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Indoor Air Quality Campaign in an Occupied Low-Energy House with a High Level of Spatial and Temporal Discretization

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Abstract: Background and gaps. The topic of indoor air quality (IAQ) in low-energy buildings has received increasing interest over the past few years. Often based on two measurement points and on passive measurements over one week, IAQ studies are struggling to allow the calculation of pollutants exposure. Objectives. We would like to improve the evaluation of the health impacts, through measurements able to estimate the exposure of the occupants. Methodology. This article presents detailed IAQ measurements taken in an energy-efficient occupied house in France. Two campaigns were conducted in winter and spring. Total volatile organic compounds (TVOC), formaldehyde, the particle numbers and $PM_{2.5}$, carbon dioxide (CO_2), relative humidity (RH), temperature (T), ventilation airflows, and weather conditions were dynamically measured in several points. Laboratory and low-cost devices were used, and an inter-comparison was carried out for them. A survey was conducted to record all the daily activities of the inhabitants. IAQ performance indicators based on the different pollutants were calculated. Results. $PM_{2.5}$ cumulative exposure did not exceed the threshold available in the literature. Formaldehyde concentrations were high, in the kitchen, where the average concentrations exceeded the threshold. However, the formaldehyde cumulative exposure of the occupants did not exceed the threshold. TVOC concentrations were found to reach the threshold. With these measurements performed with high spatial and temporal discretization, we showed that such detailed data allow for a better-quality health impacts assessment and for a better understanding of the transport of pollutants between rooms.

Keywords: indoor air quality; pollutants; low-energy buildings; measurement campaigns; performance indicators

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Citation: Kanama, N.; Ondarts, M.; Guyot, G.; Outin, J.; Gonze, E. Indoor Air Quality Campaign in an Occupied Low-Energy House with a High Level of Spatial and Temporal Discretization. *Appl. Sci.* **2021**, *11*, 11789. https://doi.org/10.3390/app112411789

Academic Editor: Paul B. Tchounwou

Received: 4 November 2021
Accepted: 7 December 2021
Published: 11 December 2021

1. Introduction

Millions of people are exposed to air pollutants ubiquitously hovering in the environment. The World Health Organization estimated that this exposure causes approximately 4 million premature deaths worldwide [1]. Because people in developed countries spend about 90% of their time indoors (schools, housing, offices, etc.), indoor air pollution has become the main source of exposure to air pollution in general [2–5]. Thus, concerns about indoor air quality have increased since the beginning of the 21st century.

Indoor air pollution differs from outdoor air pollution, particularly by the presence of certain pollutants that are not present outdoors and by the markedly higher concentrations of pollutants indoors [6,7]. Different kinds of pollutants can be found in indoor air: particulate matter, bio-aerosols, and gaseous pollutants, i.e., inorganic compounds such as nitrogen oxides or carbon monoxide, and organic compounds such as volatile organic compounds (VOCs). PM and nitrogen oxide originate from outdoors or from combustion processes indoors. VOCs are mainly derived from indoor sources such as building materials and emissions or occupant activities.

Nevertheless, indoor air quality (IAQ) depends not only on indoor and outdoor pollution sources, but also on airflow through the building envelope (i.e., infiltration and exfiltration) and between rooms induced by ventilation systems and natural drivers such as temperature differences. These airflows can import outdoor pollutants and dilute pollutants from indoor and outdoor sources once they are inside the buildings. In low-energy houses, the amount of outdoor airflow delivered for IAQ is balanced with the needs for energy efficiency. Thus, attention should be paid to secure a good performance of the ventilation systems once they are installed and used in order to avoid underventilation situations with negative impacts on IAQ.

Some work has focused on IAQ in low-energy housing, but this topic requires further investigation through campaigns combining precise measurements of IAQ and, as proposed by experts of the IEA-EBC Annex 68 program [8]. Table 1 summarizes some of these campaigns, including the country of the study, the building type, the parameters, the pollutants studied, the devices used, the number of measurements, and the outdoor air ventilation rates.

Table 1 shows that IAQ measurement campaigns in low-energy houses are not always combined with outdoor ventilation airflow and envelope air leakage measurements [9], despite their strong impact on pollutant concentrations [10]. However, the influence of outdoor air change rate (ACR) has to be taken into account. ACR is defined as the sum of all the airflows through ventilation components (outdoor ventilation airflows) and leaks normalized by the heated volume of the building. Despite the strong impact of ACR on pollutant concentrations, few studies have measured in a simultaneous and precise manner the pollutant concentrations and ACRs in occupied buildings. The accuracy of measurements of pollutant concentrations is crucial. ACRs are also influenced by weather conditions and occupant activities (closing internal doors and windows, switching mechanical ventilation speed, etc.). The accuracy of measuring ACRs [11–14] and ventilation airflow [15,16] is a broad topic of research.

Moreover, Table 1 highlights that measurement campaigns in low-energy houses include mostly measurements of two points only (living room and one bedroom) using passive sampling techniques over several days as proposed for instance by the protocol used for the French national survey [17]; this makes it difficult to estimate the dynamic occupant exposure and to study the transport of pollutants between rooms.

Finally, the accuracy of the concentration measurements remains to be studied. Data on measurement accuracy, measurement devices, and measurement calibration are often missing in the reviewed literature. Uncertainty in measurements includes the precision and bias of the measurement device, as well as the impact of the user, and is well documented in the ISO guide to the expression of uncertainty in measurement [18]. The accuracy of measurements of pollutant concentrations, notably sensor accuracy [19–24], has been studied extensively, both in situ and in laboratory research.

Within the context of these findings, the present work aims to contribute toward understanding the temporal and spatial variation of IAQ in a low-energy house combined with outdoor air ventilation airflow measurements, in order to show that such detailed data allow for a better-quality health impacts assessment and for a better understanding of the transport of pollutants between rooms.

For this purpose, after an inter-comparison phase in the laboratory using laboratory measuring devices, a detailed IAQ campaigns in an occupied low-energy house was conducted, including ventilation airflow, the particle numbers and $PM_{2.5}$, CO_2, TVOC, formaldehyde, temperature, relative humidity, and occupant questionnaires. Then, a description of the methodology is chosen for the in situ measurement. Next, the temporal evolution of the concentrations for each pollutant and for the two campaigns is achieved. Last, several IAQ performance indicators are calculated, compared with thresholders available in the literature and discussed. This work was conducted as part of efforts led by the IEA-EBC Annex 68 "Indoor Air Quality Design and Control in Low-Energy Residential Buildings".

Table 1. Literature review of IAQ in low-energy buildings.

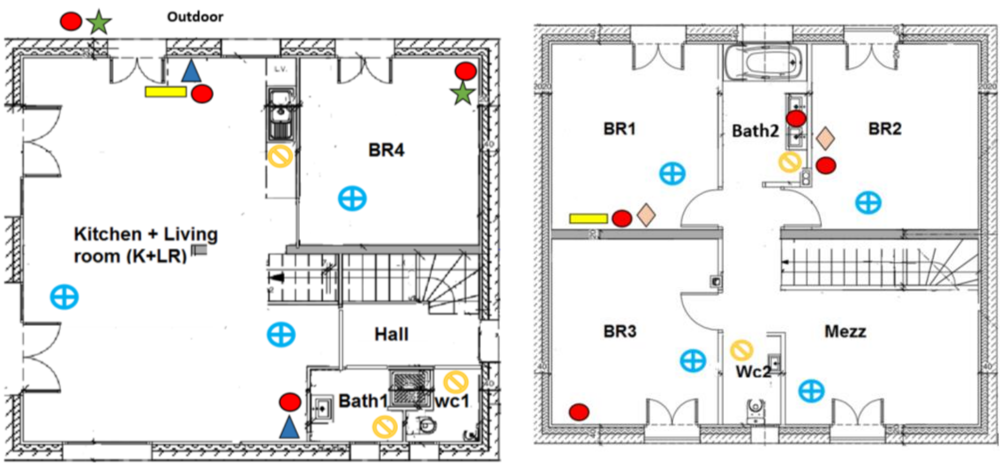
Ref.	Country	Type and Number of Buildings	Parameters and Pollutants	Type of Measurement Devices	Number of Measurement Points	Outdoor Air Ventilation Rates
[25]	France	Seven newly built, energy-efficient occupied houses	T, RH, CO_2, TVOC, VOCs, aldehydes, CO, $PM_{2.5}$, radon	Photoionization detector, non-dispersive infra-red probe, sampling by passive sampler with Carbograph 4 adsorbents/analysis by gas chromatography, mass spectrometry and flame ionization, Sampling by passive sampler with 2,4-dinitrophenylhydrazine (2,4-DNPH)-coated florisil/analysis by high-performance liquid chromatography and detection by UV absorption, electrochemical sensor, sampling system coupled to an air sampler, passive radon dosimeter	Living room/Main bedroom	Yes
[26]	France	Two low-energy single-family occupied houses	CO_2, T, RH, TVOCs, VOCs, aldehydes, $PM_{2.5}$	Photoionization detector, non-dispersive infrared probe, an optical portable aerosol spectrometer (dust monitor 1.108—Grimm), an electrochemical sensor, diffusive samplers over 7 days (Radiello®), Hydrolog sensors	Main bedroom and kitchen/living room	No
[27]	Greece	13 residences with young children under 3 years of age	PM, TVOCs, comfort parameters	GRIMM 1.108 and AQ Expert	Living room/bedroom	Yes Lower than 0.5 h^{-1}
[28]	Spain	Residential buildings	T, RH, CO_2	A Wöhler CDL 210	Living room/main bedroom	No
[29]	Belgium	25 homes and 26 schools	T, RH, CO_2, TVOC, VOCs, formaldehyde, aldehydes, $PM_{2.5}$	Radiello passive sampler, umex passive sampler, MS&T Harvard type impactor, grimm optical PM monitoring, Catec klimabox + other, CO_2-based flowbox measurements,	Living room/main bedroom/classrooms	Yes
[30]	Lithuania	11 newly built low-energy residential occupied buildings	T, RH, CO_2, NO_2, VOC, SVOC, formaldehyde	Passive sampler tubes (Radiello, Fondazione Salvatore Maugeri, Pavia, Italy), active charcoal adsorbent (Radiello), passive samplers (DIFRAM-100—Rapid Air Monitor, Gradko International Ltd., Winchester, UK), semi-permeable membrane devices (SPMDs), Real time portable indoor air quality monitor (Model HD21AB, Delta Ohm S.r.L., Selvazzano Dentro, Italy)	Living room, or in the hallway	Yes
[31]	Sweden	157 single-family houses and 148 apartments	T, RH, NO_2, formaldehyde, TVOC	Palmes Tube technique according to BS EN 13528, sampled on Tenax TA adsorbent tubes in compliance with ISO 16017-2, sampled using UmeX-100 (SKC Inc., Eighty-Four, PA, USA)		Yes
[32]	Sweden	20 new passive houses and 21 new conventionally built houses	T, RH, CO_2 NO_2, ozone, formaldehyde, TVOC, viable microbiological flora	HOBO U12-012 data loggers (Onset Computer Corp., Bourne, MA, USA), newly calibrated CARBOCAP® CO_2 monitors (GMW22, Vaisala, Vantaa, Finland), IVL passive/diffusive samplers, passive samplers—DSD-DNPH aldehyde diffusive sampling device (Supelco, Bellefonte, PA, USA), passively sampled on Tenax TA (Perkin–Elmer, Waltham, MA, USA)	Living room/balcony/Main bedroom	Yes estimated from CO_2 concentration in bedrooms

