COMPLEMENTARY APPROACHES TO ASSESS INDOOR AIR QUALITY IN URBAN ENVIRONMENTS

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ABSTRACT
With the continuous improvement of life quality, indoor air quality (IAQ) has become an important issue in recent years. IAQ is affected by many factors including the type of indoor pollution sources, ventilation conditions, as well as indoor activities. Studies revealed that the outdoor environment is also an important factor that cannot be neglected for IAQ studies. The main objective of this work is to extend the knowledge of IAQ in the urban environment by using a numerical tool to calculate the pollutants concentrations inside an office room in a typical workday. For this purpose, two main approaches were used: (a) the CONTAM model, to characterize the IAQ in terms of carbon dioxide (CO_2) concentrations; and (b) measurement data, by using reference equipments, to assess the accuracy of the results provided by the model. The Portuguese Decree nº118/2013 and its associated ordinances nº 353-A/2013 regarding ventilation for buildings, transposed from the Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, was used to estimate the exterior air inflow rate needed to keep the CO_2 concentrations below the legal limit. For the occupancy and activity performed inside the case study, an exterior minimum air inflow rate of 120 $m^3 \cdot h^{-1}$ was estimated. As this minimum flow rate is not provided on a daily basis, CONTAM model was also used to study the impact of several measures focused on natural ventilation. The scenarios were defined, taking into account the door communication with inside area and the window position: (a) window closed, and (b) window opened with different exterior air inflow rate. The results show that the simulated and measured CO_2 concentrations are in good agreement. Regarding the analysed scenarios, the one that promoted a better IAQ was the one in which the door was only open to allow users to get in and out of the office room, complemented with an open window.
Keywords: air pollution, urban areas, CO_2, indoor air quality, human health, modelling, measurements.

1 INTRODUCTION

Urban air pollution can be an important source to the indoor air quality (IAQ), especially in highly ventilated homes, or in homes near pollution sources. Similarly, indoor air pollution sources may also be important causes of urban air pollution, especially in cities where many homes use biomass fuels or coal for heating and cooking.

Nowadays, people spend in average approximately 90% of their time in indoor environments, being exposed to indoor air pollutants for larger periods than those outdoors [1]. Therefore, it is crucial to characterise not only ambient urban air but also indoor air, in order to understand its composition and, in the presence of potential harmful concentrations of chemical species dangerous for human health, identify possible causes for them (direct or indirect sources of pollutants) [2]. In 2016, indoor exposure has been associated with several health issues, such as respiratory diseases, and with a globally 3.8 million deaths [3].

Pollutants usually analysed in IAQ monitoring include carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde, total volatile organic compounds (VOC), particulate matter (PM) and, at the microbiological level, bacteria and fungi [4].

The World Health Organization [4] states that IAQ management is hampered not only because of the numerous types of indoor spaces but also due to complex relations between indoor air quality and building design, materials, operation and maintenance, ventilation and

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user behaviour. Both the Portuguese Environmental Agency [5] and the United States Environmental Protection Agency [6] consider construction materials and consumer products the most important sources contributing to the degradation of IAQ. Other common causes of poor IAQ are coating and furniture materials, human occupancy, combustion sources (oil, natural gas, kerosene, coal, wood and tobacco), asbestos, heating and cooling systems, humidification devices and infiltration of outdoor pollutants.

Currently, the legislation specifies protection thresholds for some pollutants in order to improve IAQ. IAQ legislation is very interlinked with energy performance of buildings regulation. The Directive 2002/91/EC and later the Directive 2010/31/UE, which aim to promote buildings energy performance, were implemented. Both Directives take into account outdoor climate and local conditions, as well as indoor climate requirements and cost-effectiveness. In Portugal, the first Directive was adopted as three Decrees-Law, which, directly or indirectly, seek to improve IAQ by promoting an adequate air exchange. The first, Decree-Law 78/2006 of 4 April, approved the National Energy Certification and Indoor Air Quality in Buildings; the second, Decree-Law 79/2006 of 4 April, approved the Regulation of Climate Energy Systems in Buildings (RCESB); and, finally, the third, Decree-Law 80/2006 of 4 April, approved the Regulation Characteristics of Thermal Performance of Buildings. After the second European Community Directive, the previous Portuguese Decrees were revising and merged in the Decree nº 118/2013 and subsequent regulated ordinances. In the RCESB context, the requirements to improve IAQ range from the imposition of a minimum value of air exchange rate applicable to the new buildings to the definition of concentration thresholds for several pollutants (e.g. CO, CO_2, VOC and PM). The RCESB also requires that all energy systems constructed or existing in buildings to be kept in hygienic conditions.

