Performance 2 project - Analysis of the interactions between the Humidity-based DCV systems and IAQ in homes 15 years after their construction

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ABSTRACT

The Performance 2 project (2020-2024) is a French national research project that aims to evaluate the long-term performance and durability of Humidity-based Demand Controlled Ventilation (DCV) systems installed in two multi-family social housing buildings, located in Paris and Villeurbanne, France. This study investigates the interaction between the ventilation systems and the Indoor Air Quality (IAQ) 15 years after construction.
Continuous measurements over a two-year period were conducted on the Air Terminal Devices (ATDs) of the ventilation system functioning and the IAQ (CO_2, Relative Humidity, and for Paris, Particulate Matters – $PM_{2.5}$, Volatile Organic Compounds - VOC); with the sensors located close to the ATDs. Additional monitors measuring all the IAQ parameters plus Formaldehyde were placed in dry rooms for two separate winter IAQ campaigns. Occupants interviews were used to assess occupants' behaviour over that two separate two weekly periods. This study has been carried out on 18 existing dwellings (13 in Paris and 5 in Villeurbanne, France) using data collected from November 2021 to December 2023 in Paris and from June 2022 to May 2023 in Villeurbanne.
This analysis provides insights into the dynamics of pollutant concentrations, considering both standard reference values and temporal trends (dynamics). Focus was given to $PM_{2.5}$, with findings revealing significant $PM_{2.5}$ concentrations primarily in dwellings occupied by smokers. VOC concentrations varied among dwellings, with one particular case due to an under-ventilation situation (no source of humidity detected therefore the ventilation system provides always low airflow) leading to elevated levels, however most of the cases show consistent levels due to a daily use of perfumed candles, air freshener and incense. CO_2 levels were generally low, however certain rooms exhibited higher concentrations attributed to under-ventilation in Villeurbanne and high occupancy in Paris.

KEYWORDS

Smart ventilation, residential ventilation, IAQ, energy efficiency, durability, humidity

1 INTRODUCTION

Relative humidity-controlled mechanical extract ventilation (RH-MEV) systems have been widely used in France for 40 years [1]. Most of the new residential buildings complying with RT 2012 and now RE 2020 energy performance regulations, are equipped with such systems [2] and currently they are considered as a reference system. In 2019, "Performance 2" project was launched in three phases to:

1. conduct a full winter analysis of the system after 13 years of in-situ operation using the installed sensors (non-recalibrated) and without major intervention;
2. collect the air terminal devices – ATDs (inlet and exhaust units) and sensors for laboratory testing before and after cleaning and maintenance and finally,
3. re-install the cleaned and maintained ATDs (where the hygroscopic component reminds intact) with calibrated and new (in Paris) sensors.

The phase (1) has been described in [3] and phase (2) in [1]. This paper presents the methodology and the results of the data analysis of the measurements collected over 2 years after these phases regarding the Indoor Air Quality in the dwellings studied in this project. The objectives of this study are to identify the interactions between the performance of the RH-MEV systems and the concentrations of different other pollutants, including VOC, Formaldehyde, and $PM_{2.5}$, and CO_2.
The evaluation of the durability of the RH-MEV systems in these two buildings after 15 years has been carried out by comparing the current energy performance and IAQ (RH and CO_2 only) with the results obtained at the commissioning, as well as the theoretical performances evaluated 15 years ago, and presented in previous papers [4–6].

2 METHOD

2.1 Case studies, campaigns and previous diagnosis

The two French social housing buildings studied are:

- a building of Paris Habitat where 19 dwellings were instrumented by Aereco in 2007 (from the 4th to the 8th floor), in Paris,
- a building of Lyon Métropole Habitat where 12 dwellings were instrumented by Anjos in 2007 (from the 1st to the 5th floor), in Villeurbanne (near Lyon).

