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The effect of airtightness required in building energy conservation regulations on indoor and outdoor originated pollutants

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ABSTRACT

The contradiction of indoor air quality (IAQ) and energy conservation by isolating the indoor environment from the outdoor through airtightness is one of the challenges of the building sector.

The key issue is, what are the optimum airtightness limits that can ensure IAQ in naturally ventilated buildings, taking into account the paradoxical effect of house leakages on the infiltration of outdoor pollutants and accumulation of indoor-generated pollutants?

For this purpose, the effect of different levels of airtightness required in energy-compliant, low-energy, and very low-energy buildings on the concentration of two pollutants with outdoor and indoor origin, PM2.5 and formaldehyde, respectively, were studied.

This study used a multizone model, CONTAM(W), which was validated using measured data to study the distribution of selected pollutants in a typical relatively old dwelling, to investigate the situation in Iran. Subsequently, we conducted simulations based on different combinations of scenarios for airtightness, user behavior, source strength, and meteorological parameters.

The results showed that increasing the airtightness from the baseline scenario (ACH50 = 11.11/h) to 3, 1.5, and 0.75 in closed window conditions reduced the PM2.5 by 15%, 38%, and 58%, respectively, and elevated formaldehyde by 23%, 77%, and 169%, correspondingly.

Under normal outdoor PM2.5 pollution, indoor formaldehyde levels exceeded the permissible limit only in closed window conditions, and IAQ remained acceptable in other scenarios.

However, there is no indication that IAQ can be ensured by any degree of airtightness under severe outdoor air pollution, demanding specific solutions, such as those proposed in this work.

1. Introduction

Since the energy crisis in 1970, to save cooling and heating energy, air exchange with the outside environment has been reduced. Although this method significantly saves energy, however, in complex systems such as buildings, policies focused on limited goals (in this case, reducing energy consumption in line with economic benefits and climate change mitigation policies), without considering the complexities and dynamic interrelationships between various aspects, lead to a wide range of unintended consequences [1].

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One of the challenges facing the building sector is the simultaneous provision of IAQ and energy consumption reduction through envelope airtightness, which is a key factor in air infiltration, costs related to cooling and heating, and concentration of pollutants with outdoor or indoor origin [2].

According to the fact that people spend more than 90% of their time indoors and are more exposed to indoor pollutants [3–8], investigating the unintended outcomes of energy refurbishment on IAQ is essential.

There have been various and often conflicting findings from studies on the effects of air exchange rates (ACH) on indoor air quality [9].

So, increasing the ACH with the outside environment or isolating the building from the outdoors does not necessarily guarantee IAQ and residents' health, according to the various sources of indoor and outdoor pollutants.

Taking into account the paradoxical effects of airtightness on outdoor pollutant infiltration and indoor pollutants accumulation, how is it possible to ensure an optimum airtightness limit which will be able to meet IAQ standards in naturally ventilated buildings? What are the effects of other influencing factors, including occupants' behavior, meteorological parameters, and source strength?

Several studies have examined the modifying effect of the envelope and unintended consequences of energy efficiency measures, in particular airtightness, on PM2.5 indoor exposure [10–18].

Some have researched the impact of physical characteristics of the building, including air leakages on the levels of indoor originated pollutants and humidity [19–21].

However, none have focused on the paradoxical effect of building air leakage on the infiltration of outdoor originated and exfiltration of indoor-generated contaminants.

Also, there are no domestic studies on the relationship between indoor exposure to contaminants with the indoor or outdoor origin and leakage characteristics of the existing buildings in Iran due to the lack of airtightness measuring instruments.

In this case, study we aim to address this gap by performing measurements and simulations for a typical relatively old building under natural ventilation. Moreover, the interaction of airtightness and residents' behavior in manipulating leakages on the concentration of the selected pollutants is investigated.

The experimental data for parameters such as particle penetration and deposition factors, as well as the effective leakage area of openings, have been used in previous IAQ simulation studies [10]. These parameters have been directly estimated, quantified, and integrated into the model as part of this research. Particle concentrations, temperature, and relative humidity of the outdoor environment near the building envelope were also monitored, providing more accurate values as input to the model compared to the nearest air quality control and weather station data used in other investigations [22,23].

