## 2.4 Condensation Risk

In France, in the frame of the assessment of humidity controlled ventilation, the condensation risk is evaluated through the number of hours where the relative humidity exceeds 75%.

# 3 COMPARISON OF INDICATORS BY SIMULATION WITH SEVERAL VENTILATION SYSTEMS

## 3.1 Models and assumptions

Simulations are performed using the Mathis software, a multizone IAQ analysis tool. Demouge (Demouge, 2017) described the models and assumptions used in the software. The building is a 4 room 2 storey equipped with one toilet and one bathroom. The occupancy scenario considers 3 people living in the dwelling and the weather data is typical of Paris. The simulation is performed during the heating period and four ventilation strategies are investigated:

- No ventilation at all.
- Natural air inlet in main rooms, constant airflow mechanical extraction grilles in service rooms - UVU CA.
- Humidity controlled natural air inlet in main rooms, humidity or presence controlled mechanical exhaust grilles in service rooms - UVU HB.
- Bidirectional ventilation system with constant airflow grilles: supply in main rooms, exhaust in service rooms - BVU CA.

## 3.2 Stuffiness indicators comparison in a dwelling with different ventilation strategies

Stuffiness indicators are calculated in both the living room and the main sleeping room supposed to be occupied by two adults.

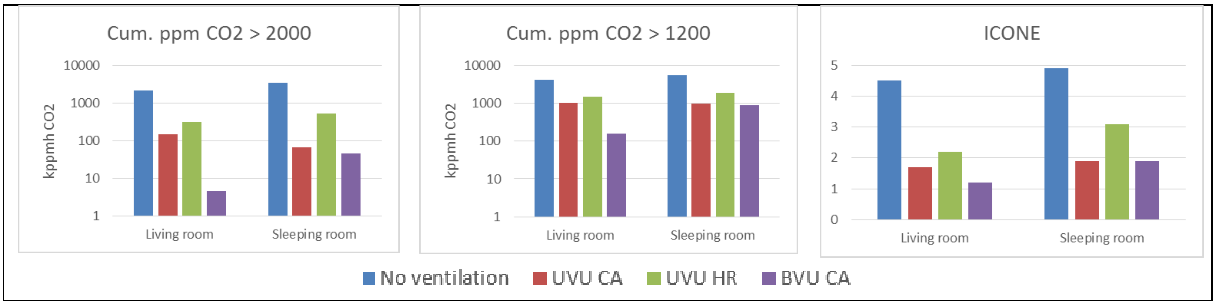


Figure 2: Comparison of stuffiness indicators in the living room and the main sleeping room of a dwelling equipped with either constant airflow extraction ventilation (UVU CA) or humidity control exhaust ventilation (UVU HB) or constant airflow bidirectional ventilation (BVU CA).

The three stuffiness indicators give similar results. The ranking of systems is the same except for ICONE where UVU CA and BVU CA in the sleeping room lead to the same level whereas BVU CA was slightly more efficient with cumulated ppm.h indicators.

Cumulated ppm.h indicators have to be reported on a logarithmic scale in order to be easily readable, validating in some way the logarithmic law chosen by Ribéron for the ICONE indicator.

Of course, the case with no ventilation is by far the worst from an IAQ perspective. Among the cases with ventilation, BVU CA is the system ensuring the best results, followed by the UVU CA, UVU HB coming third. UVU HB system performs well in the living room (ICONE = 2) but is struggling to lower the stuffiness in the sleeping room (ICONE = 3). However, the stuffiness is much lower than without ventilation.

### 3.3 Condensation risk in a dwelling with different ventilation technologies

The condensation risk is two times higher in the bathroom than in the kitchen (Figure 3). The case with no ventilation has not been reported because the number of hours with a relative humidity over 75% was above 5000 and was difficult to compare with values obtained with ventilation. In the kitchen, the three ventilation systems studied performed quite similarly. In the bathroom, the UVU HB has the best performance with the lowest number of hours with condensation risk. This is due to the peak airflow being higher than for other systems (45 m3/h compared to 30 m3/h). A lower number of condensing risk hours means also less condensation on the mirror, which is much appreciated by occupants.