At the beginning of the project, an inspection of the ventilation installations was carried out, partly applying the French Promevent protocol [8].
The Performance 2 campaigns include:

- Continuous measurements close to the ventilation terminals, which already had CO_2, Temperature and RH sensors in place since the Performance 1 project 15 years ago. For Performance 2 and only for the building located in Paris, VOC and PM measurements were added to the previous ones. Additionally, two outdoor weather stations have been installed on the Paris building;
- Two IAQ winter campaigns (one in winter 2021-2022 and another in winter 2022-2023) during which two NEMOs IAQ monitors were installed in each voluntary dwelling (one in the living room and one in the parental bedroom). These monitors measured CO_2, Temperature, RH, light VOCs, Formaldehyde and $PM_{2.5}$. Additionally, an outdoor NEMOs was installed during each winter campaign. Quality data have been collected regarding the dwelling and the occupant's behaviour using a technical questionnaire, a weekly log filled by the occupants during the winter IAQ campaign and answers of the occupants during an interview conducted at the end of the winter IAQ campaigns [7];
- Laboratory campaigns to assess the current hygro-regulated performance of the ventilation terminals, verify the operation and reliability of the on-board sensors after 13 to 15 years in the dwellings [1], and to characterize the uncertainty of the sensors (embedded and NEMOs).

2.2 Characterisation of collected data

During the different on-site campaigns (2-years monitoring at ATDs and the 2 winter IAQ campaigns) and the laboratory campaigns (ATDs and sensors characterization), we have collected the following data for each dwelling:

- information about the dwelling;
- information on the "life of the occupants" during the winter IAQ campaigns;
- information on occupants' habits, their use and knowledge of their ventilation system, and their perception of IAQ;
- results of measurements of indoor parameters and pollutants, using NEMOs sensors for 2 weeks;

- results of measurements of indoor parameters and pollutants, from embedded sensors;
- ventilation system operating measurement results.

We have identified limits for each of this type of data by analysis of the characteristics of each sensor, the results of the inter-comparison of the sensors (during laboratory campaign), the campaign protocols and the disruptive events noted during the project (Table 1). This preliminary analysis of the data is essential to assess the quality of the data and to identify analyses that cannot be carried out, in particular the use of the "absolute values" for some measured parameters. This stage, often overlooked, has raised awareness of the importance of questioning the reliability of each measurement and each data, in order to propose scientifically acceptable analyses.

Table 1: Main limitations associated with the various data collected in Performance 2 project

Parameter	Sensor	Main limits	What to do?
CO_2	NEMos	Weekly autocalibration to lowest value cannot be deactivated and cannot be traced	Paris first IAQ Campaign no useful (2 autocalibrations non traced)
	Board Sensors	Saturation ≤ 2000 ppm In Villeurbanne: weekly on lowest value which cannot be deactivated	No mean calculation
Formaldehyde	NEMos	Average over 2 hours Dispersion of values	
Total VOC	Board Sensors - Paris	"Human nose" mimicry	Vigilance on results and dynamics
Ligh VOC	NEMos	Dispersion of values	No threshold value
PM2.5	Board Sensors - Paris	High uncertainty Artifact: one-time peak	Vigilance on descriptive statistics
	NEMos	High uncertainty Dispersion of values	Vigilance on descriptive statistics
PM10	For certain NEMos	Extrapolated measurements with PM2.5	No useful
PM1	NEMos	High uncertainty	Vigilance on descriptive statistics
Emission Sources	Declarative (logbook / interview)	Cognitive biases + Social desirability	
Aeration	Declarative (logbook / interview)	Cognitive biases + Social desirability	Correlation with drop in temperature/RH/CO_2

3 RESULTS

3.1 CO_2 levels

CO_2 is not toxic in the proportions found in dwellings. It is nonetheless an excellent indicator of the occupancy/air renewal balance. To evaluate the durability of the ventilation systems, we had conducted previous analysis of the CO_2 levels in the dwellings according to an indicator used 15 years ago during the Performance 2 project [5]. This indicator used a threshold at 2000 ppm. Two dwellings in Paris were identified with high CO_2 concentrations, mainly due over-occupation in bedrooms. In a deeper analysis, we studied three new thresholds:

- 800 ppm: threshold accepted as protective against airborne transmission by both the French "Haut Conseil de Santé Publique" and the World Health Organisation (re-evaluated since the Covid crisis), and the first threshold in the ICONE index;
- 1000 ppm: defined in the French Standard Departmental Health Regulations;
- 1500 ppm: second ICONE index threshold.

