Development of an indoor air quality index for continuous monitoring in French dwellings

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Abstract. An indoor air quality (IAQ) index can translate indoor measurement data of multiple parameters into a unitless rating of the IAQ. Compared to conventional measurements at specific times, online sensors allow for more frequent sampling and timely analysis. In this context, the present work aimed to develop an IAQ index based on the sensor data to accompany the second IAQ survey in French dwellings (CNL2) for the classification of the dwellings. The first set of data obtained from CNL2 consisted of measurements carried out in 296 dwellings in 2020-2021. Indoor air temperature, relative humidity, and concentrations of carbon dioxide, $PM_{2.5}$, and PM_{10} were measured using sensors and verified using reference instruments. Therefore, the IAQ index was based on the five indicators. The index referred to French regulations and World Health Organization guidelines to determine the limit values of the measurements. For each time step, the index was calculated according to the highest ratio between the measured and the limit values among the five parameters. The index was classified into three categories, i.e., critical (> 100, thus > the limit values), good (< 50, thus < 0.5 of the limit values), and moderate (between 50 and 100). The classification of a dwelling was conducted based on the time series of its IAQ index over the whole measured period. A tolerated percentage of time, during which the IAQ index in a dwelling exceeded its category level, was defined to classify the dwelling into an IAQ category with certain exceedances over the measurement period. With a tolerated 25% time of exceedance, 6% of the instrumented dwellings were categorized as good, 44% as moderate, and 50% as critical.

1 Introduction

According to the World Health Organization (WHO), household air pollution was responsible for an estimated 3.2 million deaths per year worldwide in 2020, including over 237000 deaths of children under the age of 5 [1]. To assess indoor air quality (IAQ) on a nationwide scale, the Observatory for Indoor Air Quality (OQAI) in France has conducted two field studies in French dwellings over the past twenty years [2]. During the second field study starting in the year 2020, indoor air pollutants were sampled and measured using conventional/standardized methods. Moreover, nine parameters were continuously measured in occupied dwellings over a week using online sensors. The nine parameters included air temperature (T), air relative humidity (RH), and concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), total volatile organic compounds (TVOC), and airborne particles (PM_1, $PM_{2.5}$, PM_{10}). The first wave of data consisted of one-week measurements conducted in 296 occupied dwellings in 2020-2021.

To evaluate IAQ in a building, existing Green Building Certification schemes [3] and IAQ indexes [4] commonly rely on discrete sampling followed by standardized laboratory analysis for IAQ rating. As online measurements generate a substantial amount of data that varies over time, it is necessary to develop an IAQ evaluation method adapted to time-series data. Some recently developed IAQ indexes are calculated based on online measurements [5, 6]. However, they do not comply with French regulations for defining limit values and, as a result, cannot rank the instrumented French dwellings in accordance with these regulations. In this context, the objective of the present work was to categorize the IAQ in the instrumented French dwellings based on continuous monitoring data. To achieve this, we developed and applied an IAQ index based on continuous measurements to the first wave of 296 occupied dwellings for rating.

2 Materials and methods

2.1 Data validation

The sensors deployed continuously recorded the values of T, RH, and concentrations of CO_2, CO, NO_2, TVOC, PM_1, $PM_{2.5}$, and PM_{10} over one week in each of the 296 dwellings. Table 1 presents the sensor's characteristic parameters declared by the manufacturer (Cozy Air). Measurements of T, RH, CO_2, $PM_{2.5}$, and PM_{10} were

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consistent with measurements using reference instruments and were thus deemed valid for further analysis. However, significant differences between sensor measurements and reference instrument measurements were observed for NO_2 and TVOC. Additionally, measurements of CO and PM_1 were not compared to reference measurements; therefore, these four parameters were excluded from further studies.

Table 1. Sensor's characteristic parameters declared by the manufacturer.