2. Methods

2.1. IAQ and Airflow Measurement Campaign

The first campaign took place in winter between 8 February and 15 (C1) and the second was in spring from 2 to 9 April 2019 (C2).

The campaign was conducted in a double storey detached house built in 2013 and located near Chambéry, France, in a mountain climate. It is occupied by two non-smoker adults and two children. The volume of the house is 337 m^3 with a total floor area of 135 m^2. The house has four bedrooms, two bathrooms, two wash closets (WC), one mezzanine, and one kitchen opening into a living room and a hall, as shown in Figure 1. The indoor material finishes are plasterboard painted with A+IAQ label (walls and ceilings), wooden floors (3 upper bedrooms) and tiles (other floors and bathroom walls). The energy consumption design is for 39 kWhep·$year^{-1}$·m^{-2}, including low heating needs of 12 kWh·$year^{-1}$·m^{-2}. The air leakage of the envelope is q_{a4_surf} = 0.44 m^3·h^{-1}·m^{-2}, with tight internal partition walls: median value of q_{50} = 0.8 m^3·h^{-1}·m^{-2}. In France, the current energy performance regulation RT2012 [33] requires that all new residential buildings must comply with a limit value for the French indicator q_{a4_surf} (air leakage rate at 4 Pa divided by the loss surface area excluding the basement floor): 0.6 m^3·h^{-1}·m^{-2} for single-family houses. An extensive measurement campaign has been conducted on this house in order to identify the spatial variability of external and internal air leakage [34], using the fan pressurization method described in [9]. In this campaign, the authors identified q_{50}, the air leakage rate at 50 Pa divided by the surface of the considered wall, as more suitable for quantifying airflows through internal partition walls. The house is equipped with one whole house balanced ventilation system with integrated heat recovery, and without any air recirculation. According to the French airing regulation [35], in this seven-room house with two bathrooms and two WC, the ventilation system must extract 30 m^3·h^{-1} in each bathroom, 15 m^3·h^{-1} in each WC, and 45 m^3·h^{-1} in the kitchen. In the mezzanine and the 4 bedrooms, one supply vent is installed and two supply vents in the living room, all dimensioned for balancing the whole-house extracted airflow. All the ventilation components are located in Figure 1. As a result, the whole-house extracted airflow should be 135 m^3·h^{-1}, equating to an average dwelling air change rate of 0.4 h^{-1}. In addition to this “base” ventilation speed, a high-speed ventilation mode must also be able to extract 135 m^3·h^{-1} in the kitchen during cooking periods, thanks to a dedicated ventilation exhaust component.



(**a**) (**b**)

Figure 1. Plan of study house: ventilation components and devices locations in each setting and their symbols (**a**) 1st floor; (**b**) 2nd floor. Ventilation components (supply, exhaust); symbols of devices NODE, GRIMM, MET-ONE, NEMO, WOHLER.

We can note that French airing regulation results in ACRs among the lowest in Europe, as shown by [36,37]. Indeed, several European national regulations require that ACRs in whole residential buildings vary from 0.23 to 1.3 h^{-1}, with 0.5 h^{-1} being a common reference value.

The following parameters were monitored: temperature (T), relative humidity (RH), CO_2, TVOC, formaldehyde, the particle numbers and $PM_{2.5}$. The concentration of each parameter is measured every 10 min at least at two locations indoors and outdoors (Figure 1). To this end, the following devices, which are summarized in Tables 2 and 3, were implemented:

- Two NODE sensors of the Airvisual brand measure CO_2, RH, T and $PM_{2.5}$ (Low1-1, Low1-2);
- Two GRIMM G1.108 record $PM_{2.5}$, PM_{10} and size distribution in number between 0.3 and 20 µm (Lab2-1, Lab2-2);
- Two MET_ONE (HHPC 6+) register size distribution in number between 0.3 and 10 µm (Int3-1, Int3-2);
- Two NEMO record simultaneously CO_2, TVOC, and formaldehyde concentrations, as well as T and RH. It should be mentioned that no measurements of formaldehyde and TVOC were made because the instrument failed during C1 in BR1 (Int4);
- Eight WOHLER CDL 210 sensors measure CO_2, T, and RH (Low5). During C2, there was no WOHLER in BR1 and BR2. Thus, data from NEMO and NODE were used.

According to the French PROMEVENT protocol [23,38,39], airflows were measured at each ventilation component (exhaust and supply) of the dwelling, using a cone with a checkered thermal anemometer KIMO DBM (Figure 2), which had been calibrated less than 1 year earlier. We corrected the airflow using the calibration certificate.

Table 2. Devices of measurement in each room.

Room	Campaign	CO_2	RH	T	Particle Numbers	$PM_{2.5}$	Formaldehyde	TVOC
Bedroom 1 (BR1)	C1	Low5-1	Low5-1	Low5-1	/	Low1-1	/	/
	C2	Int4-1	Int4-1	Int4-1	/	Low1-1	Int4-1	Int4-1
Bedroom 2 (BR2)	C1	Low5-2	Low5-2	Low5-2	/	Low1-2	/	/
	C2	Low1-2	Low1-2	Low1-2	/	Low1-2	/	/
Bedroom 3 (BR3)	C1	Low5-3	Low5-3	Low5-3	/	/	/	/
	C2	Low5-3	Low1-2	Low1-2	/	/	/	/
Bedroom 4 (BR4)	C1	Low5-4	Low5-4	Low5-4	Int3-1	/	/	/
	C2	Low5-4	Low5-4	Low5-4	Int3-1	/	/	/
Kitchen	C1	Low5-5	Low5-5	Low5-5	Lab2-1	Lab2-1	Int4-2	Int4-2
	C2	Low5-5	Low5-5	Low5-5	Lab2-1	Lab2-1	Int4-2	Int4-2
Living room	C1	Low5-6	Low5-6	Low5-6	Lab2-2	Lab2-2	/	/
	C2	Low5-6	Low5-6	Low5-6	Lab2-2	Lab2-2	/	/
Bathroom 2	C1	Low5-7	Low5-7	Low5-7	/	/	/	/
	C2	Low5-7	Low5-7	Low5-7	/	/	/	/
Outdoor	C1	Low5-8	Low5-8	Low5-8	Int3-2	/	/	/
	C2	Low5-8	Low5-8	Low5-8	Int3-2	/	/	/

Table 3. Description of the five measurement devices.

Device Number	Name and Symbol	Type of Sensor	CO_2	PM	RH	T	Formaldehyde	TVOC
Low1-1 Low1-2	NODE	Low-cost (Near REF.)	NDIR An accuracy of ±0.02%	Light scattering accuracy Precision of ±10%	Non-condensing sensor over a range of 0–95%	Sensor allowance is between −10 °C and + 40 °C	/	/
Lab2-1 Lab2-2	GRIMM	Laboratory material (REF.)	/	Laser beam optical particle counter Portable aerosol spectrometer	/	/	/	/
Int3-1 Int3-2	MET-ONE	Intermediate (Near REF.)	/	Optical particle counter	/	/	/	/
Int4-1 Int4-2	NEMO	Intermediate (Near REF.)	NDIR, 0–5000 ppm, +/− 50 ppm according to LAB-REF-30	/	Capacitive, 0–95%, +/−5% complete range	CMOS, −25 to +55 °C, +/−1 °C	Optical reading, 0–2000 ppb (0–2.5 mg/m^3) (uses NE-FOR011 badges)	Electrochemistry, Measuring range 30 ppb to 5 ppm Uncertainty +/−40 ppb
Low5-1 Low5-2 Low5-3 Low5-4 Low5-5 Low5-6 Low5-7 Low5-8	WOHLER	Low-cost (REF.)	NDIR accuracy of 50 ppm ± 5%	/	5–95% RH with accuracy of ±3%	Detector allowance range from −10 °C to +60 °C, resolution is 0.1 °C with an accuracy of ±0.6 °C	/	/

Figure 2. Cone with checkered thermal anemometer.

A survey and time budget activity records were also used in order to analyze the measurements correctly, as the occupants have a major influence on the indoor environment. The occupant survey included questions about each room: How many occupants are there in each room at a given time? Which products are used/which activities take place? What schedules are followed? How and for how long are the windows and doors open? When is the high-speed ventilation used?

Meteorological conditions such as wind speed, wind direction, atmospheric pressure, and outside temperature were recorded with a 10 min time step using a Delta Ohm HD2003 station including a three-axis ultrasonic anemometer.