3.1.1 Focus on probable occupancy periods without airing

The distribution of the CO_2 values measured was analysed first over the entire monitoring period, then we focused on the difference between heating season/outside the heating season, day/night (midnight to 6 am), and finally, for the bedrooms, a focus on the night during the heating season (conditions assumed to be the most penalising). When we separated data from heating and non-heating periods, we identified a clear increase in values during the heating period, as might be expected in a period when the use of airing by windows opening is largely reduced. Then, we focused on the most critical period in terms of CO_2, which is at night, during the heating period, since this is the longest recurring period of occupancy in a room, during which only ventilation system provides air renewal. The data collected cannot be used to estimate occupant exposure, as it is too difficult (and unreliable) to judge the exact period during which they are present in a room. The advantage of successive focuses is that we can obtain information on air renewal during periods when occupancy is almost certain (at night in the bedroom), and when the risk of confinement is highest (during the heating period), without drowning out these values in the middle of periods when occupancy is much less certain. A synthesis of these night-time distributions over the heating period is given for all the main bedrooms in Villeurbanne (left) and Paris (right) in Figure 1. For six apartments in Paris, the CO_2 concentrations are above 1000 ppm around 90% of the time at night during the heating period, and for one apartment (P10) CO_2 concentrations are higher than 1000 ppm for 75% of the studied period, which illustrate an insufficient air renewable in these rooms.

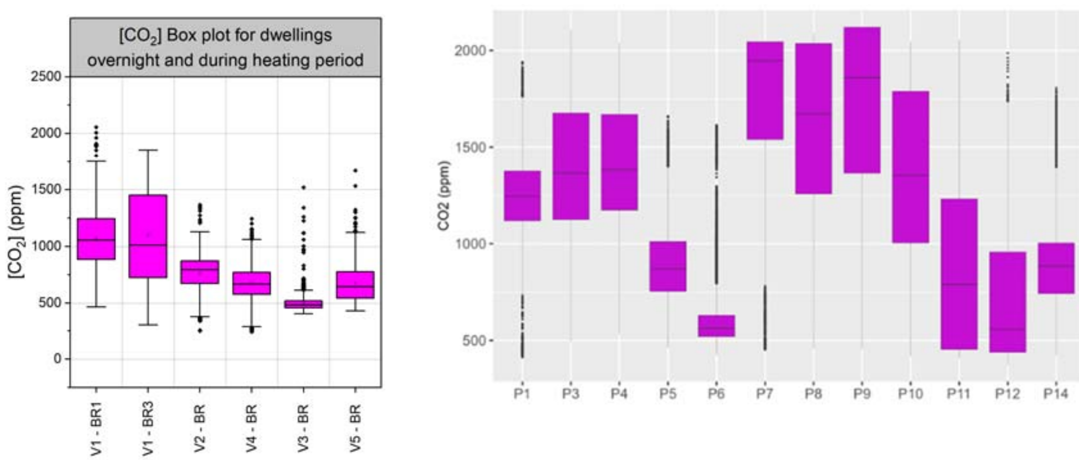

Figure 1: Distribution of CO_2 concentrations at night during the heating period in 2022 in the main bedrooms in Villeurbanne (left) and Paris (right)

Here the explanations we have been able to identify for the apartments with the higher levels of CO_2:

- P1: limitation in maximum airflow of extract ATDs and insufficient pression evidenced. So, even if the appartement presents high relative humidity production and total extracted airflow seems to be not lower than the other dwellings for the same typology, airflow is not enough to extract the production of CO_2.
- P3 and P4: no dysfunction of the ventilation system. No data collected from the occupants. Analysis of the CO_2 concentrations distribution shows that the main part of the time, the CO_2 concentration are below 1500 ppm.
- P7: extracted flows are almost at a minimum and not sufficient to evacuate the CO_2. We identify no production of humidity, shower or cooking in this apartment, explaining the very low total airflow (no explanation has been identified to explain the CO2 level during night).

- P8: 64% of the time above 1500 ppm. No dysfunction of the ventilation system. The bedroom is occupied by two persons, who have declared that they sleep with the door closed. The occupants stated that they had identified leaks around the windows in some rooms: an unequal distribution of leaks on the envelope could induce an under-ventilation of some rooms, which could explain the CO_2 values measured in the bedroom. A detailed diagnosis of the apartment airtightness and airflow modelling would be needed to confirm this hypothesis.
- P9: over-occupation of the bedroom. Used to be the "kids bedroom" but now the two kids are adults and have two big dogs with them in the small bedroom, and sleep with the door closed.
- P10: no dysfunction of the ventilation system. No data collected from the occupants.
- In Villeurbanne, both for the bedroom in V1 and V2, the air inlets showed during the laboratory campaign dysfunction with limited airflow rates. Nevertheless, the CO_2 concentrations do not exceed 1500 ppm.