Parameter	Range	Uncertainty	Validation using reference instruments
Temperature (°C)	[- 40, + 125]	± 0.3	Valid
Relative humidity (%)	[0, 100]	± 2%	Valid
CO_2 (ppm)	[400, 5000]	± 50	Valid
TVOC (ppb)	[0, 1000]	± 30	Difference observed
NO_2 (ppb)	[0, 500]	± 15	Difference observed
CO (mg/m^3)	[0.25, 10]	± 0.2	Not compared
PM_1, $PM_{2.5}$, PM_{10} ($\mu g/m^3$)	[0, 1000]	± 10	Valid for $PM_{2.5}$ and PM_{10}, not compared for PM_1

2.2 Index development

As the sensor data for five parameters, i.e., T, RH, CO_2, $PM_{2.5}$, and PM_{10}, were found to be valid, we developed the IAQ index based on these parameters for the moment. While CO, NO_2, TVOC, and PM_1 were monitored alongside the other five parameters, their results were not compared with or differed significantly from those of the reference instruments. Consequently, the measurements of these four parameters cannot be used quantitatively for index calculation. Nevertheless, the possibility of including other parameters that characterize IAQ remains open for future developments, dependent upon the reliability of measurements.

The method for calculating an air quality index varies depending on the objective. The U.S. EPA has developed an outdoor air quality (AQ) index based on time-series data for monitoring atmospheric air quality worldwide [7]. The score for each parameter in the AQ index is calculated based on the ratio between the measured data and the limit value, and the index is determined based on the most critical score among the parameters. This calculation method was adapted to the indoor monitoring parameters and data for the development of the IAQ index.

The limit values in the IAQ index were determined based on European/French regulatory values and WHO guidelines (Table 2). The limit values for $PM_{2.5}$ and PM_{10} are associated with a short-term exposure duration of 24 hours, as specified in the WHO air quality guideline and the European regulation, respectively. The exposure durations for the other three parameters are unspecified in the reference documents. As the five parameters were measured with a time step of 10 minutes in the instrumented dwellings, the IAQ index was calculated with a 10-minute time step.

Table 2. Limit values in the IAQ index.

Parameter	Limit value	Value type	Exposure duration
Temperature	18 °C	WHO guideline	Not specified
	28 °C	RE2020 French regulatory value	Not specified
Relative humidity	20 – 65%	WHO guideline	Not specified
CO_2	800 ppm	French reference value	Not specified
$PM_{2.5}$	15	WHO guideline	24 hours
PM_{10}	50	European regulatory value	24 hours

Table 3 presents the equations to calculate the scores of the five parameters with a 10-minute time step. Scores for $PM_{2.5}$ and PM_{10} were calculated using the 24-hour running average to ensure comparability with the 24-hour exposure limit value defined in Table 2. Scores for the other three parameters were calculated directly from the measured values and compared with the limit values defined in Table 2. The overall index value was calculated with a 10-minute time step according to the most critical score among the five parameters.

Table 3. IAQ index equations.

Parameter	Equation
Temperature (°C)	$\lvert(T - 23) / [(28 - 18) / 2] \times 100\rvert$
Relative humidity (%)	$\lvert(RH - 42.5) / [(65 - 20) / 2] \times 100\rvert$
CO_2 (ppm)	$(CO2 - 400) / (800 - 400) \times 100$
$PM_{2.5}$ ($\mu g/m^3$)	$PM_{2.5} / 15 \times 100$
PM_{10} ($\mu g/m^3$)	$PM10 / 50 \times 100$

2.3 Index application

The IAQ index was calculated for the instrumented dwellings using the one-week time-series data. Percentages of time exceeding the index values of 50 and 100 were determined for each dwelling over the measurement period. The percentage of time exceeding the index value of 100 indicated the duration during which at least one of the five parameters exceeded the limit values defined in Table 2, suggesting a critical IAQ during these periods. The percentage of time exceeding the index value of 50 indicated the duration during which at least one of the five parameters exceeded 50% of the limit values, suggesting a moderate IAQ during these periods. During the other periods, the measured values of the five parameters were all lower than 50% of the limit values, suggesting a good IAQ. Consequently, each dwelling was categorized into three groups (index lower than 50, between 50 and 100, and higher than 100) for certain durations. The instrumented dwellings were subsequently ranked according to their IAQ, based on the two percentages of time exceeding the index values of 50 and 100 for each dwelling.