To assess the IAQ some modelling tools have been applied, such as IAQX [7], MCMs [8], INCA-Indoor [9] and CONTAM [10]. Recent studies have modelled IAQ in specific environments, such as schools [11]–[13]. Despite of that, studies using measured data to evaluate models accuracy are very scarce (e.g. [13], [14]).

The main objective of this study is to contribute to and improve the knowledge of IAQ in the urban environment by using the CONTAM model and measurements with certified equipment to characterize the CO_2 concentrations inside an office room in a typical workday. This paper is organized as follows, Section 2 describes the case study and the approach used in this work and additionally, addresses the procedure to estimate the exterior air inflow rate and explains the monitoring and modelling process that was used. The comparison between measurements and modelling results considering different scenarios is presented in Section 3. A summary and conclusions are presented in Section 4.

2 DATA AND METHOD

2.1 Case study description

In this work, a research office room at the Department of Environment and Planning of the University of Aveiro was chosen as the case study site (Fig. 1(a)). This department is located in the city of Aveiro, Portugal, and includes classrooms, research office rooms and laboratories to support the classes and research work. The room was chosen mainly due to the easy assess and control of the monitoring parameters. The location of the department was also a key factor for its selection as a case study, since it is placed nearby a main outdoor emission source (road traffic emissions) (Fig. 1(b)).

(a) (b)

Figure 1: Location of the Environmental and Planning Department at the University of Aveiro (on the right) and location of the office room (white box on the left).

The department comprises two buildings. The main building and the second building are parallel to each other and also parallel to the road in front of the department. Each office room has one window and one door, with the windows facing the schoolyard and the door used to access the hallway. The office room selected to this study is occupied, on average, for 7.5 h a day, by five researchers. The office schedule is from 9:00 a.m. to 6:00 p.m. (local time), with a lunch break from 1:00 p.m. to 2:00 p.m. The study was performed in a winter day, starting at 0 a.m. and ending at 12:00 p.m. of the 19th of March 2019. During this time frame, the outdoor temperatures were low (between 10°C to 18°C), which led to the door being only opened to allow users to get in and out of the office room and the window remained closed (only) during the morning period.

To assess the indoor air quality in the study area two complementary approaches were applied: measurements during a monitoring campaign (Section 2.2) and a modelling approach (Section 2.3).

2.2 Monitoring campaign

The monitoring campaign was performed using the TG-610 and TG-501 probes from GreyWolf®. The application of these probes allowed continuous measurements of the concentrations of several pollutants associated with indoor air quality: CO, CO_2, Total VOCs, NO_2 and O_3 in the selected office room (see Fig. 2). The technology behind these probes is based on electrochemical gas sensors, nondispersive infrared sensors (NDIR) and photoionization detectors (PID) [15], [16]. Moreover, the Grey Wolf® probes integrate the temperature and relative humidity sensors as well. The exterior air inflow rates were evaluated through an Airflow Instruments Velocity Meter from TSI, providing accurate air velocity, relative humidity and temperature measurements [17].

During the experimental campaign, the indoor air quality was measured with a time step of one minute. When the window was open (afternoon period), beyond the air quality measurements, some air flow parameters were also measured with a time step of 30 minutes, such as, the exterior air inflow speed, air temperature and relative humidity. These parameters were used to estimate the exterior air inflow rate.

(a) (b)

Figure 2: Equipment used in this study. (a) Grey Wolf® monitor and IQ-610 (Indoor Air Quality Probe); and (b) Airflow Instruments Velocity Meter from TSI.

2.3 Modelling approach

In this section, the model applied in this study is described (Section 2.3.1). The model was applied using three different exterior air inflow rates. In the first case, the window was closed, meaning that there was not an exterior air inflow rate. In the second case, two different exterior air inflow rates were estimated and tested: one was estimated based on the legal recommendation (Section 2.3.2) and the other was estimated using data from the experimental campaign data (Section 2.3.3).