2.2. Accuracy of IAQ Measurement Devices

An inter-comparison, comprising measurements in the laboratory, was made to ensure the relevance and to estimate the accuracy of the intermediate and low-cost devices (Low1, Int3). The process consists of placing simultaneously an intermediate and low-cost device and a laboratory device in rooms and in a test chamber where the monitored parameters are varied. The different devices are placed near each other. The TVOC and formaldehyde inter-comparison was not performed because it was technically not possible. One laboratory device (Lab2-1) and one low-cost device (Low5) were chosen as reference devices. Indeed, Low5 devices have an auto-calibration procedure for CO_2 concentrations, and the measurements provided by the eight devices over 1 week were compared, yielding the following results: CO_2 ($R^2 > 0.99$ and $1 > \text{slope} > 0.94$), RH ($R^2 > 0.94$ and $1 > \text{slope} > 0.95$) and T ($R^2 > 0.88$ and $1 > \text{slope} > 0.94$). The next test compared Lab2s with Low1s for $PM_{2.5}$ and PM_{10} (mass) and Lab2s with Int3s for size distribution in number. The last test compared Low5s, Low1s, and Int4s for CO_2, T, and RH. Table 4 summarizes the linear regression results from comparison of the reference and the low-cost devices.

The general findings are a high correlation for T and RH whatever the device, with an RMSE less than 2% for RH; a lower accuracy for the CO_2 measurements using the Int4s with a coefficient correlation of 0.62 and an RMSE of approximately 100 ppm.

For the particle number, the Lab2 to Int3 comparison shows a significant overestimation of Int3, with slopes between 1.65 and 2.9, but the overall R^2 value as shown in Table 4 was between 0.86 and 0.94 for 0.3 μm and between 0.83 and 0.95 for 0.5 μm. The behaviors of the two Int3 devices similarly show an overestimation compared to the reference device.

For $PM_{2.5}$, slopes equal to 0.97 are identified for the Lab2-2 and for Low1-1 device. For the Low1-2, the slope is equal to 0.82. However, for the two Low1 devices, the R^2 values are lower than that of the Lab2 devices. The RMSE values of the Low1-1 and Low1-2 devices are equal to 0.75 $\mu g \cdot m^{-3}$ and 0.85 $\mu g \cdot m^{-3}$, respectively, which is approximately equal to 10% of the measured range. Therefore, the Low1 devices are adopted for the $PM_{2.5}$ measurement campaign.

On the contrary, for the PM_{10}, whatever the device, the slopes are quite far from 1, indicating differences in measurements. First, it is noted in the test sample that the number of particles with a diameter larger than 2.5 μm is low and equal to 0.07% on average. This observation can explain uncertainties and thereby the observed difference between the two Lab2s and the relatively poor R^2. For the two Low1 devices, the low values of the slope indicate that these devices are less sensitive in detecting large particles. In fact, according to the Low1 devices, the weight percentages of particles with a diameter between 2.5 and 10 μm are only equal to 2.0 and 2.3%, respectively, on average. According to the Lab2 devices, these values are equal on average to 29% and 30%, respectively. In addition, the two linear regressions of low1 devices are associated with two negative R^2 values, which indicates there is no linear correlation between nodes and reference Lab2 values. As a result, Low1 devices cannot be used to measure PM_{10}. So, PM_{10} was not measured in this study.

Table 4. Correlation between the reference and low-cost devices.

	Slope	SSE	R^2	RMSE
IAQ parameters (temperature, humidity) (ref. WOHLER)				
T→WOHLER (980)	0.99	0.12	0.89	0.05
T→NODE	1.07	204	0.88	0.49
T→NEMO	0.99	386	0.79	0.62
RH→WOHLER (980)	1.00	1.81	1.00	0.19
RH→NODE	1.03	1300	0.62	1.25
RH→NEMO	1.07	2127	0.84	1.46
CO_2 (ref. Wohler)				
CO_2→WOHLER (980)	0.98	2.9×10^3	1.00	7.8
CO_2→NODE	1.03	6.4×10^5	0.97	28
CO_2→NEMO	0.92	9.9×10^6	0.74	100
Number particle (Ref. Grimm)				
0.3 µm→GRIMM D	1.03	4.2×10^8	0.92	5.6×10^2
0.3 µm→MET ONE 930/931	2.89/2.86	$1.9 \times 10^9/6.2 \times 10^8$	0.86/0.94	$1.4 \times 10^3/1.4 \times 10^3$
0.5 µm→GRIMM D	0.94	2.5×10^7	0.86	137
0.5 µm→MET ONE 930/931	1.65/1.76	$2.6 \times 10^7/6.7 \times 10^6$	0.83/0.95	160/140
1 µm→GRIMM D	1.02	2.41×10^5	0.83	13.4
1 µm→MET ONE 930/931	2.82/2.77	$1.8 \times 10^6/6.3 \times 10^5$	0.11/0.53	42/43
2 µm→GRIMM D	0.89	8.6×10^4	0.88	8.04
2 µm→Met One 930/931	1.83/2.18	$4.2 \times 10^5/1.9 \times 10^5$	0.75/0.80	20/24
5 µm→GRIMM D	0.95	3.6×10^3	0.90	1.7
5 µm→MET ONE 930/931	3.31/3.23	$1.3 \times 10^4/7.5 \times 10^3$	0.75/0.78	3.6/4.7
10 µm→GRIMM D	0.98	3.0×10^3	0.84	1.5
10 µm→MET ONE 930/931	2.17/2.24	$4.1 \times 10^4/7.0 \times 10^3$	0.50/0.86	6.4/4.6
PM (Ref. Grimm)				
$PM_{2.5}$→GRIMM D	0.97	481	0.69	0.60
$PM_{2.5}$→NODE C/NODE L	0.97/0.82	941/746	0.39/0.38	0.84/0.75
PM_{10}→GRIMM D	0.64	1.3×10^5	0.28	9.84
PM_{10}→NODE C/NODE L	0.10/0.08	$5.4 \times 10^3/4.1 \times 10^3$	−1.95/−2.20	1.99/1.75

2.3. Selection of IAQ Performance Indicators

IAQ was analyzed using performance indicators based on airflows, outdoor conditions, CO_2, RH, T, the particle number and $PM_{2.5}$, formaldehyde, and TVOC.

2.3.1. Airflows

Each ventilation airflow is measured and corrected according to the calibration certificate at each of the ventilation components (air extraction in humid rooms, air supply in living room and bedrooms), and for both speeds, base speed (Q_{BASE}) and high speed

(Q_{HIGH}). Starting from the airflows we calculate the ACRs (h^{-1}) using Equation (1) and leaving out the part due to internal air leakage:

$$ACR_i = \frac{t_{BASE} * Q_{i,BASE} + t_{HIGH} * Q_{i,HIGH}}{V_i \, (t_{BASE} + t_{HIGH})} \quad (1)$$

where Q_i ($m^3 \cdot h^{-1}$) is the measured and corrected ventilation airflow in zone i, t_{BASE} (h) is the duration of the use of base speed ventilation, t_{HIGH} (h) is the duration of the use of high-speed ventilation and V_i (m^3) is the volume of zone i.

2.3.2. CO_2

Many studies have recently focused on indoor CO_2 concentrations [8,40–43]. The threshold of 1000 ppm for healthy conditions proposed by [44]. Cumulative excess exposure that constituted one of CO_2 indicators was calculated by [45]. It is expressed according to Equation (2) and is calculated for 1 week (168 h) and can be compared to the threshold value of E_{max} = 168,000 ppm·h, corresponding to a 168 h duration with the 1000 ppm value.

$$ECO_{2,i} = \sum_{j}^{168} C_{i>1000ppm}(t_j) \times t_j \quad (2)$$

where Ci > 1000 ppm is the CO_2 concentration only when it is higher than 1000 ppm in zone i, 7 zones in this study, at the timestep t_j.

An air stuffiness index called ICONE [10] is used in this study. ICONE is calculated based on the amount of time CO_2 levels are either between 1000 ppm and 1700 ppm, or above 1700 ppm. This indicator also takes into account occupancy periods. The air stuffiness level of the room is expressed by an ICONE value from 0 to 5. An ICONE value of 0 corresponds to non-stuffy air (CO_2 level always below 1000 ppm), while an ICONE value of 5 corresponds to air with extreme stuffiness (CO_2 level always above 1700 ppm during occupancy). It is calculated using Equation (3) [46]:

$$ICONE_i = 8.3 \log(1 + f_{1,i} + 3f_{2,i}) \quad (3)$$

where $f_{1,i}$ represents the proportion of CO_2 concentration values between 1000 ppm and 1700 ppm and $f_{2,i}$ the proportion of values greater than 1700 ppm.

2.3.3. RH

Two RH indicators are used. First, the percentage of time with RH higher than 70%, which is associated with condensation risk. Second, the percentage of time outside the range of 30–70%, which is associated with a health indicator [47] and TR 14788 [48]. If the air is dry it may have negative consequences on the health of the occupants, such as desiccated nasal mucosa, increased susceptibility to viral infection, increased opportunity for transmission of pathogens, and sensory irritation in the eyes and upper airways [49].

2.3.4. Particles Concentration

The particles concentration was compared with the reference long-term exposure limit value (ELV), which was set to the minimum value used throughout the world of 10 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ as proposed by [50]. The maximum exposure indicator during each complete campaign (i.e., 168 h duration), among all the occupants, is calculated with Equation (4) and compared with the threshold value of E_{ELV} = 1680 $\mu g \cdot m^{-3} \cdot h$, corresponding to a 168 h duration with the 10 $\mu g \cdot m^{-3}$ value.

$$E_{PM_{2.5}} = \max_k \left(\sum_{j}^{168} C_k(t_j) \times t_j \right) \quad (4)$$

where C_k (t_j) ($\mu g \cdot m^{-3}$) is the exposure $PM_{2.5}$ for occupant k, 4 occupants in our study, at timestep t_j.

Concentration profiles and the average of particles concentrations were also discussed.