2.4 Uncertainty analysis

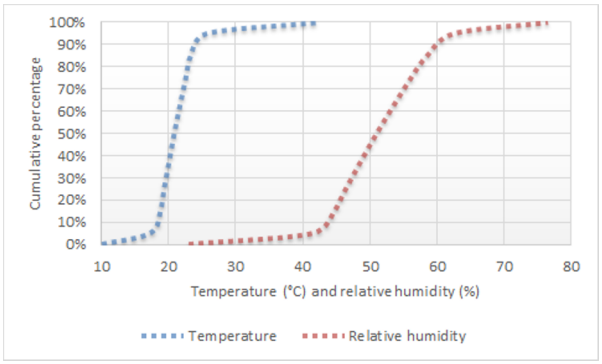
As the score for each parameter was calculated based on the measured value, the uncertainty in the score was directly associated with the uncertainty in the measured value. The overall IAQ index was determined for each time step of the calculation based on the most critical score among the five parameters, thus, the uncertainties in the scores were not aggregated. The measurement uncertainties, as indicated in Table 1, were added to the measured values to assess their impact on the scores of the five parameters.

3 Results and discussion

3.1 Data description

Fig. 1 and Table 4 present the distribution of the measured data for each parameter across all dwellings over the measurement periods. The median values were 21 °C for temperature, 51% for relative humidity, 582 ppm for CO_2, and 3 µg/m^3 for PM_{10} and $PM_{2.5}$. The concentrations of PM_{10} and $PM_{2.5}$ were significantly correlated, and no significant correlation was observed between the other parameters.

(a)



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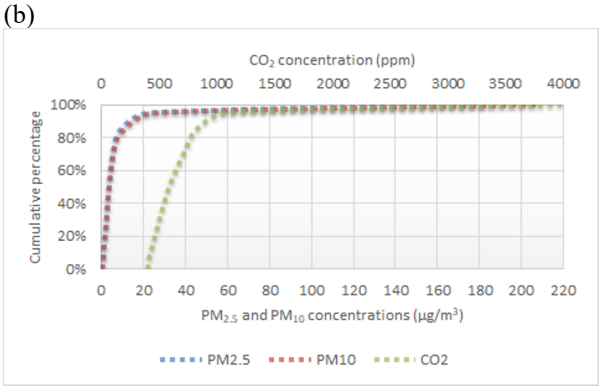

Fig. 1. Cumulative distribution of the measured data for (a) temperature and relative humidity and (b) airborne particles and CO_2

Table 4. Distribution of the measured data

Parameter	P5	P25	P50	P75	P95
Temperature (°C)	17	19	21	23	26
Relative humidity (%)	41	46	51	56	63
CO_2 (ppm)	402	478	582	738	1083
$PM_{2.5}$ (µg/m^3)	1	2	3	6	22
PM_{10} (µg/m^3)	1	2	3	6	25

3.2 Index description

Table 5 presents the distributions of the IAQ index and the score for each parameter across all dwellings over the measurement periods. The IAQ index was determined by the scores of CO_2, $PM_{2.5}$, and T for 41.8%, 16.5%, and 41.7% of the time, respectively. The scores of PM_{10} and RH were below 100 for the 95th percentile, indicating that more than 95% of the measured data did not exceed the limit values. The $PM_{2.5}$ and PM_{10} scores were significantly correlated due to the correlated concentrations. However, no significant correlation was observed among the scores for other parameters (Fig. 2).

Table 5. Distributions of the IAQ index and the parameter score

Parameter	**P5**	**P25**	**P50**	**P75**	**P95**
IAQ index	26	54	80	113	221
Temperature	6	26	50	77	118
Relative humidity	4	18	38	60	89
CO_2	1	20	45	85	171
$PM_{2.5}$	4	13	22	39	148
PM_{10}	1	4	7	13	50

