Influence of occupants' behavior on indoor CO_2 concentration of a naturally ventilated multifamily building in Porto, Portugal.

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***Abstract*—Adequate supply of fresh air is essential to provide a healthy, safe and comfortable indoor environment in buildings. Currently, the majority of the residential buildings in mild climate European countries, such as Portugal or Spain, remain naturally ventilated. This fact has raised concerns in the building sector regarding the indoor air quality present in these buildings as fresh air supply mostly relies on occupants' window opening behavior and personal habits, which can vary significantly from one apartment to the next. In this context, this work presents the indoor CO_2 concentration levels registered during more than one year in the bedrooms and living rooms of eight apartments of a naturally ventilated residential building located in Porto, Portugal. Monitored CO_2 concentrations confirmed relevant periods of time with inadequate indoor air quality, exhibiting great variations between apartments. Differential occupants' window opening behavior, personal habits as well as presence of internal CO_2 sources (e.g. smokers) were stated as the major reasons behind these wide discrepancies. Results suggest that, in some situations, implementation of mechanical ventilation systems in residential contexts should be promoted in order to guarantee adequate IAQ at all times and regardless of outdoor weather conditions or occupants' window opening behavior.**

***Index Terms*—Indoor air quality, Occupants' window opening behavior, CO_2 concentrations, Fresh airflow rates.**

I. Introduction

The building sector is responsible for a significant portion of the final energy use in the world [1]. In Europe, member states are addressing this issue aggressively by means of increasingly demanding energy building performance requirements. Ratification of the new recast of the Energy Performance Building Directive (EPBD) [2], which introduced the concept of Nearly Zero Energy Buildings (NZEB), meant an inflexion point in the building European regulatory policy. Under this directive, from 2021 all new buildings and major renovations will have to adopt nearly zero energy features. Consequently, the building sector is facing progressively stricter energy efficiency regulations, forcing all professionals involved in the building sector to adopt more energy-efficient and sustainable solutions, paying greater attention on energy conservation, integration of renewable energies and sustainability in buildings, all of which have to be achieved without compromising comfortable indoor environments or indoor air quality (IAQ).

Adequate ventilation is important for creating comfortable indoor environments, avoiding deterioration of occupants' health and productivity. This issue is becoming more relevant for the scientific community as people in developed countries spend increasing part of their life in indoor environments. Currently, the majority of the residential building stock in mild climate European countries, such as Portugal or Spain, remain naturally ventilated. This fact has raised concerns in the building community regarding the IAQ present in these residential buildings since some studies conducted on existing residential buildings have shown that they are often poorly ventilated [3]–[5], as a result of the inadequate personal habits or occupants' window opening patterns. Batog and Badura [3], studied the growth dynamics of CO_2 concentration levels present in two bedrooms during seven nights in a typical block of flats in Poland, measuring peak CO_2 concentrations between approximately 2000 and 3000 ppm for a bedroom with a volume of 20.7 m^3 and one adult sleeping, and between approximately 2000 and 3800 ppm for a bedroom with a volume of 23.6 m^3 and two adults sleeping. Authors concluded that these great variations on CO_2 concentrations were caused by the different air infiltration flow rates present in the bedrooms during the different measurement periods, as infiltration rates may be very sensitive to variables such as wind speed and indoor/outdoor temperature difference. McGill, Oyedele and McAllister [4] compared the IAQ present in eight houses constructed under similar insulation and air-tightness requirements in United Kingdom but employing different ventilation strategies. In this study, four of the houses were naturally ventilated, while the other four used mechanical ventilation with heat recovery systems. Indoor air measurements were registered at each of the houses during periods of 24 hours in the living room and bedroom for test days in summer and winter seasons. As authors expected, Measurements exhibited significant CO_2