3.1.2 ICONE index

In France, the "ICONE" index has been developed by the CSTB to assess the air stuffiness of a room by giving it a score from 0 to 5, particularly for schools (0 corresponds to absence of air stuffiness and 5 corresponds to an extreme air stuffiness). By extension to other types of buildings, the ICONE index can be used to assess the quality and efficiency of ventilation and air renewal systems in an enclosed, occupied space. It is calculated exclusively for the periods during which the room is occupied and incorporates both a notion of thresholds with two levels (800 ppm et 1500 ppm) and a notion of time, considering the length of time during which they are exceeded in the presence of the occupants. In Performance 2, we considered only the night periods (midnight to 6 am) in the bedrooms during which the occupants are *a priori* present (Figure 2). In Paris, the ICONE index shows three cases of "very high" stuffiness: the bedrooms in apartments P7, P8 and P9. Apartments P1, P3, P4 and P10 also show "high" stuffiness. These results are consistent with the previous analysis with the threshold at 1000 ppm. Like any index, the ICONE is not free from threshold effects. To consider the variability of realities within each category of the ICONE index, we calculated the percentage of time the 1500 ppm threshold is exceeded at night for each apartment in Paris (Figure 3). In P7, the threshold is exceeded more than three-quarters of the time at night, which distinguishes it from P8 and P9 by around 10 points. The difference between P1 and P3, P4 and P10 is also particularly visible on this graph. Only 10% of the night, i.e. relatively marginally, did P1 exceed the 1500 ppm threshold.
In Villeurbanne, calculation of the ICONE index shows a favourable situation for all dwellings.

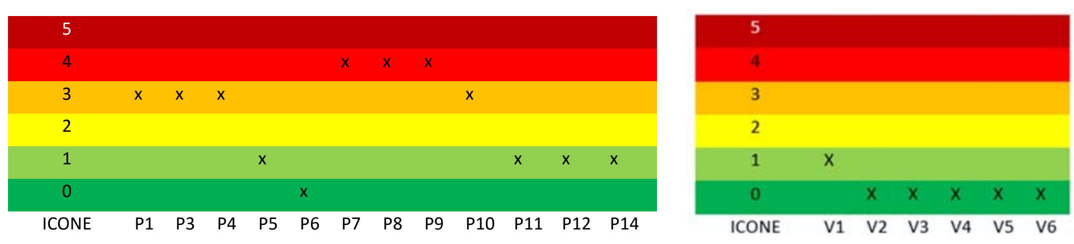

Figure 2: ICONE index calculated during night (0h – 6h) for each bedroom - Paris (left) and Villeurbanne (right)

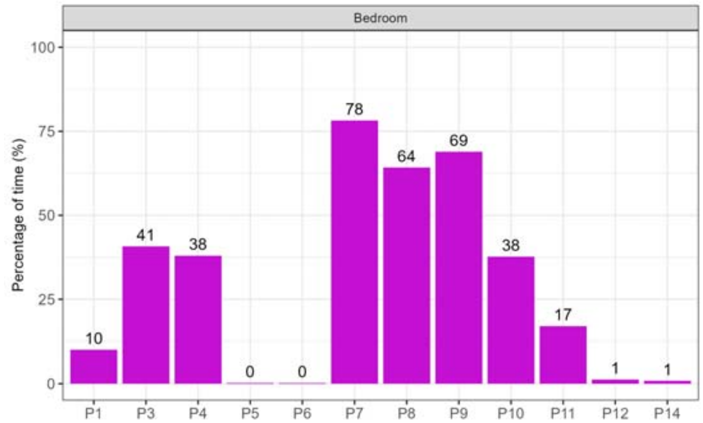

Figure 3 : Percentage of time CO_2 exceeds 1500 ppm at night during the heating season in Paris

Lastly, although some apartments are over-occupied and have occupants who sleep with the door closed, only ¼ of the bedrooms have 50% of the nighttime spent over 1500 ppm of CO_2.

3.2 PM 2.5

3.2.1 High PM2.5 concentrations in several apartments

Even if the uncertainty of the $PM_{2.5}$ sensors is quite high in relation to the thresholds, we decided to analysis the measurements results in regards the two following thresholds:

- 5 µg/m^3: threshold value proposed by the WHO for the long term;
- 15 µg/m^3: threshold value proposed by the WHO for the short term.