2.3.5. Formaldehyde

The measured concentrations are compared with the reference long-term ELV, which was used set to the minimum value used throughout the world of 9 $\mu g \cdot m^{-3}$ adapted by [50]. The maximum exposure indicator during each complete campaign (i.e., 168 h duration), among all the occupants, is calculated with Equation (5). It is compared with the total cumulative exposure to the ELV during the whole campaign E_{ELV} = 1512 $\mu g \cdot m^{-3} \cdot h$:

$$E_{formaldehyde} = max_k \left(\sum_{j}^{168} C_k(t_j) \times t_j \right) \quad (5)$$

where C_k (t_j) is the exposure to formaldehyde for occupant k at time step t_j.

2.3.6. TVOC

Due to the lack of a universal definition of the TVOC in general, no indicator will be calculated for TVOC. The concentrations are simply compared with the ELV of 210.5 ppb proposed by [51].

3. Results

3.1. Boundary Conditions

3.1.1. Occupancy Schedules

Analysis of the occupant survey reveals the occupancy schedules, which are crucial data for understanding the measurements, but also for calculating indicators such as exposure-based indicators. For each day the time spent by the occupant in each zone (presented in Table 5) with a measurement device globally, 10 h in bedrooms and 5 h in the living room. Occup. 1, 2, and 3 were in the home at the same times for both C1 and C2. It should be mentioned that one occupant (Occup. 4) was always in the home during C1.

Table 5. Occupancy schedules compiled from questionnaires to be used for calculation of IAQ indicators.

Occupants		In bedroom	In Living Room—Open Kitchen
Occup. 1 + 2 Parents BR1	C1 & C2	20:30–6:30	7:00–8:30 12:00–14:00 19:00–20:30
Occup. 3 Child BR2	C1 & C2	20:30–6:30	6:30–8:30 12:00–14:00 19:00–20:00 20:15–20:30
Occup. 4 Child BR3	C1	20:30–6:30 13:30–15:30	6:30–8:30 12:00–13:30 15:30–19:45 20:00–20:30
	C2	20:30–6:30	6:30–8:30 12:00–14:00 19:00–19:45 20:00–20:30

3.1.2. Ventilation Airflow

As explained in the Methods Section, the ventilation system operates at two speeds: base speed and high speed for cooking periods, i.e., for 1.5 h from 12:00 to 13:00 and 19:00 to 19:30, according to the questionnaire completed by the occupants. Ventilation airflows were measured at both speeds, respectively Q_{BASE} and Q_{HIGH}, and Table 6 shows the corresponding ACRs calculated for every room and for the whole house. The total exhausted airflow is for 80 $m^3 \cdot h^{-1}$ and is balanced with the total supplied airflow.

Table 6. Exhaust airflows in the French building code for this size of house at the base speed ($Q_{REG, BASE}$) and measured airflows at the maximal speed (Q_{HIGH}) and at the base speed (Q_{BASE}) with corresponding calculated ACRs in each room.

Room	Vent Component Type	$Q_{REG, BASE}$ ($m^3 \cdot h^{-1}$)	V (m^3)	Q_{HIGH} ($m^3 \cdot h^{-1}$)	Q_{BASE} ($m^3 \cdot h^{-1}$)	ACR (h^{-1})
BR1	Supply	/	32.3	21	18	0.56
BR2	Supply	/	32.9	14	12	0.37
BR3	Supply	/	31.4	14	11	0.36
BR4	Supply	/	35.5	13	11	0.31
Kitchen + Living room	2 Supplies	/	110	38	27	0.25
Kitchen + Living room	Exhaust	45	110	51	30	0.28
Bathroom 1	Exhaust	30	8.1	22	15	1.91
Bathroom 2	Exhaust	30	13.5	21	13	1.00
WC 1	Exhaust	15	4.5	16	10	2.31
WC 2	Exhaust	15	6	15	12	2.03
Whole house	Exhaust	135	337 *	124	81	0.25

*: other spaces as corridors, halls, staircase, account for 62.8 m^3.

All the measured airflows are much lower than the airflows required by the French building code as described in the Methods Section, resulting in a whole-house ventilation ACR of 0.25 h^{-1}, 40% lower than the required one.

With ACRs between 0.31 and 0.56 h^{-1}, the bedrooms are relatively under-ventilated compared to the literature. Studies of ACR in bedrooms show an ACR between 0.6 and 3 h^{-1} [52–54]. The parents' bedroom ACR is higher than the other bedrooms, 80% higher than bedroom 4.

3.1.3. Outdoor Conditions

Table 7 presents the values (median, first quartile (P25), and third quartile (P75)) for T, pressure, CO_2, and wind speed outdoors for C1 and C2. The two campaigns were conducted under different weather conditions: The median temperature during C2 was higher than during C1 by 3.5 °C. Atmospheric pressure during C1 was 1.4% higher than that during C2. The CO_2 concentration was 4.7% higher than in C2 compared to C1. The wind speed (V) was 22.2% higher during C2 compared to C1.

Table 7. Median value, P25, and P75 for T, P, CO_2, and wind speed outdoors during C1 and C2.

Parameter	Value	C1	C2
T (°C)	MEDIAN	3.1	6.6
	P25, P75	0.8, 5.1	3.1, 11.0
P (Pa)	MEDIAN	1020	1006
	P25, P75	1014, 1022	1005, 1009
CO_2 (ppm)	MEDIAN	409	428
	P25, P75	397, 439	417, 449
V (m/h)	MEDIAN	0.9	1.1
	P25, P75	0.5, 1.4	0.5, 1.7

3.2. IAQ Performance Indicators

3.2.1. CO_2

The variation in CO_2 concentration in BR1 during C1 and C2 is shown in (Figure 3). In BR1, increases in overnight CO_2 concentrations were due to metabolic emissions. The concentrations start increasing at 22:00 each day, reaching a plateau until a maximum value at 06:30 and decreasing after that, quite suddenly due to the opening of windows. The CO_2 concentration in BR1 was higher than in the other bedrooms because it was occupied by two persons, despite the higher ACR. CO_2 concentrations exceeded 2000 ppm, when the door was closed, in winter C1 while they did not reach 1650 ppm at any time during spring C2. Moreover, there was a second increase in concentrations after 06:00 because of a third person who joined the room on February 13 and 15 for one hour on each day. The CO_2 concentration at night was 30% lower than usual on February 8 because there was only one person in the room.

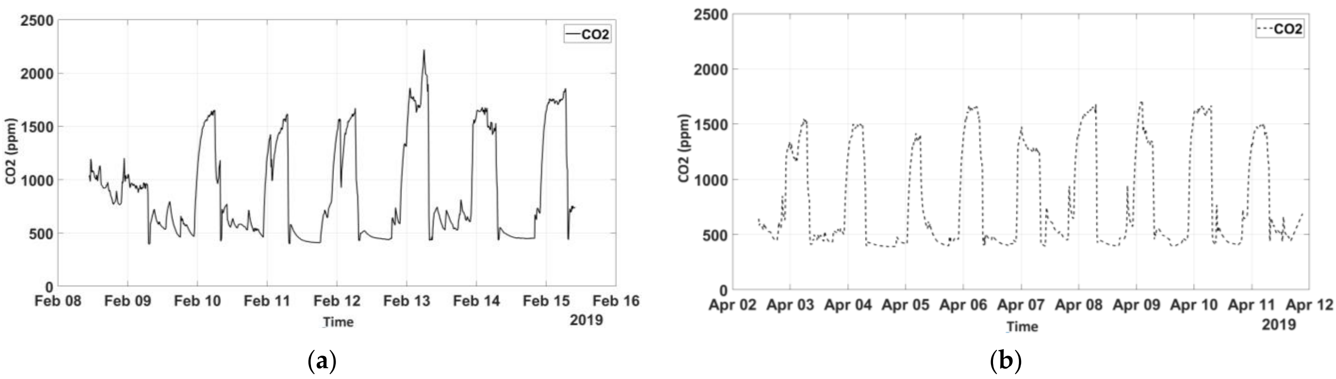


Figure 3. CO_2 concentration in BR1 during (**a**) C1; and (**b**) C2.

Figure 4 illustrates the dispersion of CO_2 in each room during the two campaigns. The median CO_2 concentrations in all the rooms in the house are in the range of 588–705 ppm and 539–656 ppm for C1 and C2, respectively. All the median concentrations are lower than the threshold of 1000 ppm. Although during C2 the outdoor median concentration of CO_2 was only slightly higher than that during C1, the indoor median concentration of CO_2 was 10% higher during C1 than during C2. The average concentration of CO_2 in our two campaigns did not exceed 1100 ppm.

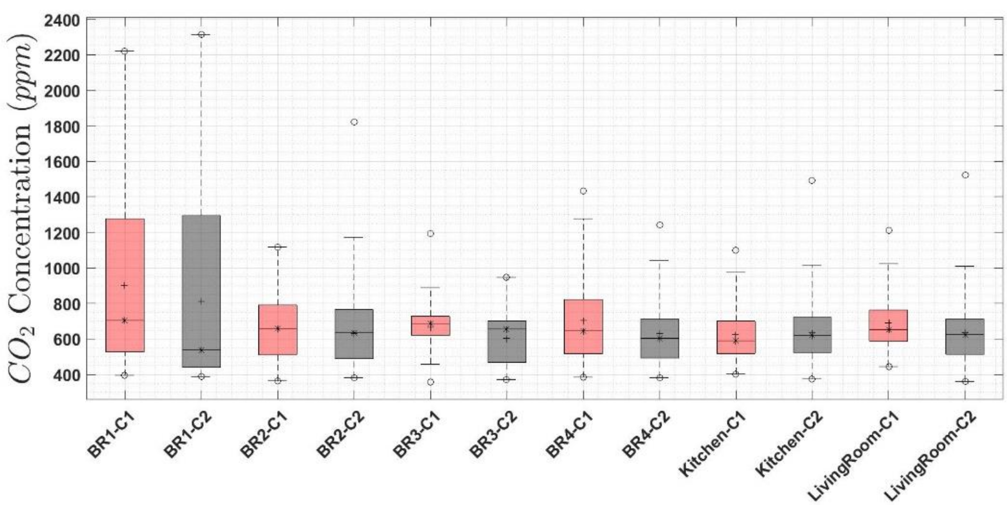


Figure 4. CO_2 concentration for each room–occupancy period (+: mean; *: median; o: minimum and maximum values).