concentration variations between the houses. While the four mechanically ventilated houses were able to maintain, at all times, CO_2 levels in the living room and bedroom below 1000 ppm for both summer and winter test periods, naturally ventilated houses registered, during the summer test day, peak values of 4173 ppm in a bedroom and 1679 ppm in a living room. Furthermore, during the winter test day, the naturally ventilated houses presented peak values of 4456 ppm in a bedroom and of 3427 ppm in the living room. Canha et al. [5] measured the concentration levels of several indoor chemical compounds (CO_2, CO, VOCs, formaldehyde, among others) present in a bedroom of an apartment located in Setubal (Portugal) during a monitoring campaign of twelve consecutive days in August. Four different ventilation settings by opening and/or closing an exterior window and the bedroom door were analyzed, comparing the resultant infiltration air change rates, which varied from $0.67 \pm 0.28h^{-1}$ to $4.85 \pm 0.57h^{-1}$, and their corresponding pollutants concentrations. The setting with the lowest ventilation rates (the one with the window and door closed) presented a continuous increase of CO_2 levels even above the limits (1250 ppm) established by the Portuguese legislation for commercial and multifamily buildings [6] during the last hours of the sleeping period.

When is not possible to supply sufficient fresh air flow rates by natural ventilation mechanisms, the employ of mechanical ventilation systems can potentially provide a solution for whatever residential context. However, the high ventilation thermal loads and fluid pumping costs associated with mechanical ventilation systems can represent a significant portion of the total energy consumption of the building. Ventilation energy costs can be particularly high in locations with severe climates, characterized by large indoor-outdoor temperature differences, where the employ of heat recovery units is highly recommended. In this context, there is increasing interest directed towards more sustainable, controllable and energy efficient ventilation methods for residential buildings, such as hybrid ventilation or demand controlled ventilation (DCV) [7], [8]. Addressing these questions is becoming more important for all professionals involved in the building sector as building energy regulations progressively with new updates demand greater fresh airflow rates per occupant and increased filtering requirements, while the maximum permitted thermal transmittances of building envelopes are reduced [9]–[11]. This effect makes ventilation systems in energy efficient buildings responsible for a greater share of the total consumption and CO_2 emissions.

II. Materials and Methods

A. Building case base

This study uses experimental data from a building monitored in the framework of the More Connect research project [12]. The Portuguese pilot building for the More-Connect project is an existing building (Fig. 1) located in Vila Nova de Gaia, Porto Metropolitan Area, in the North region of Portugal. It is a social housing neighborhood, built in 1997, and managed by Gaiurb (a municipal company). It is a multifamily building composed of three attached blocks, each with three floors, corresponding to six apartments (a two-bedroom and a three-bedroom per floor). In total, the building is constituted by eighteen apartments. Besides the apartment floors, the structure of the building includes a non-used small attic space and a cellar, used for storage.

Fig. 1. Photograph of the studied building.

Monitored apartments did not have any ventilation air supply mechanical system, and fresh air can only be provided by window opening and infiltration. Hence, occupants' window opening behavior can greatly affect IAQ. In addition, the building is not equipped with any central or decentralized heating, ventilating, and air conditioning (HVAC) system; therefore, the only option occupants have to condition their apartments is using portable electrical or gas heaters for heating, and fans or increased natural ventilation by opening windows or doors for cooling.

B. Monitoring and occupancy

A total of eight apartments have been monitored during a period longer than a year, covering the period from February 2016 to July 2017. The building has two types of apartments, the two-bedroom apartments, which have a useful area of 65 m^2, and the three-bedroom apartments with an area of 83 m^2.

The monitored variables correspond to air dry bulb temperature, absolute humidity (with relative humidity and wet bulb temperature being computed as dependent variables of those) and CO_2 concentration level. Indoor sensors in the apartments were located in the living rooms and bedrooms (denoted by LR and BR, respectively, in Fig. 2), because it is in these zones where occupants typically spend most of their time when they are in the apartment, representing therefore the most adequate zones for assessing occupants' exposure to CO_2. Given the configuration of the apartments, two three-bedroom apartments and a two-bedroom apartment were monitored by block, with the exception of one block where only two apartments were monitored. These apartments (a total of eight) were selected in order to be able to compare similar rooms with different contextual and boundary positioning. An additional monitoring equipment was placed inside a protective box in the NorthEast facade of the building to measure outdoor conditions.