We have adopted PM2.5 and formaldehyde for evaluating the IAQ. In recent years, due to the increasing urbanization and traffic in Tehran [24], the capital of Iran, the concentration of PM2.5, the determinant pollutant of Tehran, has been elevating, which reaches its peak in seasonal inversion conditions. The Air Pollution Emergency Committee advises people to stay home in such a situation. On the other hand, more than 60% of the buildings in Tehran are more than 15 years old, and due to non-compliance with the national energy code and airtightness requirements, the occupants are more susceptible to being exposed to higher levels of PM2.5 [25]. Therefore, in the present work, PM2.5 is adopted as a pollutant of the outside origin in the absence of internal sources.

Formaldehyde (HCHO), among indoor pollutants, is one of the biggest concerns due to its high inherent cancer risk, especially in residential environments [26–28], and abundance in closed spaces.

Gilbert et al., 2008, found that air leakages effectively reduce the indoor formaldehyde concentration and are the primary solution for indoor formaldehyde removal [29]. It seems that formaldehyde pollution from indoor sources continues throughout the lifetime of residences [30]. Considering that the source of formaldehyde (mainly wooden furniture or cabinets) is present in residential buildings regardless of the presence and activity of inhabitants, the age and characteristics of the buildings, and on the other hand, its outdoor concentration is not significant [31], it could be considered as a specific pollutant of the indoor environment, as adopted in this work.

A better understanding of the factors influencing indoor exposure to pollutants requires extensive use of expensive measuring equipment and complex methods to consider all factors and their combination. When the influence of possible scenarios in the future (meteorological parameters, ventilation, outdoor air pollution, and airtightness) is concerned, using the modeling and introducing data from field studies to the model is a suitable option for research [32,33].

Additionally, due to the buildings' design, materials, and implementation techniques, which are different in each country and each climate zone, and local differences in indoor and outdoor pollutants source strength, the necessity of conducting regional and local studies is revealed.

Consequently, in order to investigate the situation in Iran, a multizone model CONTAM (W) was used in this study and has been validated by using measured data for investigating the distribution of selected pollutants in typical old dwellings.

In Iran, the construction sector is responsible for more than 35% of energy consumption and the production of more than 22% of greenhouse gases [34].

Measures related to airtightness and energy loss reduction in buildings have received more attention. For example, in the new draft of Issue 19 of the National Energy Conservation Code [35], three energy categories include "buildings conforming to Issue 19 or energy compliant (EC)" as a mandatory category, "low-energy buildings (EC+)" and "very Low Energy Buildings (EC++)" are currently defined as optional categories. These criteria limit the air infiltration in typical buildings to less than 3/hr (9 $\frac{m^3}{hr.m^2}$) at a pressure difference of 50 Pa. These values are reduced to half in low-energy buildings (1.5/hr @ 50 Pa) and to a quarter (0.75/hr @ 50 Pa) in very low-energy buildings.

We have performed simulations based on different combinations of scenarios for air tightness (as indicated in Iran's energy code for different levels of energy efficiency), occupant opening-window behavior, source emission variations, and meteorological factors.

First, real-time measurements revealed hourly changes in indoor and outdoor concentrations of PM2.5 as well as formaldehyde ACHs.

Subsequently, based on the time series of the concentration and ACH data, the parameters of PM2.5 penetration and deposition coefficient were estimated as input for precise simulation. Accounting for the airtightness of the building is a challenge in simulating the airflow. In order to address this problem, leakage parameters have been derived from a variety of airtightness tests for different building zones.

Finally, the modeling was validated through a statistical analysis comparing monitored and modeled transient levels followed by simulations for multiple scenarios involving differing airtightness levels, opening window status as well as source strength.

The results obtained by providing insight into the consequences of energy efficiency measures will lead to policies and strategies to minimize negative impacts and maximize the co-benefits of energy saving and health.

2. Materials and methods

2.1. Site description

The studied site, a residential apartment in Tehran, is typical of apartments over 15 years old (more than 60% of buildings) that do not comply with the new airtightness regulations. We compared the concentration of selected pollutants in the current conditions and after the airtightness enhancement.

The apartment is located in a building block, which includes five residential floors and ten units, in geographical location (35°43′37.5″N and 51°21′04.3″E). Fig. 1 shows the unit's plan, location, and position of measurement devices. The apartment is located on the third floor.

In 2006, Gemenetzis et al. indicated that although a partial reduction in outdoor PM2.5 was observed with increasing height, it could be regarded as insignificant up to the 5th floor [36].

Considering that the simulation will be done for bedroom No.1 to obtain the data required for the model verification, measurements were carried out with the door closed (similar to the resting period at night). In order to consider the influence of the adjacent spaces and enter their window leakage data into the model, we also conducted leakage tests for bedroom No.2 and the entire apartment.