Table 8 summarizes the CO_2-based indicators used in this study. The cumulative exposure exceeding 1000 ppm was higher during C1 compared to C2 for each room. The highest exposure was reached in BR1 where the cumulative exposure was 48% higher than the threshold (1.68×10^5 ppm·h). This was due to the change in seasons (C1 in winter and C2 in spring) and the permanent occupancy by at least one person during C1, while an occupant was not always present during C2. Windows and doors were opened during C2 due to favorable weather conditions, playing a role in the cumulative excess exposure not exceeding the threshold.

Table 8. Cumulative excess exposure to 1000 ppm and ICONE air stuffiness index for C1 and C2.

	BR1	BR2	BR3	BR4	Kitchen	Living Room	Bath 2
Cumulative excess exposure 1000 ppm C1 (ppm·h)	2.49×10^5	1.77×10^5	1.86×10^5	2×10^5	1.78×10^5	1.76×10^5	2.33×10^5
ICONE air stuffiness index—C1	1.57	0.11	0.03	0.46	0.04	0.22	0.12
Cumulative excess exposure 1000 ppm C2 (ppm·h)	1.36×10^5	1.06×10^5	1.02×10^5	1.6×10^5	1.01×10^5	1.04×10^5	1.15×10^5
ICONE air stuffiness index—C2	1.06	0.02	0.00	0.25	0.00	0.00	0.13

According to the ICONE indicator, there were non-stuffy conditions in all rooms, except in BR1 which had low-stuffy conditions during both campaigns (1.57 in C1; 1.06 in C2).

3.2.2. RH

During the two campaigns, the time during which RH was greater than 70% (condensation risk) did not exceed 0.12% in all the rooms. Consequently, there was no condensation risk in the rooms.

Figure 5 presents the percentage of time during the two campaigns when RH is outside the range of 30–70% (that being outside this range is a health risk) and mostly lower than 30% for most rooms. The range of RH measured across all rooms was 0.40–44.53% and 0.0–14.07% for C1 and C2, respectively. The RH is greater in the kitchen and living room than in the bedrooms. The RH was less than 30% in the kitchen and living room during C1 for approximately 35% and 45% of the campaign, respectively, due to frequency of opening windows.

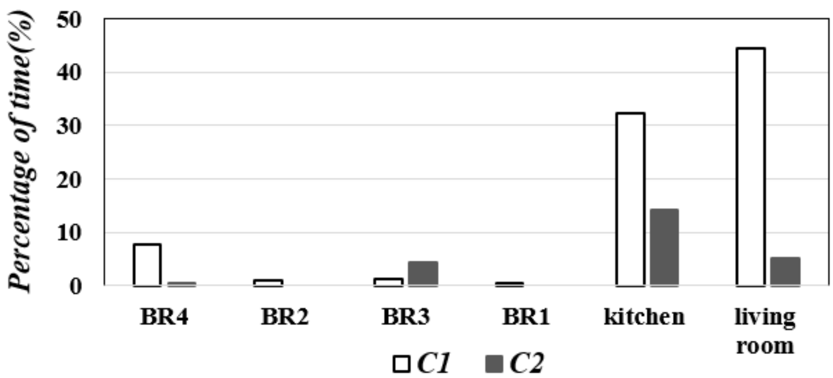


Figure 5. Percentage of time outside the range of 30–70% (health risk).

3.2.3. Particles Concentration

Figure 6 presents the particle number outdoors and in the kitchen during C1 and C2. The outdoor concentrations for both campaigns displayed disturbances where one device stopped recording for three days during C1 as shown in Figure 6c. During C2, the outdoor peaked at midday and then were their lowest at midnight. Only on 7 April outdoor particle counts were higher at night than in the morning. The increases in concentrations were found in the kitchen and mainly attributed to fine particles, i.e., particles having diameters less than 1 μm, for which concentrations as high as 4.4×10^5 and 8×10^5 number. L^{-1} were recorded during C1 and C2, respectively.

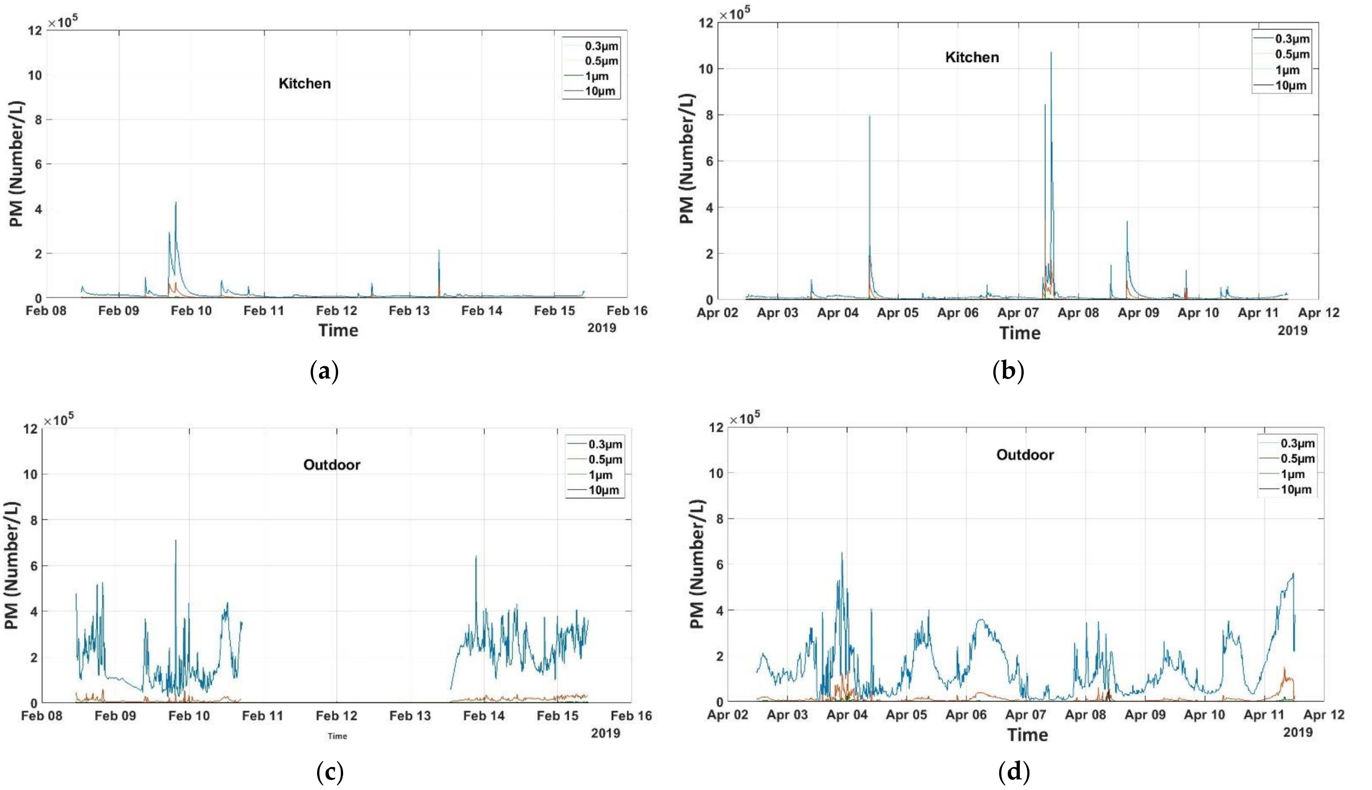


Figure 6. Particle numbers in: (**a**) kitchen during C1; (**b**) kitchen during C2; (**c**) outdoor during C1; and (**d**) outdoor during C2.

The increases in indoor concentrations were sometimes correlated with increases in outdoor concentrations. This is particularly evident during the increase in concentrations during C1, which was recorded on February 9 at 20:00 for about two hours. At this time, we observe a peak outdoor concentration, followed by a peak in the kitchen outside of a cooking period (no cooking). The indoor peak is approximately 37% lower than the outdoor concentration. These results demonstrate that there can be a link between indoor and outdoor PM concentrations.

The concentration increases in the kitchen can be clearly attributed to indoor activities such as cooking (frying, grilling, etc.) and no cooking activities. The increase in concentrations during C2 on 7 April was attributed to cooking activities (burned meal and frying). In the same way, cooking pancakes on February 9 at 16:00 was correlated with high particle numbers of approximately 3×10^5 number. L^{-1}.

For the two campaigns, $PM_{2.5}$ in the living room, kitchen, BR1, and BR2 were calculated and are reported in Figure 7. The average $PM_{2.5}$ are within the range of 3.8–6.7 $\mu g \cdot m^{-3}$ and 3.9–7.7 $\mu g \cdot m^{-3}$ with median ranges of 3.0–4.0 $\mu g \cdot m^{-3}$ and 3.0–3.3 $\mu g \cdot m^{-3}$ for C1 and C2, respectively.

Figure 8 shows the $PM_{2.5}$ in the kitchen, BR1, and BR2. On February 9, the same events that caused spikes in particle numbers in the kitchen were also observed for $PM_{2.5}$ in the kitchen and bedrooms. The peaks during C2 were also attributed to analyzing the occupant survey. The occupants wrote that they opened fully all the windows and the doors.