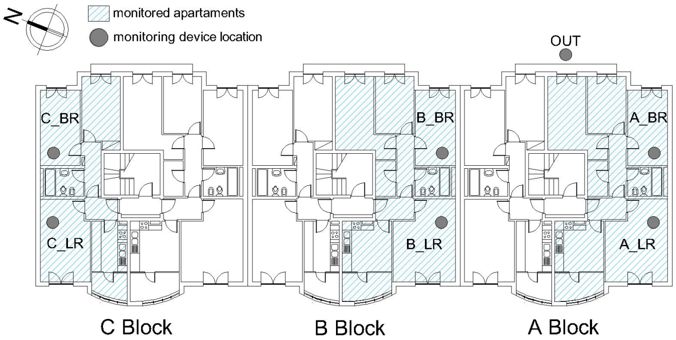


Fig. 2. Floor plant and monitoring devices location.

The instruments used for the measurements of the indoor temperature, absolute humidity and CO2 concentration were the Delta Ohm HD35ED Data Loggers [13]. This wireless equipment has the capability of storing continuous data with 5-minute interval in a range of a month without the need of data downloading. Particular attention was paid to the location of data logging devices, namely, the devices were located further than 0.5 m from corners and windows, no suffering influence of direct solar radiation, and spaced away from any electric or gas heater, fan or infiltration air leakage from window or door cracks. Fig. 3 shows some examples of locations and positioning of the data loggers in the apartments (upper photographs correspond to a bedroom, while the lower photograph to a living room).

Fig. 3. Data Loggers, location and positioning examples

Additionally, information regarding occupancy (which includes context, typical occupation schedule and type of environment regarding smoking), was gathered through interviews to users, conducted on a visit to the building. Table I shows the results of the inquiries made to the occupants in terms of occupancy context and schedule. From the eight apartments analyzed, one had five occupants and two apartments had four occupants. Three of the apartments had three permanent occupants. Only one apartment had two occupants and other only had one person occupying the space (although just on weekends). In the majority of the apartments analyzed (a total of six apartments) is a common practice to smoke indoors by, at least, one of the occupants.

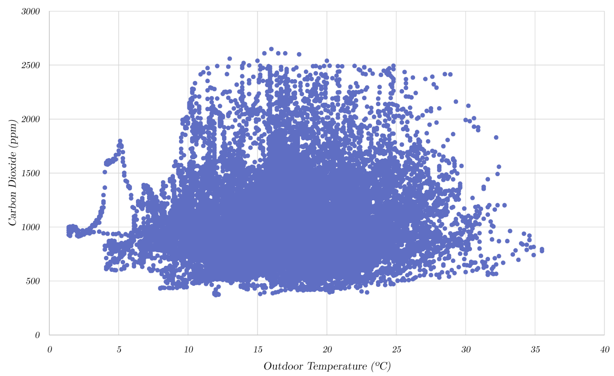
TABLE I
APARTMENTS OPERATIONAL INFORMATION GATHERED AND AVERAGE CO_2 CONCENTRATIONS REGISTERED

Apart.	Occupants	Occupancy context	Schedule of occupancy	Smokers	Living room $\overline{c}_{CO_2}$(ppm)	Bedroom $\overline{c}_{CO_2}$(ppm)
1	4	1 Employed (night shifts) 1 Retired 1 Disabled 1 Unemployed	Full time occupancy	YES	971.09	1173.08
2	3	2 Unemployed 1 Employed (doing shifts)	Full time occupancy	YES	954.35	1210.78
3	4	2 Employed 2 Students	Weeks:18h-8h	YES	920.73	1203.08
4	3	1 Unemployed 2 Students	Full time occupancy	YES	792.36	1154.81
5	2	2 Employed	Weeks:18h-8h	YES	688.68	944.85
6	1	1 Employed (working abroad)	Weekends	YES	653.70	712.77
7	5	2 Unemployed 2 Students 1 Baby	Full time occupancy	NO	872.18	1141.87
8	3	2 Unemployed 1 Employed	Full time occupancy	YES	682.87	759.28