2.3.1 Model description and configuration

CONTAM-Multizone Airflow and Contaminant Transport Analysis Software [10] is an IAQ and ventilation model, which allows for the estimation of indoor air parameters such as airflows, pollutant concentrations and human exposure to these contaminants. These features, and the fact that the CONTAM model is a free online software with constant upgrades and developments justify its selection for this study.

The outputs of the CONTAM model include data on pollutant concentrations and temperature variation over time, and air exchange rates between all simulated rooms in a given zone.

The CONTAM model allows different methods of airflow and contaminant simulations, namely steady state for airflows without contaminants, transient state for airflows and transient state for both airflows and contaminants. In the first simulation, the model enables the user to observe the direction of the airflows and to obtain the airflow rates in all zones of the building under a constant building system and/or weather conditions; the second method, the model calculates time-dependent airflow rates under a changing building system and/ or weather conditions; finally, the third method is used to obtain time-dependent airflow rates and pollutants concentrations, taking into account variations in outdoor air conditions [10]. The model requires a wide variety of input data, as shown in Table 1.

Table 1: Input data required for the CONTAM model [13].

Model input data	Indoor	Outdoor
Building characteristics	Area, volume, height, number and type of zones, number of levels (floors) and control network components	
Airflow paths	Air leakage paths (windows, doors, cracks), ventilation system elements (fans, ducts, vents)	
Weather conditions	Temperature and pressure	**Ambient temperature, barometric pressure, humidity ratio, wind speed and direction**
Contaminants	**Initial concentration of contaminants, contaminant sources, filters and sinks**	**Ambient contaminant concentrations**

Fig. 3 shows the CONTAM model layout of the building's department second floor, as well as the case study (office room) with other spaces added to accurately represent the distribution of the office rooms in the building. Furthermore, the overall characteristics and size of the studied office room, including room surface area and volume, windows and door, were included in the model. Another model input is the CO_2 flux emitted by the occupants in the office room, which can be estimated based on the average weight of each researcher and the level of physical activity. It was assumed that the five researchers placed in the office were not doing any heavy physical activity. For the CO_2 flux calculations, equations and table given in the abbex of the Ordinance 353-A/2013 were used. Thus, the sum of the CO_2 fluxes of the 5 researchers in the office room was equal to 183600 $mg \cdot h^{-1}$.

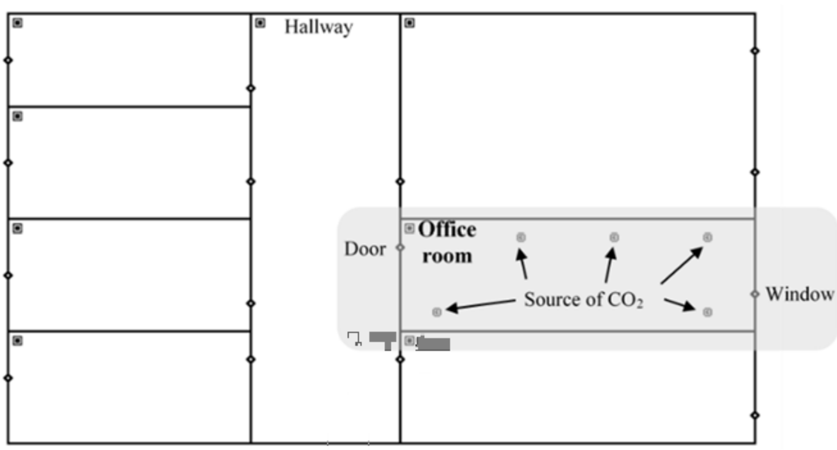

Figure 3: Section of the second-floor layout of the main building of the Department of Environment and Planning. The grey region highlights the office room selected for this case study.

2.3.2 Estimation of the exterior air inflow rate as recommended by the Portuguese Decree

The Portuguese Ordinandes nº 353-A/2013 regarding ventilation for buildings was used to estimate the exterior air inflow rate needed to keep the CO_2 concentrations below the legal limit. According to this decree, there are two equivalent methods to calculate the minimum exterior air inflow rate required for a building: the analytical and the prescriptive.