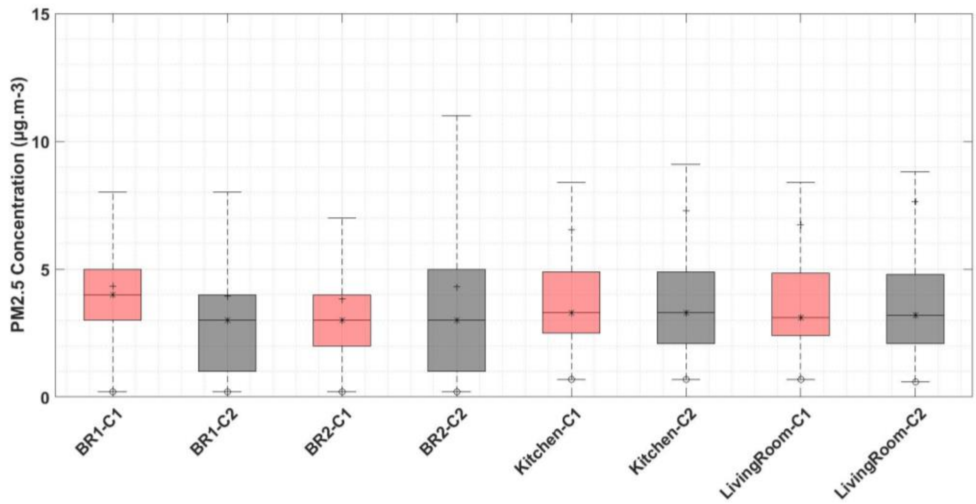
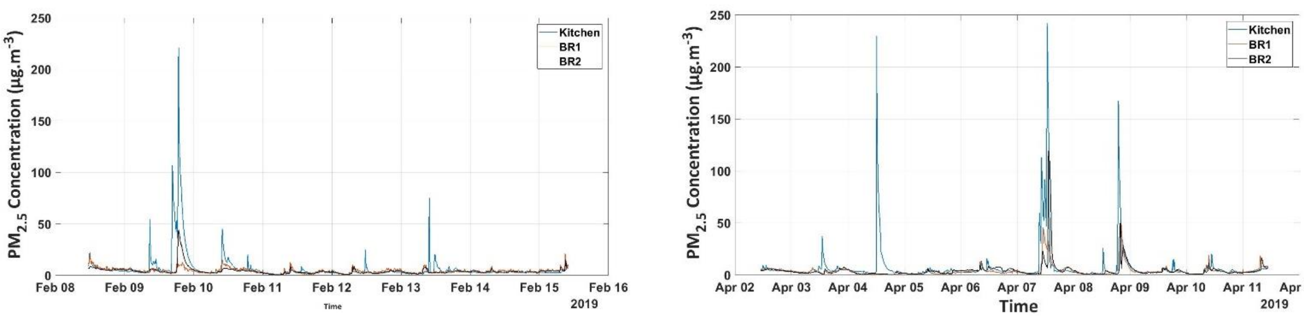


Figure 7. $PM_{2.5}$ in each room during C1 and C2 (+: mean; *: median and o: minimum values).

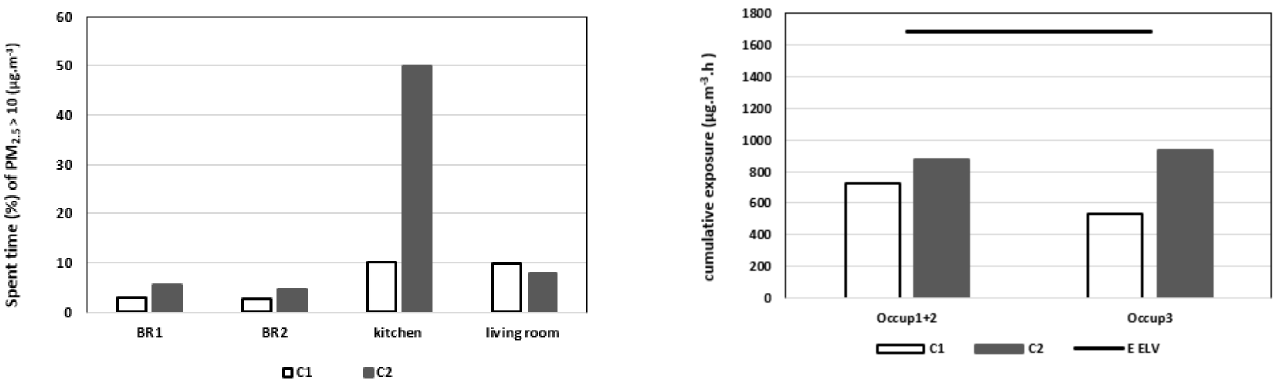


(**a**) (**b**)

Figure 8. $PM_{2.5}$ in the kitchen, BR1, and BR2 during (**a**) C1; and (**b**) C2.

The $PM_{2.5}$ in BR1 and in BR2 were lower than in the kitchen; they occasionally exceeded the ELV, but only for 50 min. Two peaks of 44 μg·m^{-3} and 46 μg·m^{-3} were measured during C2 in BR1. They were most likely correlated with the concentration increases in the kitchen in which the internal door of BR1 were open at that time. The same behaviors can be observed during the same time in BR2 with two $PM_{2.5}$ peaks of 120 μg·m^{-3} and 40 μg·m^{-3} were recorded during C2 in BR2. On February 9 at end of the day, the impact of peak of $PM_{2.5}$ outside is observed in all rooms. On the contrary, in BR1, with a closed internal door at that time, the peak was 66% lower than the peak in BR2, which had an open internal door. A peak of 100 μg·m^{-3} was recorded in the kitchen during C2 on 7 April due to cooking, which is 50% higher than the peak in BR1 at the same time, perhaps because of the closed internal door in BR1. By mid-day on 8 April, a peak in $PM_{2.5}$ was seen in both rooms, but it was 4% higher in BR1 than in BR2, with a closed internal door in BR1.

Figure 9 presents the percentage of time and cumulative exposure to $PM_{2.5}$ higher than 10 μg·m^{-3}. This percentage of time in the rooms was lower during C1 (range 2.74–10.1%) than during C2 (range 4.67–50%). The highest values of 10.1% and 50% were reached in the kitchen, while the lower values of 2.74% and 4.67% were reached in BR2 for C1 and C2, respectively. The $PM_{2.5}$ cumulative exposure for the occupants was 425–436 μg·m^{-3}·h for both occupants 1 and 2 and 482–651 μg·m^{-3}·h for occupant 3 during C1 and C2, respectively. The cumulative exposure for occupant 3 was 33% lower than the cumulative exposure for both occupants 1 and 2 during C1, but it was 12% higher during C2 as the time spent by occupants in C1 was more than in C2.

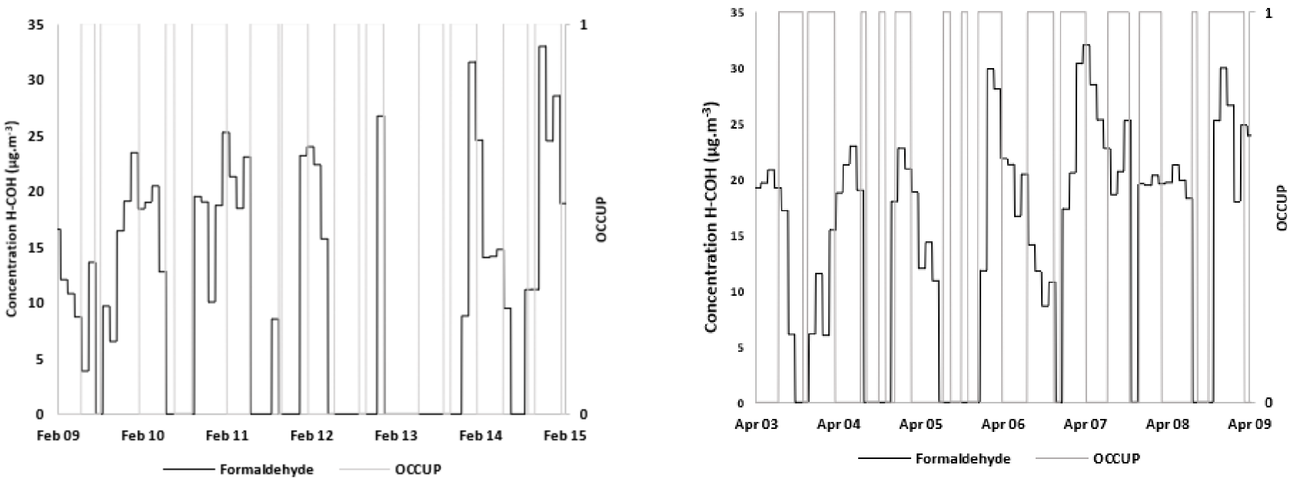


(a) (b)

Figure 9. (**a**) Percentage of time spent with concentrations of $PM_{2.5}$ over 10 µg·m^{-3}; and (**b**) total cumulative exposure.

3.2.4. Formaldehyde

Figure 10 presents the formaldehyde concentrations measured during C1 and C2 and the occupancy in the kitchen. The concentration exceeded the ELV of 9 µg·m^{-3} about 55% of the time. The higher values were reached mostly at night after dinner. This may be due to increased humidity and temperature during dinner preparation, which are known to influence formaldehyde emissions [55,56]. During C1, there were always at least two occupants in the house. By contrast, during C2, the house was empty in the morning except on the weekend (6 and 7 April). Thus, these findings may highlight a link between increased concentrations of formaldehyde and the presence of occupants and their activities.



(a) (b)

Figure 10. Formaldehyde concentration and occupancy in the kitchen during (**a**) C1; and (**b**) C2.

Figure 11 shows that the formaldehyde concentration in the BR1 during C2 was above the ELV for 42% of the time. The maximum values were recorded at night and were in the range of 10–18 µg·m^{-3}. Formaldehyde concentrations seem to increase at night (when the room is occupied) and to decrease in the morning when the room is unoccupied. It can be assumed that the emission in the bedroom increased the concentration. When the windows were opened in the morning, there was a decrease in concentration; after closing the windows, the concentration gradually increased again.