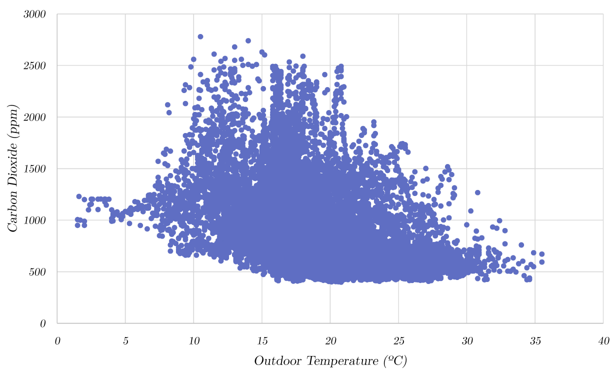
C. Occupants' average exposure to CO_2 concentrations - A simple comparative method

Compare the differential occupants's exposure to CO_2 levels present in different apartments is not a simple task, as exposure time, indoor CO_2 sources and personal habits or occupants' window opening patterns play a relevant role in the assessment, and correlations between CO_2 levels and other variables such as outdoor conditions may not be as clear as one might expect. For instance, Fig. 4 shows the CO_2 levels versus outdoor temperatures registered during the measurement period for the living rooms of the apartments 1 (Fig. 4(a)) and 7 (Fig. 4(b)). Although, it should be expected that the higher CO_2 levels would occur at lower outdoor temperatures, due to the lower ventilation rates, apartment 1 did not follow this trend. However, a certain correlation between outdoor temperatures and CO_2 levels can be observed for apartment 7. Both apartments are densely occupied with 4 and 5 occupants, respectively, but no smokers were reported for the apartment 7, this is, indoor CO_2 sources can play a relevant role in occupants's exposure. Similar behavior to apartment 7 can be reported for apartment 8 (which is the apartment with the lower CO_2 levels), although in this case smokers were present, suggesting that adequate occupants window opening pattern also plays a relevant role (maybe the greatest).

A valid and simple approach to evaluate and compare occupants' average exposure to CO_2 concentration levels, can be conducted by using cumulative frequency distributions (histograms), constructed from the relative frequency



(a)



(b)

Fig. 4. CO_2 concentration levels measured in the living rooms of the apartment 1 (a), and 7 (b).

distribution gathered over the total length of the monitored period. This approach is widely used by building designers for predicting thermal comfort and energy demand in passive buildings, using the indoor air dry bulb temperature as key performance variable to consider. The cumulative frequency of occurrence corresponding to every monitored zone (8 Bedrooms and 8 Living Rooms), indicates the percentage of hours that the CO_2 concentration exceeds or is below a certain level in a given indoor ambient. For example, Fig. 5 shows the CO_2 concentration frequency and cumulative frequency of occurrence corresponding to the apartment that presented the highest CO_2 levels during the monitored period, which was the apartment 1. This figure indicates that approximately during the 57% of the time of the monitored period, the indoor CO_2 concentration levels present in the living room were below the maximum recommended reference concentration indicated in some building guides of good practice in Portugal (1800 mg/m^3 $\approx$ 984 ppm), and approximately the 83% of the time the CO2 levels were below the limit value of 2250 mg/m^3 ($\approx$ 1250 ppm) established by the Portuguese legislation for commercial and multifamily buildings [6]. Obviously, these results can also be interpreted in an alternative manner. During 43 and 17% of the monitored time, respectively, the CO_2 concentration levels exceeded those limits. Even more concerning were the CO_2 concentration levels registered in the bedroom of the apartment 1, shown in the lower part