2.2. Study design

2.2.1. Measurements

In this research, real-time indoor and outdoor PM2.5 and indoor formaldehyde were recorded with a time interval of 1 min. No

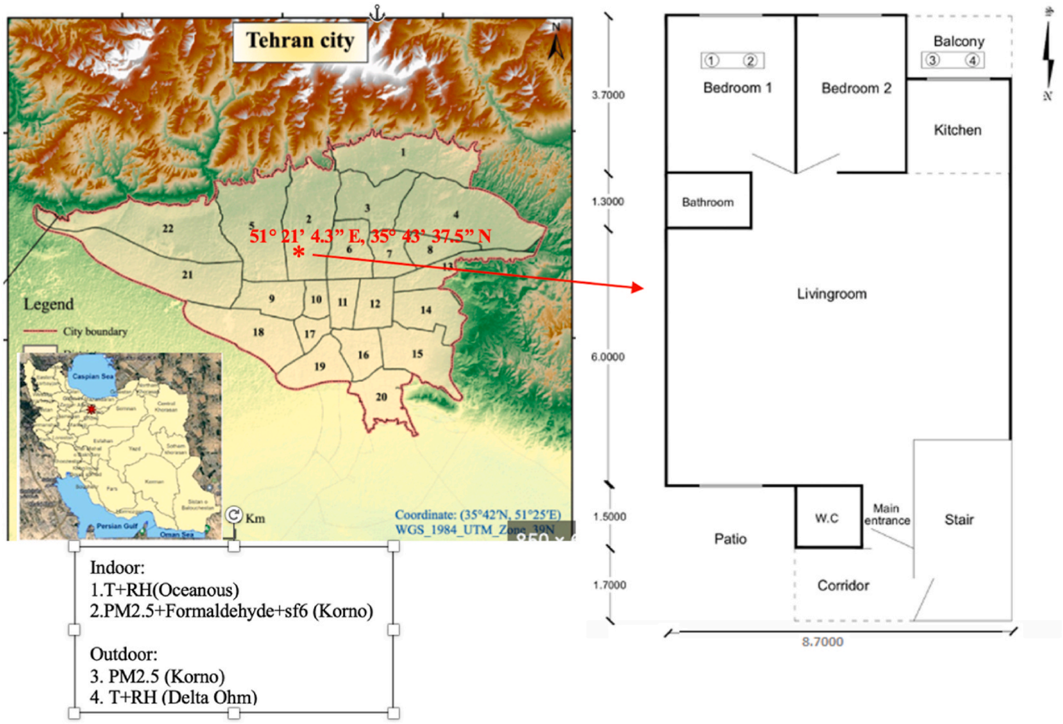

Fig. 1. Geographic location map and site plan.

indoor particle generation activity occurred during the experiment.

Measurements were carried out in bedroom No 1 during the winter period from 20 February to 28 February, about 202 h which will be used for verification of the model.

In addition, we continuously monitored the ACH, utilizing the tracer gas dilution method during the test. Two particle and gas detectors (KORNO- GT1000 series) performed measurements of pollutants through scattering photometric technology for PM2.5 and by electrochemical sensor for formaldehyde. A reputable agency calibrated the devices before testing. The indoor devices were placed 1.2 m from the floor and at a central point at least 1.5 m away from doors and walls. The outdoor instruments were placed in an encasement (to protect them from direct sunlight and rain) on the balcony of the south side of the building. We calibrated indoor and outdoor particle detectors at different times by co-locating and comparing them with a reference station in Tehran. We found some differences (an average of 10%) in the readings and adjusted the data accordingly.

Temperature and relative humidity parameters were also measured as input to the model, employing an Oceanus instrument (OC-1000) outfitted with a data logger. In addition, outdoor data was checked by the Delta Ohm device (HD206-2), which was calibrated with the Testo 177H1 (BHRC Energy laboratory reference device). The data was then modified to: −0.4 °C for temperature and −8% relative humidity.

We recorded ACH using the ISO12569 standard SF6 tracer gas dilution test. SF6 was periodically injected at intervals of 3–6 h up to an approximate concentration of 300 ppm. We recorded decay concentrations at 1-min intervals using KORNO GT-1000 electrochemical sensor with an accuracy of 0.1 ppm. Using the logarithmic function of decayed concentrations Eq. (1), we have:

$$\ln C_i(t) = \ln C_0 - \lambda * (t_i) \tag{1}$$

That C_0 = concentration of the tracer gas at the injection time ($t = 0$), and λ = air change rate (hr^{-1}) or the gradient of the linear regression in Eq. (1). In addition, the effective leakage area (ELA) of the building was measured by the blower door test (Retrotec 5000 with DM32, USA) based on the EN13829 test method, and the discrepancy in air volume measurement resulted in an error of −5%.