The value of 5 µg/m^3 makes sense in terms of an annual average. Occasional exceedances during the year are therefore "normal", or at least not alarming. In fact, most apartments regularly exceed it. We focused more on the 15 µg/m^3 value over a one-hour period, which can lead to short-term health problems. Figure 4 represents the percentage of time above this value for the year 2022 in Paris (no data available in Villeurbanne). This indicator clearly brings P6 and P9 out, with $PM_{2.5}$ concentration higher than 15 µg/m^3 more than 30% of the time. The occupants' questionnaires indicate that these are smoking apartments. The kitchen in P11 also has high values. In the absence of a questionnaire conducted in this apartment, a possible explanation would be the frequent use of a frying pan, but this cannot be verified here.

Figure 4: Percentage of time (in dark) PM2.5 concentrations are above 5 µg/m^3 and mean value (in red) of PM2.5 for each room in Paris in 2022

To eliminate the small variations of the measurement that do not have health significance in relation to a long-term value, we decided to consider the sliding average value over one hour for each apartment (**Error! Reference source not found.**). P6 and P9 still present bad results without surprise. Apartment P8 also obtained relatively high values, which can be linked to the "very regular" use of scented candles and even incense mentioned in the questionnaire. As P10 was not included in winter IAQ campaign, we no dot have information regarding $PM_{2.5}$ emission in the dwelling.

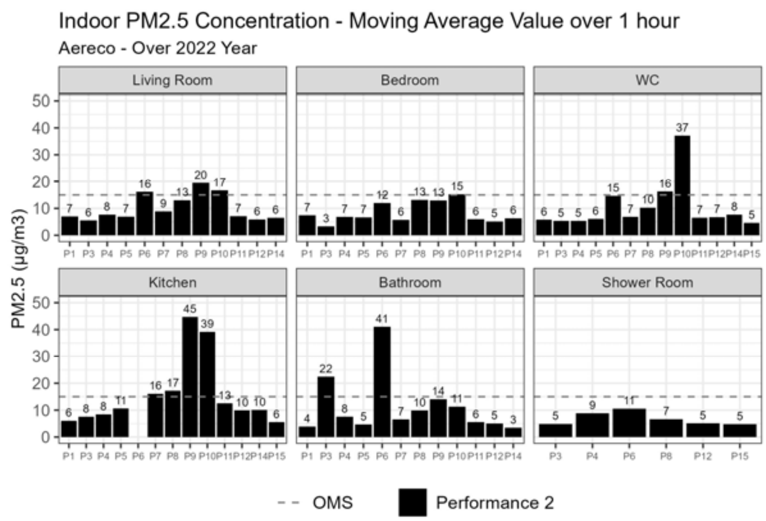

Figure 5: 1-hour moving average PM2.5 concentration per room in Paris in 2022

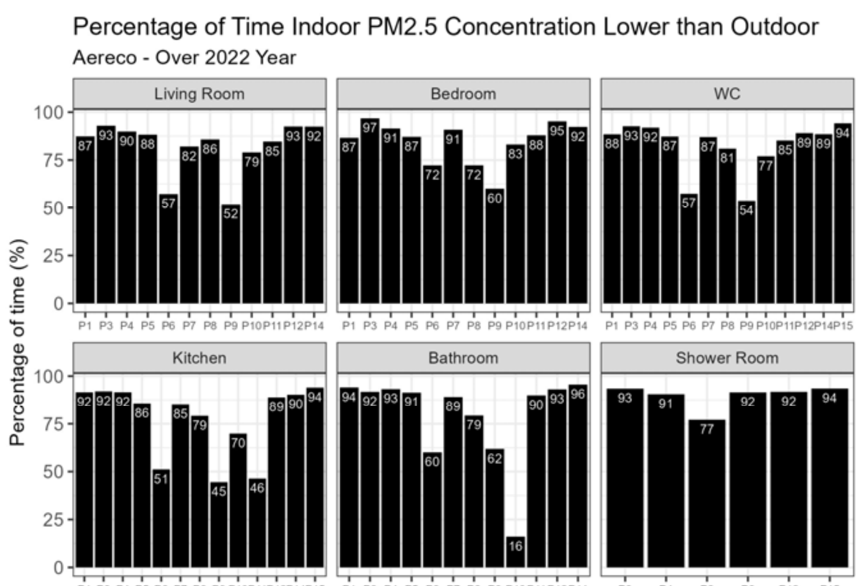

Figure 6: Percentage of time when the indoor PM2.5 concentration is lower than the outdoor concentration for each room in Paris in 2022

3.2.2 Comparison $PM_{2.5}$ concentration inside and outside

As the main source of $PM_{2.5}$ is usually from outdoor, we evaluated the time when indoor concentrations are lower than those from outdoors (**Error! Reference source not found.**). Excepted for smoking apartments P6 and P9, $PM_{2.5}$ concentrations are lower in living rooms than outdoors 80% to 97% of the time. This is also generally the case in the utility rooms, but with greater variation between apartments.