The analytical method implies a more complex calculation as it is based on the hourly evolution of the predicted CO_2 concentration rate for each specific space inside the building, accounting for the occupancy profile, ventilation profile and the physical characteristics of the occupants. The hourly calculation is usually not feasible due to the lack of the data required for the calculation, which should be provided by contractors or project managers. As this is ta common reality in most projects, the decree provides an alternative, stating that, in such cases, the calculation should be made for the circumstance when a permanent regime is achieved. In this circumstance, the required exterior air inflow (Q_{an}) is calculated through eqn (1):

$$Q_{an} = \frac{G}{C_{lp} - C_{ext}} \quad [m^3/h], \tag{1}$$

where C_{lp} is the limit value for indoor CO_2 concentration defined by the Portuguese legislation (2250 mg.m^{-3}), C_{ext} is the average typical CO_2 concentration value of the outdoor air found in the area where the building is located (702 mg.m^{-3} for every location, according to the cited Portuguese decree) and G is the CO_2 generation rate calculated using the eqn (2)

$$G_{CO_2} = (17000 \cdot A_{Du} \cdot M) \cdot N \quad [mg/h]. \tag{2}$$

A_{Du} represents the DuBois body surface area and M is the metabolic rate of the N occupants inside the room. The DuBois area may be calculated through a mathematical expression that relates it to typical height and body mass. Also, an approximation can be applied using the values presented in Table 2, which are provided by the decree.

Table 2: DuBois area (m^2) per age of the occupants.

Age of the occupants	A_{Du} (m^2)
3 years old	0.65
Up to 6 years old	0.80
Up to 9 years old	1.10
Up to 11 years old	1.30
Up to 14 years old	1.60
Up to 18 years old and adults	1.80

For this particular case study, every occupant is an adult, and thus the considered DuBois area was 1.8 m^2.

The metabolic rate of the occupants is also provided by the decree, according to the type of activity developed inside the space for which the calculations are being performed. A metabolic rate of 1.2 was defined because the five occupants inside the office were in a sedentary mode. Applying these data to eqns (1) and (2), the required exterior air inflow rate calculated through the analytical method is equal to 118.60 m^3.h^{-1}. The decree states that this value must be compared to the minimum exterior air inflow rate required for buildings where the emission of specific pollutants does not happen. A factor of 3 m^3.h^{-1}.m^{-2} must be multiplied by the surface area of the office (20 m^2) resulting on a minimum exterior air inflow rate of 60 $m^3.h^{-1}$. This value is lower than the previously calculated and so, the first one should be considered.

The analytical method could be more precise when an hourly analysis of the required airflow is done. However, as the required data is usually not available, a simpler approach was introduced on the ordinance: the prescriptive method. The prescriptive method assumes the calculation of the air inflow for a permanent regime but without considering the DuBois area, only accounting for the metabolic rate, occupancy and specific pollutants emission. An average metabolic rate of the N people inside a room can be calculated based on eqn (4) and on the data provided in Table 3

$$M_{med} = \frac{\sum_i (N_{Mi} \cdot M_i)}{\sum_i N_{Mi}} \quad [met], \tag{3}$$

$$Q_{an} = M_{med} \cdot Q_{an,1\,met} \cdot N \quad [m^3/h]. \tag{4}$$

Table 3: Metabolic rate (met) and exterior air inflow ($m^3.h^{-1}$ $person^{-1}$) per type of activity.

Type of activity	Metabolic rate – M (met)	Exterior air inflow ($m^3.h^{-1}$ $person^{-1}$)
Sleep	0.8	16
Rest	1.0	20
Sedentary	1.2	24
Moderate	1.75 (1.4 to 2.0)	35
High	2.5 (2.0 to 3.0)	49
Very high	5.0 (3.0 to 9.0)	98

The calculated averaged metabolic rate of the people inside the room is then used on eqn (4) where it is multiplied by the minimum exterior air inflow rate cited by the decree for an average metabolic rate of 1.2 met, which is 24 $m^3.(h.person)^{-1}$. The multiplication by N people inside the room results on the required exterior air inflow rate, which is 120.0 $m^3.h^{-1}$ for the case office room Once again, this value must be compared to the minimum exterior air inflow rate required for buildings where the emission of specific pollutants does not happen, which for the case study is 24 $m^3.h^{-1}$. Yet again, this inflow rate is smaller than the one required by the occupancy and activity performed inside the room and so the last was considered.