In order to ensure that accurate leakage data is entered into the model, the tests were carried out for the bedrooms (installation of the blower door at the entrance door of the room) and the entire apartment (installation of the blower door at the entrance of the apartment), separately.

The basis of the device's work is to establish a power relationship between the airflow produced by the fan and the pressure difference of the inside and outside environment, Eq. (2). Coefficients C and n are obtained in different pressure differences (usually 3-point or 5-point test) [17].

$$Q = C\ \Delta P^n \tag{2}$$

Which, Q is the airflow rate from the envelope (m^3/h), ΔP is the pressure difference between inside and outside (pa), C is the flow coefficient in terms of ($\frac{m^3}{s.\ pa^n}$) and n is the flow power (dimensionless). The flow coefficient, C, is directly related to the total leakage area of the building. The value of n is between 0.5 and 1.0.

The test site's effective leakage area (ELA) is displayed in terms of m^2 and represents the area with the same flow in a determined pressure difference and is calculated from Eq. (3) [17,37], which subsequently will be used as input data for the model.

$$\mathrm{ELA} = C\ \Delta P_{\mathrm{ref}}^{n-0.5} \sqrt{\frac{\rho}{2}} \tag{3}$$

That ΔP_{ref} is the base pressure difference (4 Pa), and ρ is the air density (assuming 1.2 kg/m^3).

Therefore, for different airtightness levels and ACH50 recommended in Iran's energy regulations, by measuring the flow power for the entire apartment by the blower door, the leakage area of the entire apartment can be calculated through Eq. (3). Then, based on the perimeter of each window, this leakage can be distributed between the windows. Considering that we have also measured the leakage area of the bedrooms separately, these data can be used to verify the results of the leakage calculations.

2.3. Analysis

2.3.1. Particle penetration factor(P) and deposition rate(K)

In order to enter detailed information related to the penetration and deposition of particles in the model, these factors are calculated as follows:

Considering the lack of indoor sources, the main determining factors of indoor PM2.5 are penetration of particles from the outdoor environment, deposition rate in the indoor environment, and ACH. Assuming that the indoor air is completely mixed in a mass conservation model, the variations of indoor PM2.5 is expressed as Eq. (4):

$$\frac{dC_{in}}{dt} = P.ACH.C_{out} - (ACH + k)C_{in} \tag{4}$$

In short time intervals ($\Delta t = 1$min), equation (4) can be written as a differential equation Eq. (5), from the nonlinear solution of which the unknown coefficients P and k are obtained [38].

$$C_{in_{t+1}} = P.ACH.\Delta t\ C_{out_{t+1}} + (1 - (ACH + k)\Delta t)C_{in_t} \tag{5}$$

Where C_{in}, indoor concentration (μg/m^3), C_{out}, outdoor concentration (μg/m^3), and Δt is the time difference (1 min). Whereas the above relationship does not consider any internal source, the effect of the indoor source should be censored if it exists.

We used an Excel optimization algorithm called the solver plugin (Microsoft Excel for Mac version 16.54) to obtain the best estimate of P and K for the measured PM2.5 time series (approximately 12,000-min data) through minimizing the absolute relative error between the measured and modeled concentrations in Eq. (5).

The missing ACH data were replaced with the mean measured values for the adjacent periods.

2.3.2. Correlation analysis

Using Pearson's correlation analysis, the relationship between indoor and outdoor PM2.5 concentration as well as measured and simulated data was done. Pearson analysis is a statistical method to analyze the linear relationship between two variables and confirm their statistical significance. The correlation coefficient, r, changes between −1 and 1 Eq. (6).

$$r = \frac{\sum_{i=1}^{n} \left(X_i - \overline{X}\right) \left(Y_i - \overline{Y}\right)}{(n-1)\, S_x\, S_y} \tag{6}$$

A high correlation is achieved when the r value is close to 1. Therefore, a correlation coefficient higher than 0.7 indicates a strong correlation between two variables [39]. In addition, the Statistical significance of correlation analysis was performed based on the P-value calculated from the *t*-test between two variables. When the P-value is smaller than 0.05, the result is statistically significant.