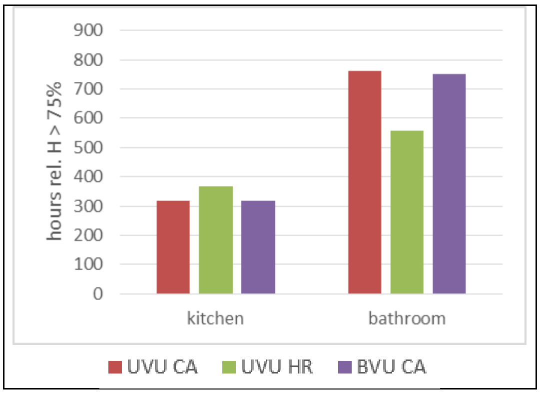


Figure 3: Condensation risk in the kitchen and in the bathroom of a dwelling equipped with either constant airflow extraction ventilation (UVU CA) or humidity control exhaust ventilation (UVU HB) or constant airflow bidirectional ventilation (BVU CA).

## 4 IAQ MONITORING WITH AN IAQ CONNECTED OBJECT

### 4.1 Description of the IAQ connected object and protocol

The IAQ connected object consists in different sensors to account for several aspects of air quality: usual data on CO2, on relative and absolute humidity (accessible through simultaneous temperature measurement) are collected but also data on VOC and on particles.
The accuracy of the sensors is given in the table below.

Air Quality Sensor Module:
PM2.5 (0.3-2.5um)
CO2: 0-2000ppm
VOC: 0-3ppm
RH:0-99%
T:-10-50℃

Table 1 – specifications of the sensors.

Thanks to an optional wireless connection to customers, each IAQ connected object but also every ventilation product equipped with these sensors send data every 5 minutes to the cloud. The number of data is very high for each dwelling.

The datasets available are of several kinds: those of the sensors but also the ones of user's settings like speed control (boost), vacation schedule etc.

Data is encrypted and decrypted at the end of the chain in the cloud where it joins data directly obtained from the Breezometer[3] cloud for external pollution evaluation: we calculate a sub-index of indoor and outdoor pollution which allows the user to follow daily, weekly or monthly indicators reporting air pollution. PM 2.5 concentration measured inside is compared to hourly outside PM 2.5 concentration at the same location.

Figure 4 – Principle of IAQ connected object.

Thanks to this IAQ connected object, work can be carried out on real data and compared to results obtained from simulated models, especially on CO2.

For this study, we selected sleeping room datasets spanning over a duration of more than 3 months amongst the ca 100 available datasets. Four datasets fulfilled these conditions.

## 4.2 Detection of occupancy

Occupancy detection is needed to compute IAQ indicators as they are calculated only during occupancy periods. Indeed, if people are absent, the CO2 level will be low and the IAQ indicators will be artificially good, even with a poor ventilation system. The goal of these indicators is to assess the IAQ when people are present. This is particularly important for onsite monitoring where occupancy scenarii may vary a lot from a dwelling to another.

But onsite monitoring and occupancy detection may be tricky. Itard (Itard, Ioannou, Meijer, Rasooli, & Kornaat, 2016) developed a hybrid methodology based on the analysis of CO2 concentration variations and the data from a PIR sensor. They obtained good results although the methodology hasn't been cross-compared with any other reliable method.

We developed our own method based on CO2 concentration dynamic analysis. It was calibrated to detect only significant presence and neglect very short time movements. We applied our detection algorithm to our available sleeping room datasets. We decided to focus on sleeping rooms since it is where the stuffiness usually reaches the highest level in dwellings. Furthermore, it is really difficult to track presence in the rest of the dwelling as underlined by Ribéron (Ribéron, et al., 2016).

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[3] https://breezometer.com/ Breezometer is a company providing an outdoor air quality map computed from air quality monitoring organizations' data, meteorological data and traffic data.