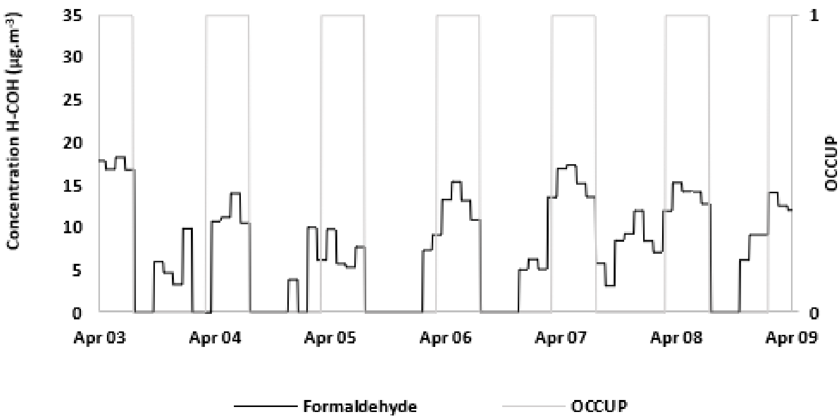


Figure 11. Formaldehyde concentration in BR1 during C2.

The formaldehyde concentrations in BR1 and in the kitchen are presented in Figure 12 during two periods (occupied and unoccupied). The average formaldehyde concentrations in the kitchen were 15 $\mu g \cdot m^{-3}$ and 16 $\mu g \cdot m^{-3}$ with occupants and 11 $\mu g \cdot m^{-3}$ and 13 $\mu g \cdot m^{-3}$ without occupants during C1 and C2, respectively. The median concentrations were 18 $\mu g \cdot m^{-3}$ and 19.6 $\mu g \cdot m^{-3}$ with occupants and 10 $\mu g \cdot m^{-3}$ and 15 $\mu g \cdot m^{-3}$ without occupants during C1 and C2, respectively.

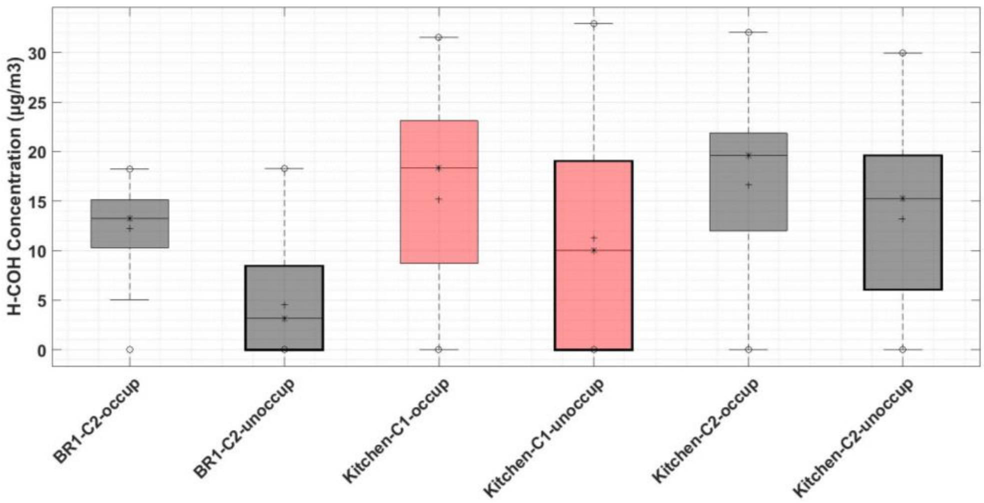


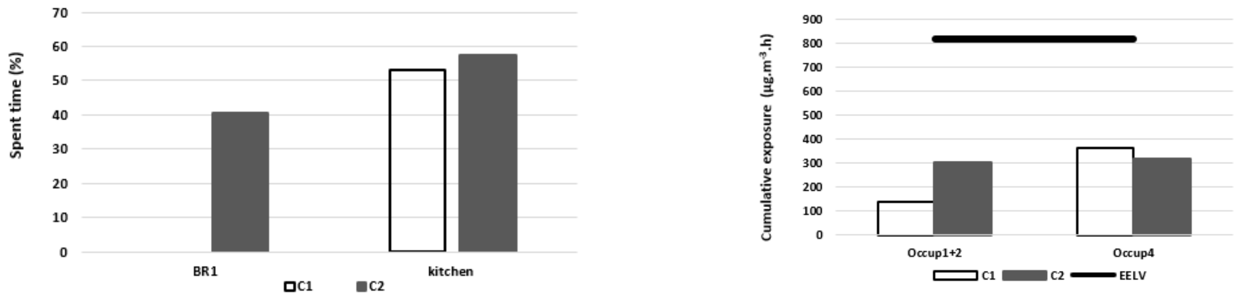
Figure 12. Formaldehyde concentration in BR1 during C2 and in the kitchen during C1 and C2 in occupied and unoccupied periods (+: mean; *: median; o: minimum and maximum values).

In BR1, the average concentration was 12 $\mu g \cdot m^{-3}$ with occupants and 4.6 $\mu g \cdot m^{-3}$ without occupants. The median concentration was 13 $\mu g \cdot m^{-3}$ with occupants and 3 $\mu g \cdot m^{-3}$ without occupants.

In both campaigns, the higher formaldehyde concentrations seem to be associated with the presence of the occupants.

Figure 13 presents the percentage of time and total cumulative exposure of the occupants to a formaldehyde concentration greater than 9 $\mu g \cdot m^{-3}$. The percentage of time over ELV is 54% and 57% of the time in the kitchen during C1 and C2 and it was 41% of the time in BR1 during C2.

The maximum cumulative exposure of the occupants in the kitchen was 137 $\mu g \cdot m^{-3} \cdot h$ and 304 $\mu g \cdot m^{-3} \cdot h$ for occupants 1 + 2, during C1 and C2, respectively. It was 363 $\mu g \cdot m^{-3} \cdot h$ and 321 $\mu g \cdot m^{-3} \cdot h$ for occupant 4, who was always at home during C1, for C1 and C2, respectively. The cumulative exposure for occupant 4 was 60% higher than the cumulative exposure for both occupants 1 and 2 during C1 and it was 10% higher during C2. Additionally, the cumulative exposure for occupant 4 was 12% higher during C1 than C2. Despite higher concentrations in the kitchen during C2, due to higher outdoor temperatures compared with C1, the cumulative exposure of occupant 4 was higher for C1 compared with C2. This is attributed to the time spent by occupant 4, which was larger during C1 than C2. For all occupants and during the two campaigns, cumulative exposure did not exceed the ELV exposure.

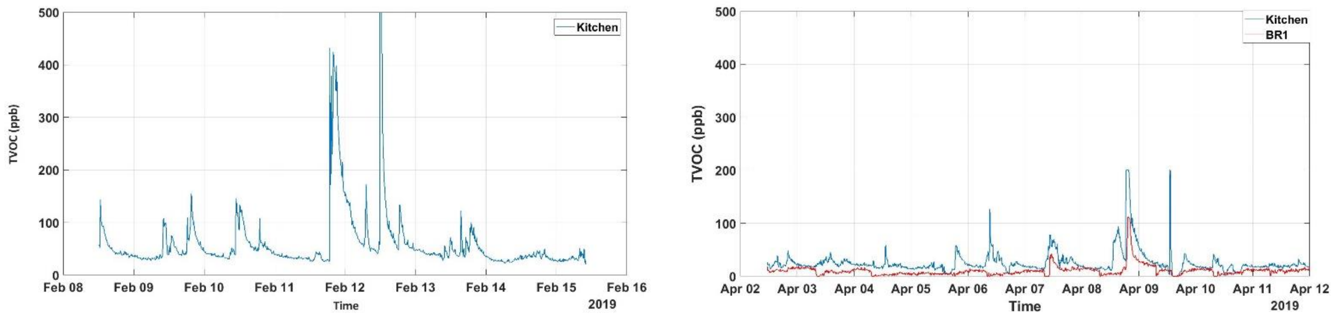


(**a**) (**b**)

Figure 13. (**a**) Percentage of hours of formaldehyde over ELV; and (**b**) total cumulative exposure of the occupant to formaldehyde over ELV.

3.2.5. TVOC

Figure 14 shows the TVOC concentrations measured in the kitchen and in BR1 during the two campaigns. There are permanent emissions attributable to building and other materials and peaks in emissions due to specific short-term activities such as using perfume or chemical products, etc. The median TVOC concentrations were 44 ppb and 20 ppb during C1 and C2, respectively. These concentrations were variable; several quick increases occurred, which were followed by a rapid drop. Figure 14a was cut because the second peak reached 5000 ppb and made it unreadable.



(**a**) (**b**)

Figure 14. TVOC concentration (**a**) in the kitchen during C1; and (**b**) in the kitchen and BR1 during C2.

The TVOC peaks on 11 and 12 February could be clearly attributed to the use of lavender essential oil. Using essential oil explains the temporal evolution of the concentration: Emissions were higher during the use of the essential oil which is applied on hair. After the use of essential oil, there was no longer any emission, and the concentration decreased because of the ventilation. During C2, TVOC concentrations were slightly lower in BR1 compared with those measured in the kitchen. The median concentration was 9 ppb in BR1 and 20 ppb in kitchen. In general, the TVOC concentrations in BR1 tracked those measured in the kitchen. On 8 April, a peak of 110 ppb was measured in BR1 at the same time as a peak of approximately 200 ppb was measured in the kitchen during C2. Similarly, on 7 April, an increase in TVOC in the kitchen also increased concentrations in BR1.

The TVOC concentrations in BR1 and in the kitchen are presented in Figure 15 during two periods (occupied and unoccupied). In the kitchen, the average TVOC concentrations were 66 ppb and 34 ppb with occupants and 57 ppb and 25 ppb without occupants for C1 and C2, respectively. The median concentrations were 42 ppb and 25 ppb with occupants and 40 ppb and 20 ppb without occupants for C1 and C2, respectively. In BR1, the average concentrations were 12 ppb with occupants and 10 ppb without occupants, while the median concentrations were 12 ppb with occupants and 6 ppb without occupants in C2. Despite the differences in concentration within the uncertainty range of the measuring devices, there is a trend between occupancy and higher concentration values. This trend is confirmed even more strongly for the 3rd quartile and the maximum values. This observation should therefore be validated with sensors better suited to the observed concentration ranges.