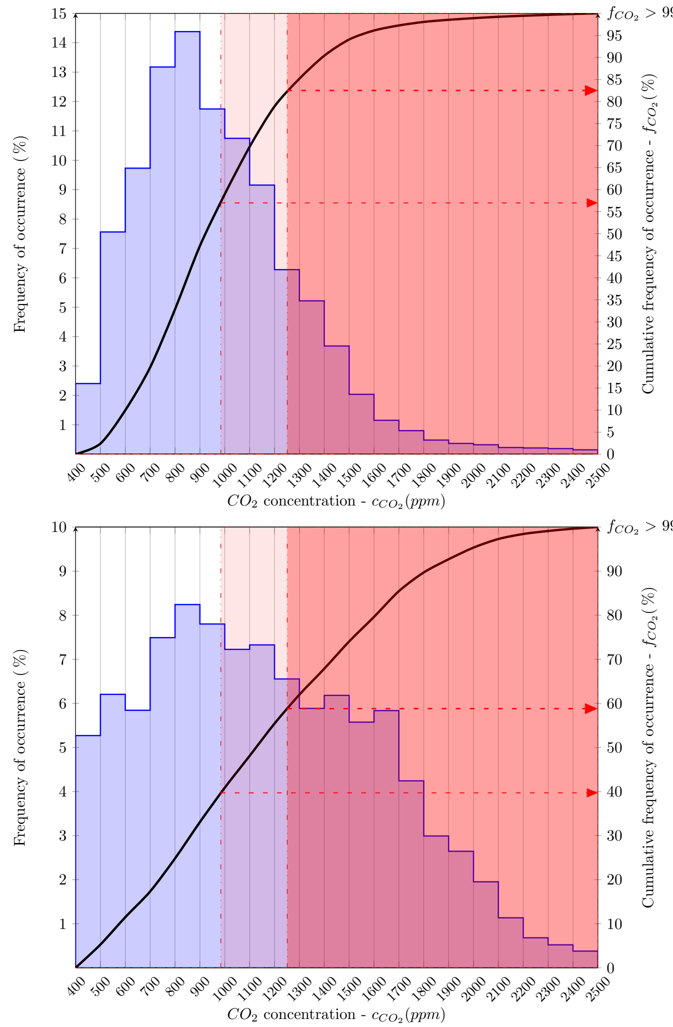


Fig. 5. CO_2 concentration levels measured in the living room (upper part) and bedroom (lower part) of the apartment 1.

of Fig. 5, where approximately during the 40% of the total monitored time, CO_2 concentrations were higher than 1250 ppm. From simple exploration of the experimental raw data, it can be observed that the highest concentration values were mainly measured during the last hours of the sleeping period (between the 5:00 and 9:00 hours), as expected.

Based on this approach, from the exposure to CO_2 standpoint, two occupants located in different zones with identical cumulative frequency distributions constructed over the same exposure period, at the end of the period, have been exposed to the same indoor CO_2 concentration levels during the same periods of time, i.e., identical exposure. This statistical approach has been found particularly suitable for the purpose of this study for two reasons: (1) because the amount of measured data is considerable, corresponding to a monitored period longer than a year, namely approximately 18 months of data, logged at 5-minutes intervals, and (2) because it allows a simple method to make comparisons between different apartments, only requiring the direct comparison of the overlapped cumulative frequency distribution curves of the analyzed zones (as it is illustrated in figure 5, for example), as these curves account all the mechanisms involved in this type of analysis, including the CO_2 diluting mechanisms, such as actual infiltration flow rates and occupants' window opening behavior, as well as the indoor CO_2 generation sources such as occupants' metabolisms, occupants' activities (smoking, etc.), and other indoor generation sources (combustion processes in heaters, cooking appliances, etc.).

III. Results and Discussion

Fig. 6 shows the histograms corresponding to CO_2 concentration levels measured in the apartments. Results indicate that a significant amount of monitored time CO_2 levels exceeded the recommended reference CO2 concentration of 984 ppm (f_{CO_2} >984 ppm). Additionally, results clearly point out the presence of relevant variations between apartments regarding CO_2 levels, suggesting not only a distinctive occupants window opening behavior, but also the presence of indoor sources of CO2 (e.g., smokers, gas powered heaters or cooking appliances, etc.). CO_2 Levels found in bedrooms are particularly discrepant, for example, occupants' exposure of concentration values higher than the recommended limit of 984 ppm, f_{CO_2} >984 ppm, ranged from 15 to 60% of the total monitored time depending on the apartment. In the case of the living rooms, these discrepancies are lower but still relevant, meaning that between 5 and 40% of the time that occupants are at the living room, were exposed to CO_2 concentration levels above maximum recommended values of 984 ppm.