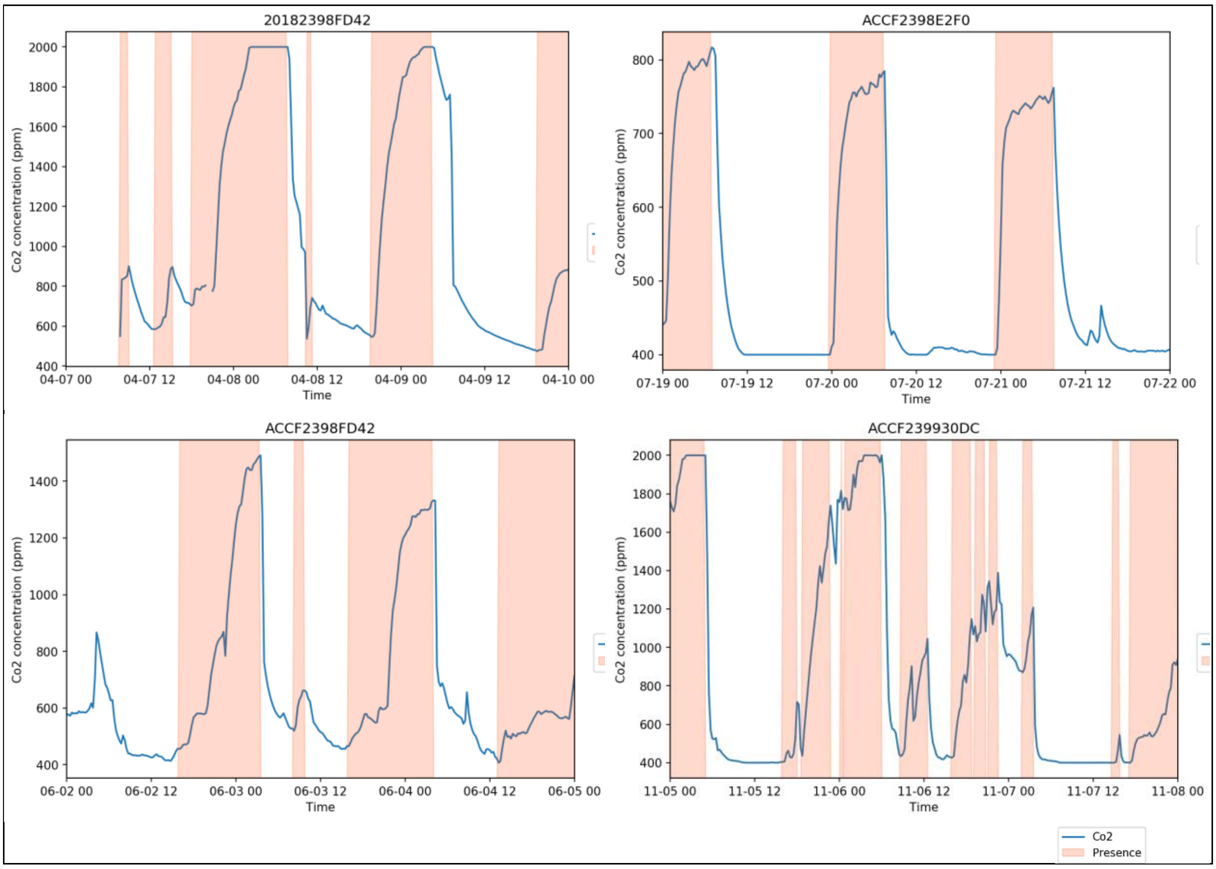


Figure 5 – Occupancy detection examples over a 3-day period for several sensors.

We applied the detection algorithm on datasets with sufficient data (duration > 4 weeks). As we can see on Figure 5, the detection algorithm performs very well. However, there are some limitations: the detection could be disturbed by window or door openings inducing fast CO2 drops and making the algorithm falsely detect people leaving the room. A compromise is also to be found between the robustness and the accuracy of the detection. A more accurate detection will probably detect movements that are not meaningful while a more robust algorithm will probably miss movements. It may be useful for further validation of the algorithm to compare its detection results with the presence occurrences obtained through an accurate reporting from inhabitant or thanks to a webcam. It would also help to assess the detection uncertainty which may be useful when we calculate IAQ indicators.