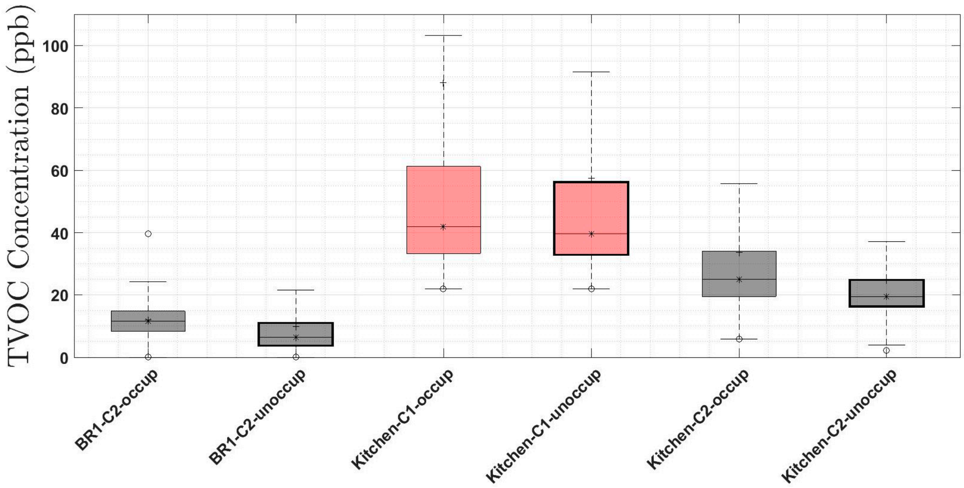
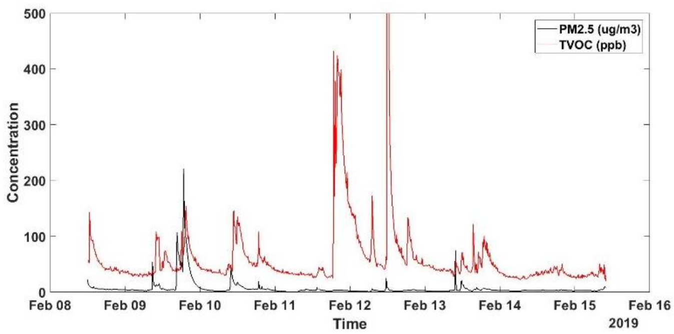
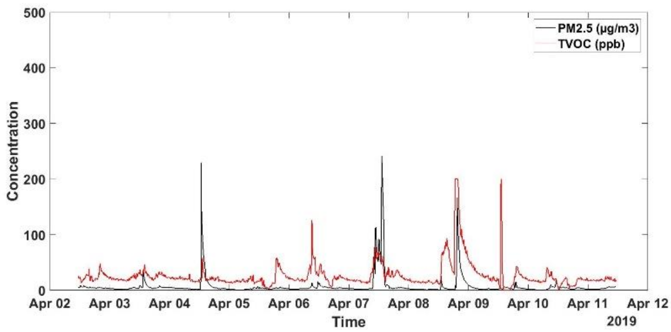


Figure 15. TVOC concentration in BR1 during C2 and in the kitchen during C1 and C2 in occupied and unoccupied periods (+: mean; *: median; o: minimum and maximum values).

Figure 16 presents a comparison of profiles between $PM_{2.5}$ and TVOC during C1 and C2. All peaks of concentrations of $PM_{2.5}$ are associated with an increasing TVOC concentration. However, there is no impact of an increase in TVOC on the $PM_{2.5}$ profile. Figure 16a was cut because the second peak reached 5000 ppb and made it unreadable.



(**a**)



(**b**)

Figure 16. Comparison of $PM_{2.5}$ and TVOC in the kitchen during (**a**) C1; and (**b**) C2.

4. Discussion on the IAQ Global Assessment at the Dwelling Scale According to the Indicators

With common IAQ studies including only two measurement points and passive measurements over 1-week as shown in Table 1, the average concentrations must be used to assess IAQ performance, while it is well known that the cumulative exposure of occupants is a better indicator for quantifying the health impacts of indoor pollutants such as formaldehyde or particle matters.

The present study demonstrated that there is a large gap between both types of indicators: average concentrations (obtained by common IAQ studies) and occupant cumulative exposures (obtained by detailed IAQ studies).

Concerning CO_2, on the one hand, the cumulative excess exposure did surpass the threshold during C1 in all the rooms. On the other hand, the ICONE was non-stuffy air except in BR1 which was low-stuffy air.

For formaldehyde, too, the conclusions on IAQ are different if we look at the concentrations or at the cumulative exposure during C2. The formaldehyde concentration increased during C2 compared with C1 because of outdoor high temperatures; however, cumulative exposure decreased because occupants spent more time indoors during C1 compared to C2.

For $PM_{2.5}$, although during C2 the percentage of time spent with $PM_{2.5}$ over the threshold in the kitchen was reached 50% of the time, the cumulative exposure of the occupants remained less than the E_{ELV}.

In order to summarize the IAQ measured at the dwelling scale, it is important to note that the dwelling was a low-energy house, with a whole-house ACR 40% lower than the required one. The five required IAQ performance indicators were calculated and normalized by the threshold values, which are given in Table 9.

Table 9. IAQ performance indicators.

	Maximal CO_2 E_{1000} ppm·h	**Maximal Time-Spent with RH Out of 30–70%**	**Maximal Time-Spent with RH > 70%**	**$PM_{2.5}$ E_{max} $\mu g \cdot m^{-3} \cdot h$**	**Formal-dehyde E_{max} $\mu g \cdot m^{-3} \cdot h$**
C1	2.45×10^5	44	1.2	728	363
C2	1.6×10^5	14	2.42	936	321
Relative gap (%)	−35%	−68%	102%	29%	−11%
Threshold	1.68×10^5	30.78	38.48	1680	1512

5. Conclusions and Perspectives

The limited published literature with detailed IAQ and airflow measurements in low-energy occupied buildings was highlighted during the IEA-EBC Annex68 "Indoor air quality design and control in low-energy residential buildings" project, which prompted us to conduct these measurement campaigns. We carried out an inter-comparison study of several types of devices (low-cost, laboratory devices, intermediate devices) for validation and/or correction of measurements. During our two campaigns, the measurement devices were set up in all of the rooms and outside the house recording measurements every 10 min. In some rooms, two or more types of devices measuring the same parameter, were used to ensure the precision of the measurements. Ventilation airflow at each supply and exhaust was measured. The survey completed regularly by occupants explained many of our queries.

IAQ performance indicators related to pollutants (formaldehyde, particle numbers and $PM_{2.5}$, RH, TVOC, and CO_2) were reviewed and used. For long-term exposure we used the reference exposure limit value (ELV) set to the minimum value used throughout the world, i.e., 9 $\mu g \cdot m^{-3}$ for formaldehyde (Office of Environmental Health Hazard Assessment [57]) and 10 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ [58]. Thus, for formaldehyde and PM we compared the calculated cumulative exposures to the threshold exposure corresponding to a constant threshold concentration.

These measurements confirm previous results from several studies: cooking, grilling, and toasting are the activities that emit the most particles. Our results highlighted several other interesting issues.

First, the relevance of the selected IAQ performance indicators related to the conclusion on the IAQ. Indeed, we showed that the conclusions on IAQ differ depending on whether we look at the concentrations or at the cumulative exposure. The latter one is more precise because it takes into account the concentrations only where and when the occupants are present. Nevertheless, this indicator is rarely calculated as we lack detailed measurements with spatial and temporal discretization.

Second, we showed that such detailed measurement campaigns improve our knowledge on the transport of pollutants between rooms, which cannot be assessed with common IAQ studies including only two measurements points and passive measurements over 1 week. Here, the transfer of pollutants was clearly observed between rooms. The kitchen was mostly the main source of producing $PM_{2.5}$ and from there it spread variably to the other rooms depending on the speed of the ventilation system, its position, and/or opening and closing the doors. The same is true for TVOC which is diffused from kitchen to BR1 as was observed on 7 and 8 April, the time of preparing meals with a high speed of ventilation and opening doors at the same time.

Finally, even if these are preliminary results at this stage, we observed that occupancy periods were correlated with higher pollutant concentrations, at least for TVOC and formaldehyde.

Lastly, we can conclude that the ventilation system helps explain the changes in concentrations, but alone it is not enough. It is observed from the cumulative exposure of occupants in BR1, where ACR was 0.56 h^{-1}. However, it is interesting to note that despite a ventilation exhaust located in the kitchen, pollutants emitted in the kitchen can reach the adjacent bedroom at a. Secondly, concentrations of pollutants increase or decrease according to changes in the weather between winter and spring.

Several issues could be improved: Surveys can offer some relevant data on occupancy schedules, but they are not precise enough to give information about the occupancy in each room of the house. Thus, we hope to conduct a more detailed study with longer duration in the future. Additionally, we believe that using devices for measuring formaldehyde and $PM_{2.5}$ outside will be more helpful in comparing concentrations indoors and outdoors during future campaigns.

This article highlighted the benefits of a study with a high level of temporal and spatial discretization, combined with precise and simultaneous measurements of pollutants and ventilation rates.

As a perspective, we are further investigating the collected data using inverse methods in other to quantify the emission rates due to humans (CO_2, RH) and also furniture and building materials (TVOC, formaldehyde), especially in the bedrooms. Indeed, in those rooms, the boundary conditions are less varying, notably due to known occupants' patterns and a constant supplied ventilation airflow, measured with a high level of accuracy.

Author Contributions: Experimental campaign: N.K., G.G., M.O. and J.O.; Investigation: N.K., G.G., M.O., J.O. and E.G.; writing—original draft preparation: N.K., G.G. and M.O.; manuscript review: E.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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