3.3 VOC

3.3.1 Total VOC

Due to the high uncertainty of the sensors used during the campaign, the analysis of the measurements data needs to be considered with a lot of precaution. Thus, our approach consists mainly in identifying the more polluted apartments in terms of VOCs and identifying the probable sources. Figure 7 represents the measured value of VOC for which the concentration are above 70% of the time. We identify that the rooms with the highest values of VOC are toilets, bathrooms and shower rooms. These are the rooms where the use of scented products, particularly in spray form, is most widespread. P6 has particularly high concentrations in its toilets (massive use of air fresheners), and to a lesser extent in the bathroom (use of cosmetics). On the contrary, in living rooms, we measured relatively low values, despite the use of scented candles, which can be compared with the very good performance of the ventilation in this dwelling. Indeed, in addition to important air flow rates, the direction of circulation generated by the ventilation is particularly favorable in the case of pollutants emitted mainly in utility rooms. P8 has the second highest values in the living room, which can be linked to the daily use of essential oils and scented candles. The bathroom also has high values, which can be linked to the systematic use of eau de Cologne.

In dwellings where ventilation malfunctions, we identified that even relatively low emissions in utility rooms can lead to relatively high concentrations in living rooms. This is particularly noticeable in P7, which was identified during the CO_2 analysis, where concentrations in the toilets are rather low compared with the other dwellings, but which have the highest value in the living rooms. We also observed that the apartments with high CO_2 values are also those with the highest VOC concentration in the living rooms, that illustrate interaction between exposure to VOCs and air renewal.

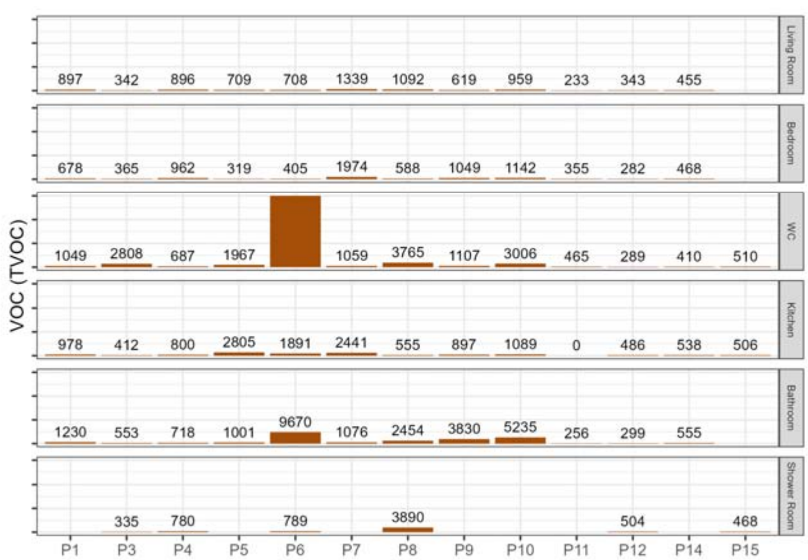

Figure 7: Measured value of VOC for which the concentration are above 70% of the time in Paris

3.4 Formaldehyde

Two threshold values are considered:

- 30 µg/m^3: French regulation for monitoring IAQ in establishments open to the public buildings (i.e. schools);
- 100 µg/m^3: Indoor Air Guide Value (VGAI) - Anses.

As only the NEMOs measured the formaldehyde, we have data only for apartments included in the winter IAQ campaigns (Figure 8).

Two apartments in Villeurbanne significantly exceeded the 30 µg/m^3 threshold during the first campaign, and much less so during the second. In one case, the occupants changed their habits between the two campaigns thanks to a personal inscription to a training on indoor air quality. For the second, the renovation of the floor and wall paintings before the 1st campaign could be responsible for the levels we measured. In Paris, an apartment exceeded the 30 µg/m^3 threshold almost 20% of the time during the first campaign, whereas this no longer occurred at all during the second. The information gathered from the occupants does not allow us to put forward any hypothesis to explain the difference between the 1st and 2nd campaigns. Regarding the second threshold, no apartment have reached 100 µg/m^3.