## 4.3 Calculation of indicators and discussion

Now that we have detected occupancy, it is possible to compute the stuffiness indicators. They are computed with sleeping room datasets for the entire period of the dataset, ranging from 14 to 22 weeks depending on sensors. For the need of the study, the cumulated ppm indicator is recomputed over a one week duration in order to compare the values whatever the length of the datasets.

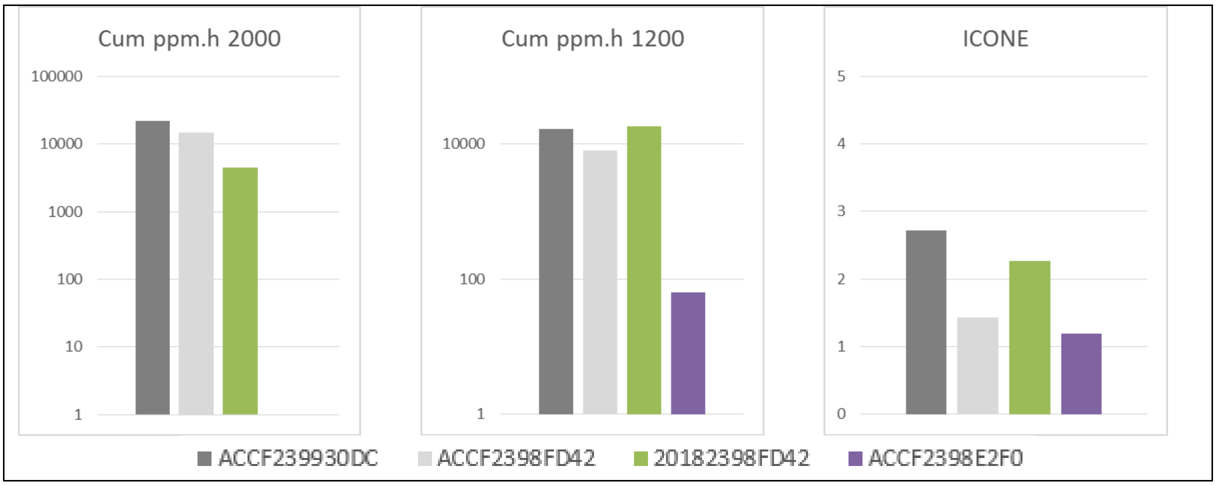


Figure 6 – Air stuffiness indicator value for 4 sensors in sleeping rooms.

The sensor 20182398FD42 (green) was positioned in a dwelling ventilated by humidity control exhaust ventilation. A bathroom is connected to the sleeping room. The bathroom is equipped with an extraction grille. The ICONE value is 2 which is good.

The sensor ACCF2398E2F0 (violet) was positioned in a dwelling with bidirectional ventilation in a sleeping room adjacent to a bathroom with an extraction grille. The ICONE value is 1. This means that the CO2 concentration is rarely above 1000 ppm. The IAQ is very good.

We do not have any information on the ventilation system of the dwelling where sensors ACCF239930DC (dark grey) and ACCF2398FD42 (light grey) were positioned.

Regarding sensor comparison, the purple one did not account for any value with the cum. ppm.h 2000 indicator due to a too high threshold. This indicator does not capture as much information as the two other.