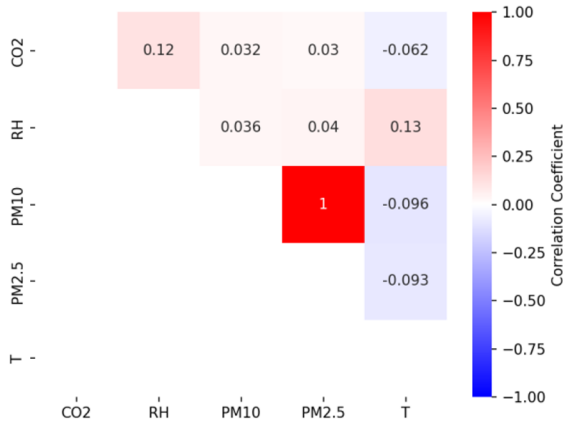

Fig. 2. Correlations between the index parameters

3.3 Index uncertainty

Table 6 presents the uncertainty in the score of each parameter. The measurement uncertainties for T, RH, and CO_2 indicated in Table 1 did not have a significant impact on the parameter score (less than ± 6). However, the uncertainties in the scores of $PM_{2.5}$ and PM_{10} were higher than those in the other three parameters (higher than ± 20). This is because the measurement uncertainty for airborne particles is 10 µg/m^3, which is close to the limit values for calculating the score, particularly for $PM_{2.5}$ (15 µg/m^3). As 16.5% of the IAQ index across all dwellings over the measurement periods was determined by the $PM_{2.5}$ score, the uncertainty in these index values was ± 67. The other index values were determined by the score of T or CO_2, thus, the uncertainty was less than ± 6.

Table 6. Uncertainties in the parameter scores

Parameter	**Uncertainty in the score**
Temperature	± 2
Relative humidity	± 2
CO_2	± 6
$PM_{2.5}$	± 67
PM_{10}	± 20

3.4 Building ranking

For each dwelling, the IAQ index calculated using the time-series data varied over time. The percentages of time exceeding the index values of 100 and 50 were calculated for each dwelling. These indicated the percentages of time when the limit values or its half were exceeded for at least one parameter. The index value of 100 was never exceeded in 8% of the instrumented dwellings (Fig. 3), thus, the measured values of the five parameters did not exceed the limit values throughout the measurement periods in these dwellings. The index value of 100 was exceeded in 75% of the dwellings for more than 5% of the time, in 50% of the dwellings for more than 25% of the time, and in 25% of the dwellings for more than 54% of the time. The index value of 50 was exceeded in 75% of the dwellings for more than 66% of the time, in 50% of the dwellings for more than 88% of the time, and in 25% of the dwellings for more than 99% of the time.

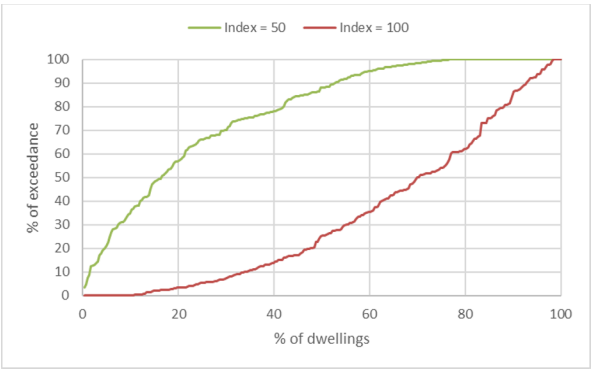

Fig. 3. Percentage of time exceeding the index values of 100 and 50

The IAQ was classified into three groups based on index values of 100 and 50, i.e., index higher than 100 (indicating critical IAQ), between 50 and 100 (indicating moderate IAQ), and less than 50 (indicating good IAQ). The number of dwellings categorized in these three groups varied depending on the percentage of time exceeding the index values of 100 and 50. Fig. 4 defines three criteria for classifying dwellings based on 75% (criterion #1), 50% (criterion #2), and 25% (criterion #3) of time exceedance. Among these three criteria, a maximum percentage of 25% of exceedance time is the strictest, and a maximum percentage of 75% of time exceedance is the least strict for building ranking.