Where r is the correlation coefficient, $\overline{X}$ and $\overline{Y}$ are the mean of the samples x and y respectively, S_x and S_y are the standard deviation of the samples x and y and n is the number of samples.

2.3.3. Simulation

Considering the scope, objectives, and level of complexity required in this study, CONTAM v3.4 was chosen as the primary tool for the modeling. CONTAM is a freely available multi-zonal air flow and pollutant transport simulation tool that enables the construction of various models with inputs from different data sources. For large buildings, multizone models are computationally fast and can provide precise results [40]. CONTAM can be adjusted to calculate the effect of different sources and sinks on the concentration of pollutants in the indoor environment (Dols & Polidoro, 2020). In the macroscopic view of this model, it is assumed that the air of each zone is well mixed and temperature, pressure, and contaminant concentration are uniform amongst zones.

The airflow calculations in CONTAM are based on the algorithms developed in AIRNET [Walton 1989].

The airflow rate from zone j to zone i, $F_{j,i}$[kg/s], determined through mass balance equations, is a function of the pressure differentiation along the flow path in Eq. (7).

$$F_{i,j} = f\left(P_i - P_j\right) \tag{7}$$

The mass of air, m_i [kg], in zone i is given by the ideal gas law (Eq. (8)), where V_i is the zone volume, T_i is the zone temperature, P_i is the zone air pressure, ρ_i is the zone air density $\frac{kg}{m^3}$ and R is the gas constant for air $\left(287.055\ \frac{J}{kg\ K}\right)$.

$$m_i = \rho_i\, V_i = \frac{P_i\, V_i}{R_i T_i} \tag{8}$$

For a transient solution, the principle of conservation of mass is given in Eq. (9), where F_{ji} is the airflow between zones i and zone j, and t is the time [41].

$$\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\partial \rho_i}{\partial t} = \sum_i F_{ji} + F_i \tag{9}$$

Most infiltration models are based on the power law relationship between the flow and the pressure difference across a crack or opening in the building envelope Eq. (10), where the mass flow rate, F [kg/s], is a simple function of the pressure drop.

$$F = C\ (\Delta P)^n \tag{10}$$

A second variation is related to the orifice equation Eq. (11), where C_d is the discharge coefficient, A is the orifice leakage area, and Q is the volumetric flow rate ($\frac{m^3}{s}$).

$$Q = C_d\, A \sqrt{\frac{2\Delta P}{\rho}} \tag{11}$$

Theoretically, the value of the flow exponent, n, should lie between 0.5 and 1.0. In this study the value of n as well as the apartment leakage area (A), is measured through a blower door test, to confirm the accuracy of input values.

The basis for contaminant dispersal analysis is the application of conservation of mass for all species in a control volume (c.v.). A c.v. is a CONTAM zone. The particle deposition model is represented in Eq. (12).

$$R_\alpha(t) = K_d V_z\, \rho_{air}(t)\, C_\alpha(t) \tag{12}$$

Where $R_\alpha(t)$ is the particle removal rate at time t ($\frac{kg}{s}$), K_d is deposition rate (1/s), $\rho_{air}(t)$ is the density of air in the source zone at time t (kg/m^3), $C_\alpha(t)$ is the concentration of contaminant α at time t (kg/kg), and V_z is the zone volume (m^3). The K_d value will be calculated subsequently.

The formaldehyde is modeled as a constant coefficient model which allows constant contaminant generation and decay rates in Eq. (13), where G is the generation rate ($\frac{kg}{s}$) (e.g: formaldehyde emission from furniture), D is the decay rate ($\frac{kg}{s}$), and C(t) is the concentration of the contaminant at time t (kg/kg).

$$S_t = G - D\,C(t) \tag{13}$$

The input data to this software includes the building diagram (architecture, position of doors, windows, and other air paths such as openings, as well as the location of sources and residents), elements of the fresh air delivery system, sources, sinks, and pollutant filters, which several parameters determine each.

By implementing sensitivity analysis, it is possible to identify the key inputs that affect indoor exposure to pollutants, including particles and formaldehyde, and variables that have a negligible effect and do not require detailed specifications.

Using the Transient weather with variable wind speed and direction enables the user to model more realistic scenarios than what is obtained with constant values. In addition, buoyancy and stack effects are generated using variable indoor and outdoor temperature profiles. Then it is possible to predict the indoor concentration of pollutants dispersed by these air flows.