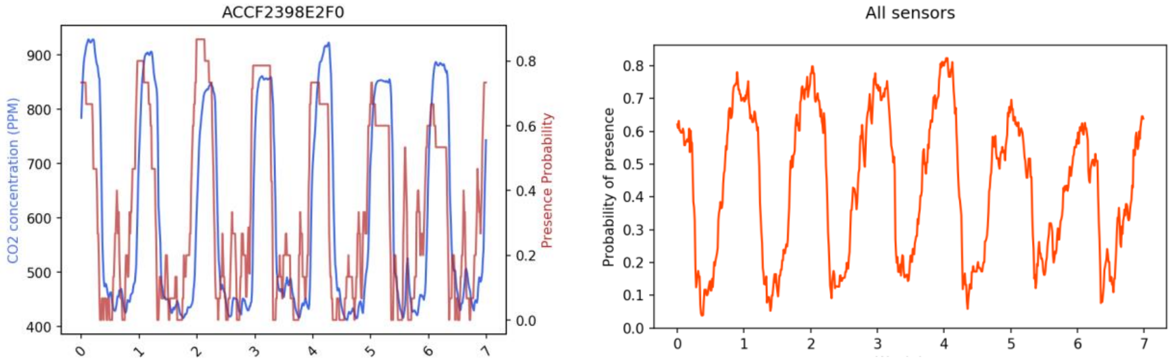
A drawback of cum ppm.h indicators is that the value obtained is proportional to the measurement duration and does not allow a real time calculation. To compare the cum ppm.h 2000 indicator with a simulation, the measurement should last for a year! Real time calculation is only possible with the ICONE indicator. Another benefit of ICONE is that it is constructed on 2 thresholds, which makes it less sensitive to threshold effects than cumulated ppm indicators.

Monitoring IAQ on site is now possible and allows the calculation of stuffiness indicators. This can be done after the reception of the ventilation system to check if it performs correctly. The information may also be displayed in real time to the user to alert him and to provide him with advices in case the IAQ deteriorates too much. For these reasons, ICONE is the most convenient stuffiness indicator among the 3 investigated ones for onsite monitoring.

## 4.4 Other uses of occupancy data

Beyond the calculation of IAQ indicators, occupancy data and IAQ parameter monitoring opens the door to more advanced control strategies for the ventilation system.

We can also use these data at large scale to increase our knowledge of typical occupancy patterns or habits. This knowledge may be used in future normative or regulatory work to improve the accuracy of the models and in turn the efficiency of ventilation systems.



a) Typical weekly CO2 and occupancy pattern.

b) Average typical weekly occupancy pattern.

Figure 7 - Typical weekly patterns.

From occupancy data further analyses can be made such as the average time spent in the bedroom as displayed in Table 2.

It is also possible to detect intrusions during vacations. The case occurred with one sensor and it was possible to know the exact schedule (start time and duration) of the robbery!

| | |
|---|---|
| 20182398FD42 | 8.0 h |
| ACCF2398E2F0 | 8.4 h |
| ACCF239930DC | 8.9 h |
| ACCF2398FD42 | 7.3 h |

Table 2: Duration of the night (presence in the room).

### 4.5 PM 2.5 : comparison of indoor and outdoor concentrations

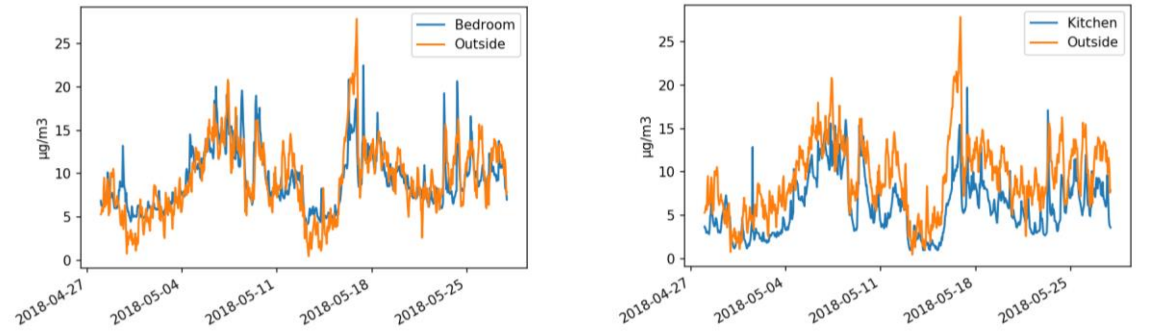
As explained in 4.1, the IAQ connected object also measures PM2.5 concentrations and gathers the data of the outside environment. We used this data to investigate the PM2.5 transfer from the outside to the inside.

Kirchner (Kirchner, et al., 2002) conducted an experiment in 2000 in an unoccupied ventilated apartment in Paris to investigate the transfer of pollutants from the outside to the inside. They found that the indoor / outdoor (I/O) ratio was around 0.8. A ratio lower than 1 means that there are less particles inside than outside.