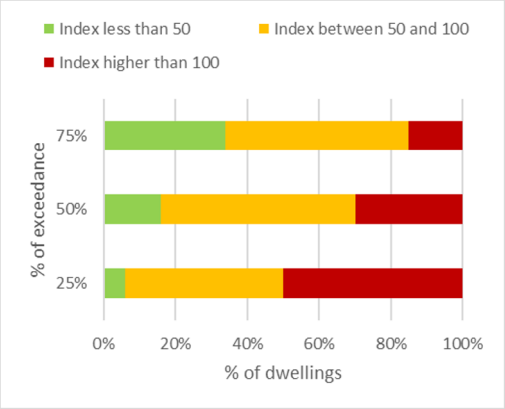

Fig. 4. Three criteria for building ranking

Ranking the instrumented dwellings according to criterion #1, 34% of the dwellings had a good IAQ, 51% had a moderate IAQ, and 15% had a critical IAQ (Fig. 5). For the dwellings classified in the critical IAQ category, the limit values were exceeded 39% of the time for CO_2, 38% of the time for $PM_{2.5}$, 36% of the time for temperature, and 10% of the time for PM_{10}. For the dwellings classified in the moderate IAQ category, the limit value for PM_{10} was not exceeded, and the limit values for CO_2 and temperature were exceeded for more than 11% of the time. For the dwellings classified in the good IAQ category, the limit values for PM_{10} and temperature were not exceeded, and the exceedance of the limit values was 2% for $PM_{2.5}$ and relative humidity. The classification according to criterion #1 identified 15% of the dwellings with a critical IAQ level, where the levels were critical for CO_2, $PM_{2.5}$, PM_{10}, and temperature compared to their limit values.

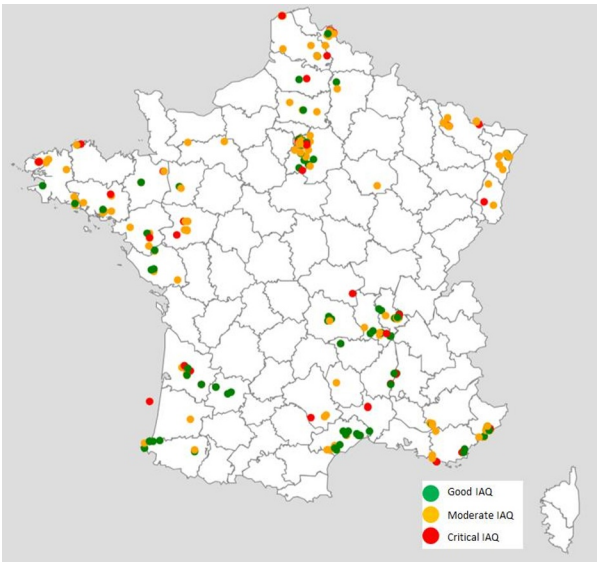

Fig. 5. Building ranking according to criterion #1

Ranking the instrumented dwellings according to criterion #2, 16% of the dwellings had a good IAQ, 54% had a moderate IAQ, and 30% had a critical IAQ (Fig. 6). For the dwellings classified in the critical category, the limit values were exceeded 36% of the time for CO_2, 29% of the time for temperature, 23% of the time for $PM_{2.5}$, 5% of the time for PM_{10}, and 1% of the time for relative humidity. The classification according to criterion #2 identified 70% of the dwellings with a good or moderate IAQ level, where the exceedance of the limit values was less than 4% of the time for $PM_{2.5}$, PM_{10}, temperature, and relative humidity. In these dwellings, CO_2 was the critical parameter that had 14% of time exceedance.

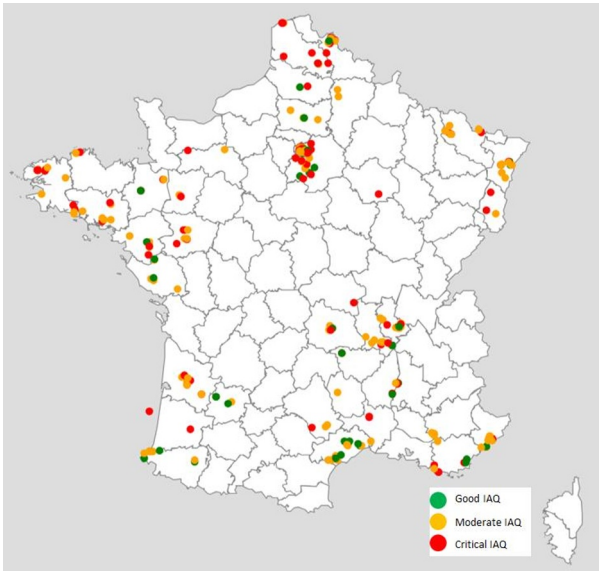

Fig. 6. Building ranking according to criterion #2

Ranking the instrumented dwellings according to criterion #3, 6% of the dwellings had a good IAQ, 44% had a moderate IAQ, and 50% had a critical IAQ (Fig. 7). For the dwellings classified in the critical category, the limit values were exceeded 32% of the time for CO_2, 20% of the time for temperature, 15% of the time for $PM_{2.5}$, 3% of the time for PM_{10}, and 1% of the time for relative humidity. The classification according to criterion #3 identified 50% of the dwellings with a good or moderate IAQ level, where the exceedance of limit values was less than 5% of the time for all five parameters.