The decree does not indicate which of method should be considered, because both are equally correct. The ultimate decision lays on the person in charge of the project. Although the minimum exterior air inflow rates resulting from both methods are very similar, usually the highest one is chosen in order to be certain that all legal parameters are fulfilled in future on-site inspections. Therefore, for the occupancy and activity performed inside the case study office room, an exterior air inflow rate of 120.0 $m^3 \cdot h^{-1}$ was considered.

2.3.3 Estimation of the exterior air inflow rate based on measurements

The air flow parameters measured during the monitoring campaign (see Section 2.2) were used to estimate the exterior air inflow rate. These air flow parameters were measured with a time step of 30 minutes during the afternoon period when the window was open (Table 4).

The window was only opened during a short period (between 2 and 5 p.m) and six measurements were made during this period. The area of the window is of 595 cm^2. The considered air flow velocity rate was the average of all data measured: 0.49 $m \cdot s^{-1}$. The measured based exterior air inflow rate was 105.8 $m^3 \cdot h^{-1}$.

Table 4: Measured air flow parameters by the Airflow Instrument Velocity Meter (Fig. 2(b)).

Time	Velocity ($m \cdot s^{-1}$)	Temp (°C)	RH (%)
14:30	0.44	19.4	61.1
15:00	0.34	20.2	53.0
15:30	0.38	20.0	50.5
16:00	0.50	21.0	52.5
16:30	0.61	19.3	54.3
17:00	0.69	20.0	55.0
Average	0.49	20.0	54.4

3 RESULTS AND DISCUSSION

In this section, the results and discussion are presented. It is divided into three sub-sections: the first section shows the monitoring results, the second section presents the modelling results for different scenarios with and without the window open, and the last section shows the comparison between monitoring data and modelling results. All results were focused on CO_2 concentrations.

3.1 Indoor air quality measurement data

The monitoring campaign results were focused on the CO_2 concentration levels registered (Fig. 4). The influence of the window position on CO_2 values is visible as well as the behaviour of the occupants during the studied period.

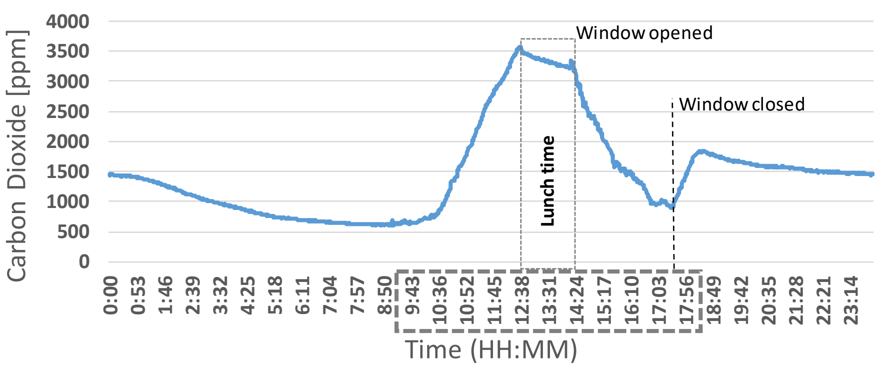

Figure 4: CO_2 concentrations (ppm) measured during the study period (19th March 2019).

Fig. 4 represents the typical CO_2 concentration profile observed during one working day. It is clear the influence of the occupancy of the office room and the window position. During the morning period, the increase of the CO_2 concentration values is evident. The highest CO_2 value of 3,500 ppm was observed at 00:30 p.m., because the window was permanently closed and almost of the occupants stayed steadily inside the office room. Also during lunchtime the window was closed, but people left the room for lunch and the CO_2 concentrations decreased about 350 ppm. After lunch, the window was opened between 2:15 p.m. and 5:00 p.m. to decrease the CO_2 concentrations and improve the IAQ. During this period, the CO_2 concentrations decreased to 900 ppm, which is below the protection threshold value

(1,250 ppm). After 5:00 p.m. and during the night time the window was closed again. At 6:00 p.m. the workday ended and the office room was empty. An increase of CO_2 concentrations was observed between 5:00 p.m. to 6:00 p.m. During the night period, without CO_2 indoor sources the concentrations slowly decayed. In conclusion, to improve the IAQ the position of the window is of great importance.