They also found that the value of the correlation factor between hourly outdoor and indoor concentrations was 0.89. The correlation factor expresses the statistic relationship between two data series. A value of 1 means that inside and outside concentrations fluctuates in an exactly proportional way, therefore a value of 0.89 reflects a very high synchronization.

We positioned an IAQ connected object in an occupied dwelling in Lyon's urban area, the dwelling being equipped with humidity controlled extraction ventilation (UVU HB). The PM2.5 level was monitored in the sleeping room and in the kitchen during May 2018. The dwelling was regularly occupied by a 4 people family.

The measured PM2.5 level inside is compared to the estimated level outside and plotted n Figure 8.



a) Sleeping room and outside. b) Kitchen and outside.

Figure 8 - comparison of outside and inside PM2.5 concentrations.

The first takeaway is that inside and outside curves fit very well and have a correlation factor of respectively 0.79 and 0.78 in the sleeping room and in the kitchen. This is a very good correlation since *measured* data inside were compared to *estimated* data outside. Most of outside peaks coincide with inside peaks. In our study, the correlation is slightly lower than the one measured by Kirchner since Kirchner measured the outside level whereas in our case the value is estimated from distant measurement and computation which is of course less accurate. Furthermore, there may be also some influence of human occupancy in the dwelling, especially in the kitchen.

The second takeaway is that the levels in the sleeping room and in the kitchen are strongly correlated (cor = 0.93). Actually, settlement time for PM2.5 is ranging from hours to weeks, which means that, in a ventilated dwelling, PM2.5 entering main rooms will not have time to settle, being removed quickly by the ventilation in service rooms. This also makes us conclude that there are few or no PM 2.5 sources in the dwelling. There are some emissions in the kitchen due to the use of the oven but this pollution is short lasting and does not affect significantly average values.

From Figure 8 we could conclude that the PM2.5 level is lower in the kitchen than in the sleeping room. Actually, we made a verification by putting the two sensors side by side. There was still a discrepancy of a few µg/m3 between the two sensors. For this reason, we cannot conclude further on the absolute level. In the same way, it does not make any sense to compute an indoor/outdoor ratio since any offset between a sensor output and an outdoor value would dramatically impact the ratio value.

However, based on the high correlation factor between outside and inside concentrations, we can conclude that PM2.5 levels in a dwelling are mainly due to ambient pollution and that there is no or little PM2.5 emission or reemission in the dwelling itself, even in the kitchen. PM 2.5 being harmful, it would make sense to block them with high efficiency filters when fresh air is entering the dwelling. We expect this filtration would strongly decrease the indoor level compared to the outdoor one.

## 5 CONCLUSIONS

Multizone simulation of ventilation systems in a 4 room dwelling shows that the bidirectional ventilation system is the one ensuring the best IAQ in main rooms and humidity controlled exhaust ventilation is the one ensuring the best comfort in the bathroom.

The analysis of data collected from cloud connected IAQ objects has enabled us to compute and to compare stuffiness indicators. Until now, these indicators were mainly used in simulation for normative compliance verification purposes. Actually, they are calculated only for occupancy period and this information is difficult to get. Now, thanks to IAQ connected objects and the detection algorithm developed, it is possible to assess them onsite, either as post calculation or in real time. Post calculation is useful to compare real life data (IAQ indicators and occupancy scenarios) to simulation outputs. It may lead to adapt the normative assumptions. Real time data is useful to the user to detect anomalies and carry out corrective measures such as activating the boost ventilation in case of internal pollution overshoot. Thanks to connectivity and a dedicated smartphone application, the boost function is very easy to trigger.

The comparison of air stuffiness indicators enables us to conclude that the ICONE is the best indicator between the three we analyzed: the scale is easy to understand and the output is independent of the length of the measurement period.

Furthermore, we found out that in an occupied dwelling, outdoor and indoor levels are strongly correlated which means that PM2.5 indoor concentration is mainly driven by the outside concentration. The human activity inside has little or no influence on that level of pollutant.

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