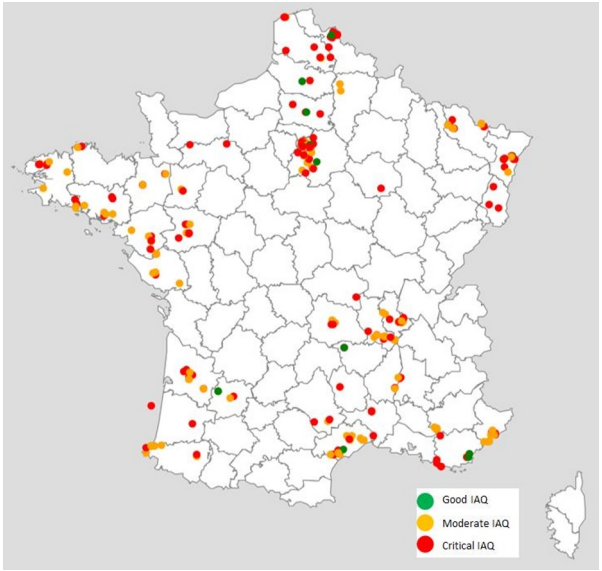

Fig. 7. Building ranking according to criterion #3

3.5 Limitations of the study

The results were derived from a dataset of 296 occupied dwellings in France from 2020 to 2021, which have not been extrapolated to a nationwide scale. Using the index values of 50 and 100 and a tolerated percentage of time exceedance, dwellings can be classified into three categories based on the time-series data of the IAQ index. Adjusting this tolerated percentage of time exceedance allowed for a more or less strict classification of dwellings. However, across all classifications, the CO_2, $PM_{2.5}$, and temperature consistently showed higher percentages of exceedance of the limit values compared to PM_{10} and relative humidity.

To identify the factors contributing to the exceedance of the limit values for these parameters, it is necessary to explore the characteristics and usage patterns of the dwellings in future studies. Moreover, CO, NO_2, TVOC, and PM_1 were monitored along with the other five parameters, but the results were deemed invalid and, thus, not analyzed. These parameters are relevant for characterizing IAQ and could potentially be included in the IAQ index in future studies, depending on the consistency of sensor measurements with reference instrumentation.

4 Conclusions

The field study conducted in the selected French dwellings using online sensors allowed testing the feasibility of continuous measurements for a large dataset of buildings. Based on the measured values acquired in 2020-2021, an IAQ index was developed to assist in the analysis and interpretation of continuous measurements. This index relied on temperature, relative humidity, CO_2, PM_{10}, and $PM_{2.5}$, as the measurements were verified using reference instrumentation.

For each time step of the measured data, the calculation of parameter scores relied on regulatory values and WHO guidelines associated with short-term exposure. The IAQ index was calculated based on the most critical score among the five parameters to identify all exceedances of the limit values. In the database of the present work, the IAQ index was determined according to the scores of CO_2, $PM_{2.5}$, and temperature for 41.8%, 16.5%, and 41.7% of the time, respectively. The concentrations of PM_{10} were significantly correlated with those of $PM_{2.5}$, but the PM_{10} score was consistently less critical than that of $PM_{2.5}$. Exceeding the limit values for relative humidity occurred less than 5% of the time. Therefore, relative humidity did not pose a significant problem compared to the other parameters.

As the uncertainty in the index was directly associated with measurement uncertainty, $PM_{2.5}$ measurements introduced a higher uncertainty in the index value compared to the other parameters. This affected 16.5% of the index values across all dwellings over the measurement periods, suggesting that the reliability of the index can be improved, providing a more precise measurement of airborne particles.

The IAQ index values of 50 and 100 were exceeded in almost all the dwellings for certain periods of time. Defining a tolerated percentage of time exceedance allowed ranking the buildings according to the IAQ. With a 75% of time exceedance, 15% of the instrumented dwellings had a critical IAQ level, where CO_2, $PM_{2.5}$, PM_{10}, and temperature were improvable. With a 50% of time exceedance, 70% of the dwellings had a good or moderate IAQ level, where CO_2 remained improvable compared to the other four parameters. With a 25% of time exceedance, 50% of the dwellings had a good or moderate IAQ level, where the exceedance of the limit values was less than 5% of the time for all five parameters.

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