3.2 Indoor air quality modelling results

In this section, the modelling results are presented and assessed. Section 3.2.1 describes the modelling results for the morning period with the window closed, and Section 3.2.2 presents the modelling results for the afternoon period with the window opened and with different exterior air inflow rates.

3.2.1 Window closed

The results from the modelling simulation with the window closed are shown in Fig. 5. The simulation started with 860 ppm as initial CO_2 concentration. This value was selected tanking into account the results of the measurement campaign.

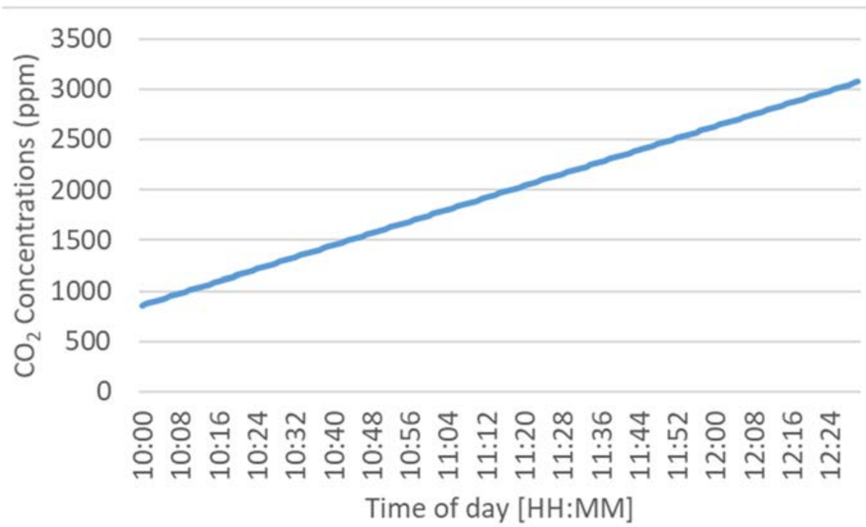

Figure 5: Modelling results of CO_2 concentrations (ppm) for the morning period with the window closed.

Fig. 5 shows a strong increase of the CO_2 concentrations that could be related to the closed window and the researchers inside the office room. This situation was also observed during the monitoring campaign (Fig. 4).

3.2.2 Window open with measured based and recommended exterior air inflow rate

Fig. 6 shows the modelling results for the different exterior air inflow rates in terms of CO_2 concentrations. The procedure to estimate the exterior air inflow rates was explained in the methodology section. The value based on measurements was 105.8 $m^3 \cdot h^{-1}$ and the value estimated based on the legislation requirements is 120.0 $m^3 \cdot h^{-1}$ (. The simulation started with 3,500 ppm as initial CO_2 concentration (value estimated based on the measurements).