Another concerning issue that arises from the analysis of Fig. 6 is the occupants' exposure to CO_2 concentration levels above the limit value of 2250 mg/m^3 ($\approx$ 1250 ppm). According to this figure, occupants' exposure to higher concentrations, f_{CO_2} >1250 ppm, ranged between approximately 5 and 40% for the bedrooms, being less concerning for living rooms where cumulative frequencies of occurrence above concentration limits fell below 20% for all apartments.

With the aim of specifically focus on the effect of occupant's behavior on CO_2 levels, i.e., conducting a sensitivity analysis of this parameter, a first stage was to isolate this effect from the rest of parameters, such as the different number of occupants, occupancy schedule and smoking activity. Very similar (although not identical) occupancy contexts were found between two apartments, namely apartments 2 and 4. As both apartments have the same number of occupants, approximately same occupancy schedule (although the different types of jobs can affect it) and declared indoor smoking activity. Registered CO2 levels indicated variations of f_{CO_2} >1250 ppm between 80 and 92.5% for the living rooms, and between approximately 57.5 and 62.5% for the bedrooms, of the apartments 2 and 4, respectively. Being so, apartment 4 presented better IAQ, which was significant (a difference of 12.5% in f_{CO_2} >1250 ppm) in the case of the living rooms, and slightly less notable (only a 5% in f_{CO_2} >1250 ppm) in the case of the bedrooms. This suggests a greater sensitivity of the IAQ present in living rooms to occupants' habits, as occupants can for example

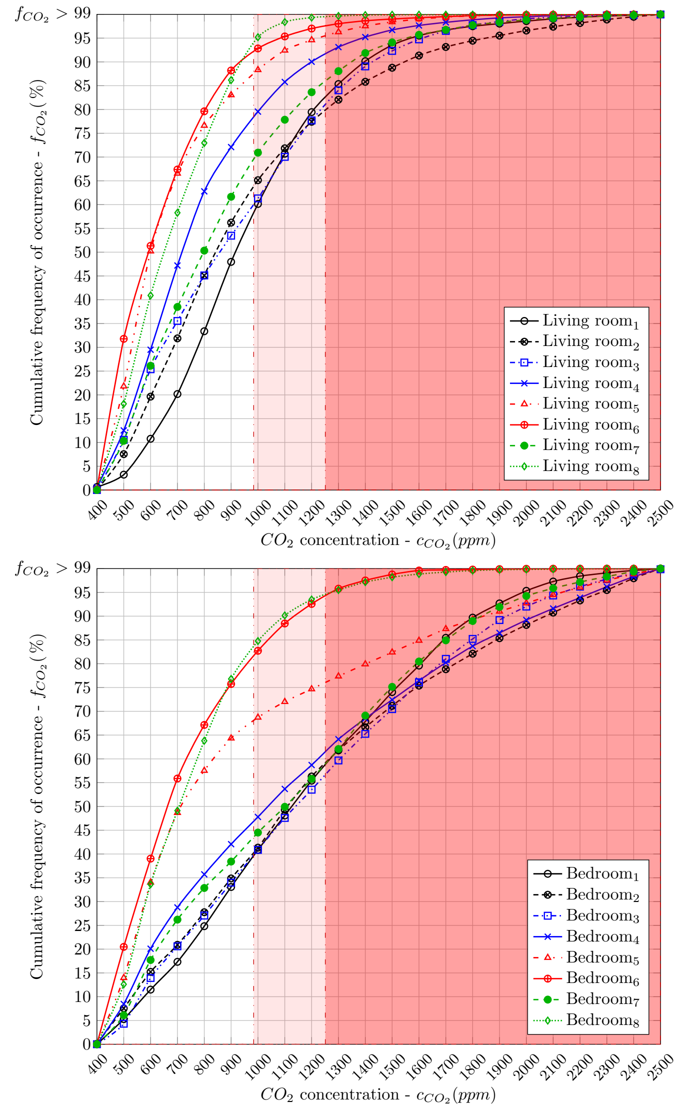


Fig. 6. CO_2 concentration levels measured in the living rooms (upper part) and bedrooms (lower part) of the 8 monitored apartments.

smoke more or less, can open the windows/doors more or less time, etc.