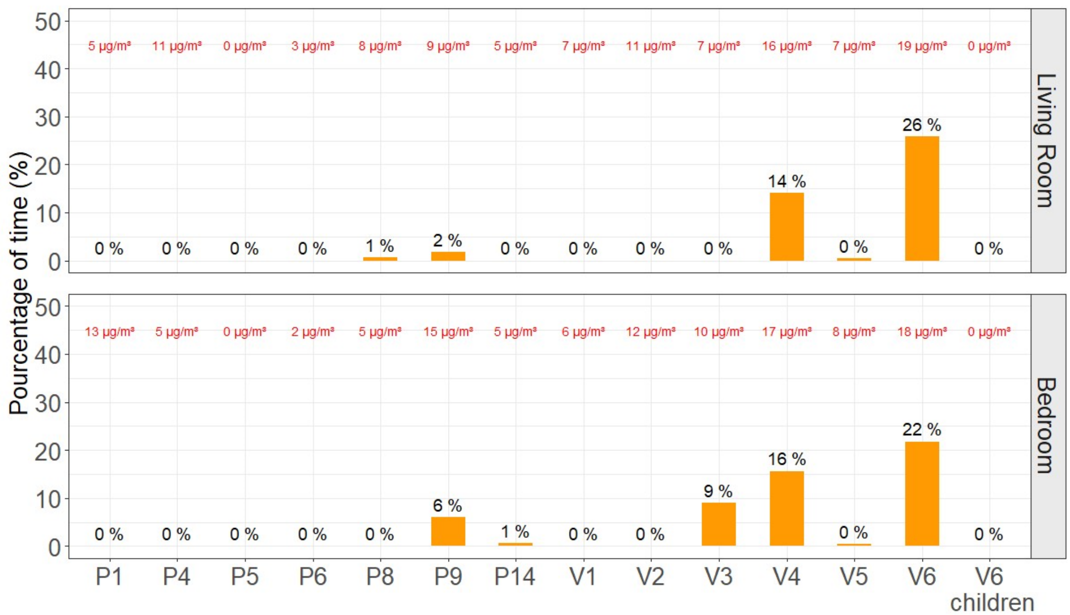

Figure 8: Percentage of time the 30 µg/m^3 value is exceeded in the instrumented rooms of each dwelling during the 1st winter IAQ campaign

4 CONCLUSIONS

The Performance 2 project focused on the ventilation system performance in two multi-family social housing buildings, located in Paris and Villeurbanne (France), built 15 years ago and equipped with Humidity-based Demand Controlled Ventilation. It included the analyses of data collected during 2 years from monitoring at ATDs, winter IAQ campaign with IAQ sensors and interviews of occupants, and laboratory campaigns on the ATDs and the IAQ sensors. This paper presented the main results of the analysis dedicated to the IAQ in the dwellings studied in the project.

Overall, the CO_2 concentrations are quite acceptable within the limits considered (800 ppm, 1000 ppm and 1500 ppm). The high CO_2 concentration measured in some bedrooms are mostly due to over-occupation with closed door during the night.

The measurements of $PM_{2.5}$ carried out showed that:

- The values are around the long-term guide value 5 µg/m^3 recommended by the WHO as an annual average (but the uncertainty of the sensor is high) ;

- Indoor particle levels are generally lower than outdoor levels, almost systematically in dwellings, except for the smoking apartments;
- The values measured in smoking dwellings recurrently exceed the short-term guide value 15 µg/m^3, regardless of the effectiveness of the ventilation system;
- To a lesser extent, the use of scented candles or incense significantly increases indoor PM levels.

The measurements of VOC, even with very high uncertainty of the sensors, show that:

- The rooms most affected by high VOC concentrations are utility rooms, due to the use of scented products in spray form;
- Living rooms are, on average, more polluted with VOCs than bedrooms;
- Changing household products has a direct impact in terms of lowering formaldehyde concentrations, which is much less obvious for light VOCs;
- Even high emissions in utility rooms are diluted by ventilation without generating pollution in the living areas when there is no dysfunction of the ventilation system.

5 ACKNOWLEDGEMENTS

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