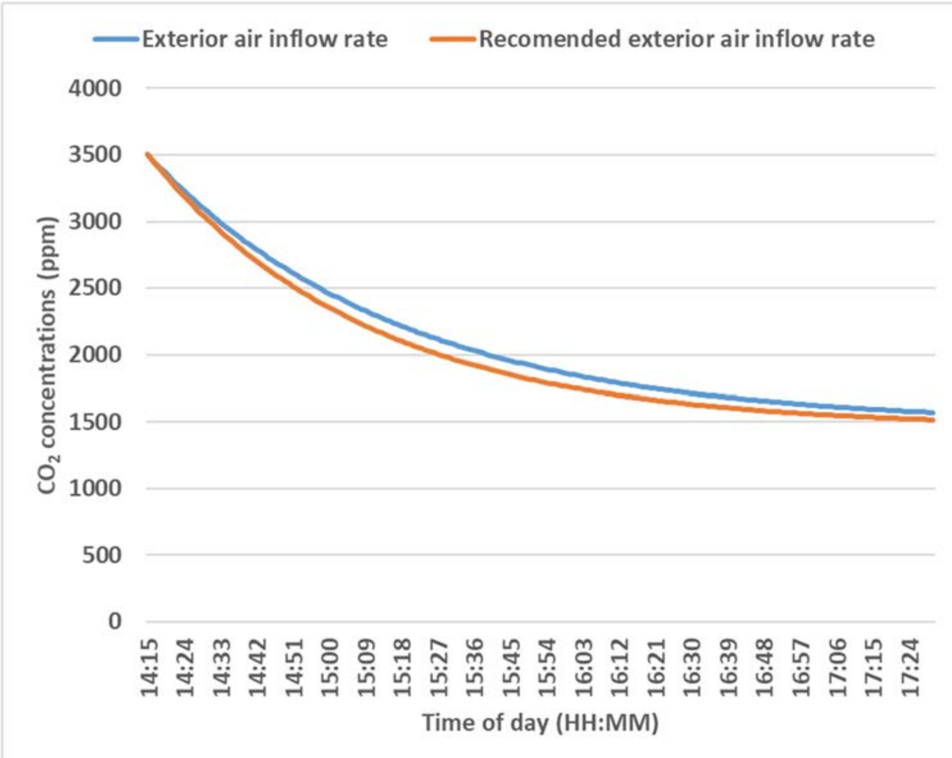

Figure 6: Modelling results of CO_2 concentrations for the afternoon period with the window open (using different exterior air inflow rates).

Fig. 6 shows a decreasing CO_2 concentration during the afternoon period, similar to the monitoring data presented in Section 3.1. The reason for that is the fact that the window was opened during this period. When comparing both air inflow rates the modelling results did not show considerable differences. The minimum CO_2 concentrations were near 1,500 ppm. That value is above the protection threshold value present on the legislation (1,250 ppm), which means that the ventilation rate should have been increased, by a natural or mechanical way. Another alternative could have been to open the window earlier.

3.3 Comparison between modelling and monitoring CO_2 concentrations

In this section, the comparison between modelling results and monitoring data in terms of CO_2 concentrations is presented. The influence of two different window positions, closed and opened, on the CO_2 concentrations was also assessed. During the study period, the door was only open to allow users to get in and out of the office room. Fig. 7 shows this comparison.

Fig. 7 shows a good correlation ($R = 0.91$) between modelling and measured data, for both window cases, indicating that the model has the capability to reproduce the hourly behaviour of the measured data. Despite this good correlation, the model sub estimated the CO_2 concentration at the morning period and overestimated the CO_2 concentration in the afternoon. The differences between modelling results and monitoring data are explained by the location of the equipment installed inside the office room.

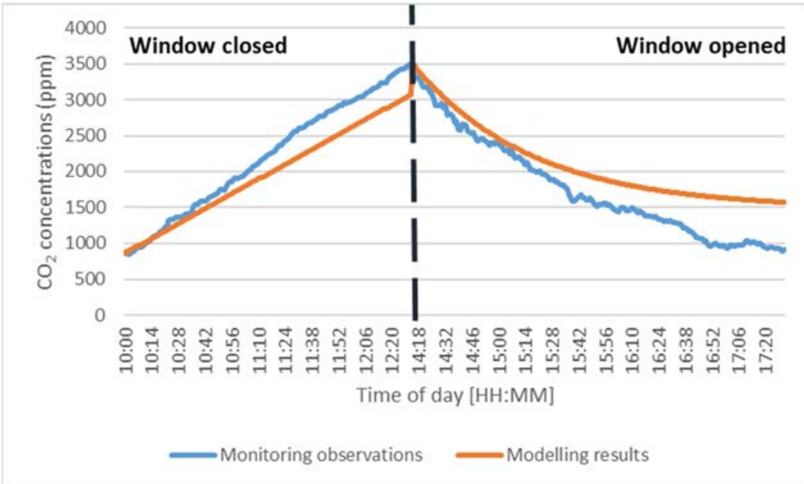

Figure 7: Modelling and monitoring CO_2 concentrations obtained with the window closed and opened.

4 CONCLUSIONS

In recent years, the IAQ has become an important issue and extensive research was carried out by the scientific community. IAQ is affected by many factors including the type of indoor pollution sources, ventilation conditions, indoor activities as well as outdoor sources.

The objective of this work was to evaluate the IAQ during a typical working day in an office room of the Department of Environment and Planning of the University of Aveiro in the Aveiro town (Portugal), using a modelling approach (with the CONTAM model) and monitoring campaign data to compare both results.

The results show that the modelled and measured CO_2 concentrations are in good agreement (correlation value of 0.91). Regarding the different conditions analysed, the one that promoted a better IAQ was the one in which the door was only open to allow users to get in and out of the office room, complemented with an open window. The results clearly showed the importance of promoting a continuous air ventilation of the office to ensure a good IAQ and to protect the health of the office room occupants.

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