The best IAQ was found in apartments 6 and 8. Showing f_{CO_2} >1250 ppm above 97% for the living rooms and above 95% for the bedrooms, maintaining adequate IAQ during the entire monitored periods (18 months). These results could be expected for the apartment 6, as it is only occupied on weekends, but not for apartment 8, which is highly occupied. The reason of this adequate IAQ during the entire year can be attributed to adequate occupants window opening patterns.

According to experimental data, not a clear correlation can be observed between the presence of smokers and CO_2 concentration levels registered in the living rooms. The reason behind this conclusion can be attributed to the fact that the apartments with more occupants (apartments 1 and 7, with five and four occupants, respectively) are those in which were declared non-smoking practices, counteracting in some manner both effects: the greater amount of CO_2 generated by the presence of more occupants, with the additional CO_2 produced by smokers. Hence, it should be take into account that smoking is not the only indoor pollution source, without forgetting the important role that occupants' window opening patterns play in IAQ.

IV. Future Work

The long-term experimental data collected in this work can be used in future analyses to support the development and calibration of building models, which can be used to estimate the ventilation flow rates required to maintain an adequate indoor air quality by using a mechanical ventilation system. This kind of experimental data allows, for example, analyses of the differential performance of constant volume flow rate and DCV systems in residential contexts, where the level of complexity of the implemented systems is generally the major limiting factor, and DCV systems have to convincingly demonstrate their higher operating cost benefits.

Of particular interest may be the use of cumulative frequency of occurrence curves (histograms), not only for comparing the occupants' exposure in different zones, but also to greatly simplify the calibration process between building models and experimental data.

V. Conclusions

This work presents a simple and reliable comparative method for assessing occupants average exposure to CO_2 concentrations (method theoretically valid for any pollutant) based on the direct comparison of overlapped cumulative frequency distribution curves (histograms).

Indoor CO_2 concentration levels registered during more than one year in the bedrooms and living rooms of eight apartments of a naturally ventilated residential building located in Porto, revealed that very different indoor air quality may be present in residential buildings. Particularly poor indoor air qualities were registered in bedrooms, where CO_2 concentration levels achieved in the worst case, exceeded the limits (1250 ppm) established by the Portuguese legislation during approximately 40% of the monitored time. Living rooms did not show such concerning levels showing, however, very sensitive behavior to differential occupants window opening habits and presence of indoor CO_2 sources (e.g., smokers). Results suggest that, in some situations, implementation of mechanical ventilation systems in residential contexts should be promoted in order to guarantee adequate IAQ regardless of outdoor weather conditions (i.e., infiltration is quite sensitive to wind speed) or occupants' window opening behavior, guaranteeing adequate indoor air quality at all times.

VI. Acknowledgments

MORE-CONNECT is funded by the European Commission within the framework of the Horizon 2020 program. This support is gratefully acknowledged. The authors would like to thank the availability and use of data that is an integral part of the More-Connect research project (http://www.more-connect.eu/).

We also acknowledge funding from the University of Castilla-La Mancha through its call for visitations and stays for Professors and researchers in other research centers and universities in 2017, which provided support for the collaboration of the Professor J.F. Belmonte at the University of Minho.

VII. Notation

A. Latin letters

- f_{CO_2}: Cumulative frequency of occurrence associated with a certain level of CO2 concentration.
- c_{CO_2}: CO_2 concentration level.
- $\overline{c}_{CO_2}$: Average CO_2 concentration level.

B. Abbreviations and acronyms

- DCV: Demand control ventilation
- HVAC: Heating, ventilation and air conditioning
- IAQ: Indoor air quality

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