In addition, the effect of various parameters such as different levels of airtightness, types of ventilation systems, the behavior of residents in manual ventilation of the building, the schedule of the production or elimination of pollutants, as well as the schedule of the presence of residents on the indoor exposure can be simulated by CONTAM.

In order to investigate the effect of different airtightness scenarios on the concentration of PM2.5 and formaldehyde in the indoor environment, first the building floor plan and its physical characteristics were entered in the CONTAM software Fig. 2. Every room was modeled as a separate zone having two openings (a door and a window), living room and kitchen were considered as a single zone and kitchen was connected to the exterior with a balcony door.

Subsequently, to specialize for the selected site, several parameters were properly adjusted in CONTAM(W), and other variables were set accordingly. The flow paths and leakage data were introduced according to the data measured by the blower door test (Table 1). Also, the transient meteorological data, including measured temperature, measured relative humidity, along with wind speed and direction data, which were requested from the National Meteorological Organization, were introduced to the model.

Transient outdoor PM2.5 concentration data based on the measured values and calculated values of penetration and deposition factor of PM2.5 were introduced to the model. We extracted the formaldehyde emission rate of furniture from EPA emission coefficients tables.

(database attached to the software), which is 55 $\frac{\mu g}{hr.m^2}$. The wind pressure profile based on the height and dimensions of the building was extracted from the relevant ASHRAE tables [42] and entered into the program, as shown in Fig. 3.

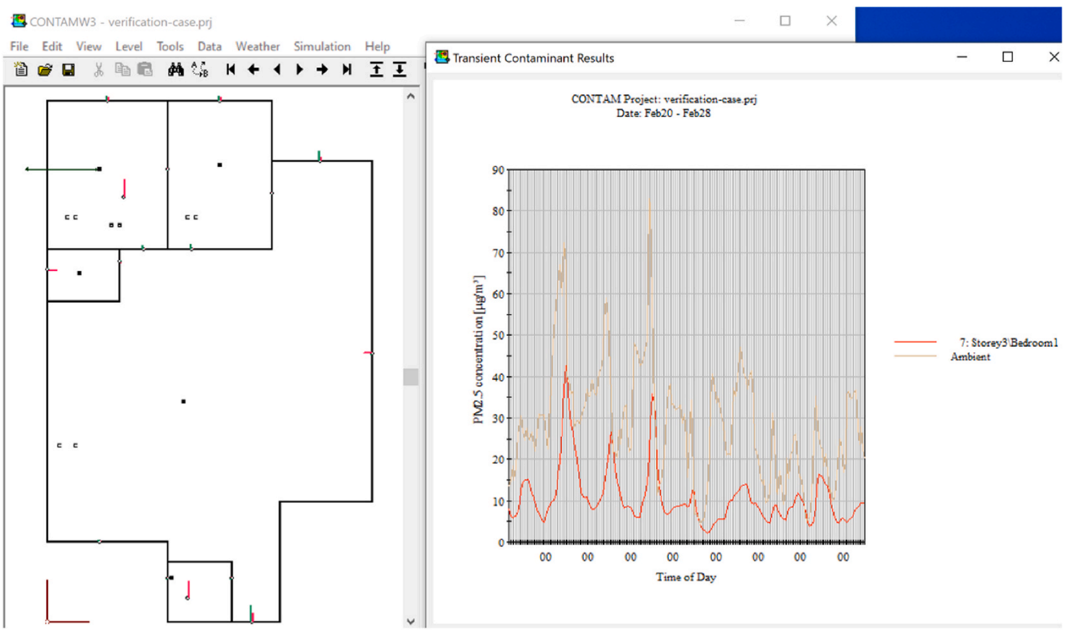

Fig. 2. Software environment in CONTAM and apartment floor plan.

Table 1
Blower door test results regarding leakage characteristics of the measurement site.

Site	C ($\frac{m^3}{hr.\,pa^n}$)	n(−) 95% Confidence level	ACH50 (h^{-1}) Error	ELA[a] (cm2) Error	Envelope ELA (cm2/m2) Error
Bedroom 1	104.1	0.58 (0.5–0.65)	33.81 ± 2.8%	231 ± 10%	26.6 ± 2.8%
Bedroom 2	44.9	0.62 (0.54–0.69)	19.92 ± 3.0%	153.5 ± 3.1%	20.2 ± 3.0%
Whole apartment	95.74	0.87 (0.74–0.98)	11.11 ± 5.6%	565 ± 15%	24.8 ± 3.0%

[a] Effective Leakage area.

3. Results and discussion

3.1. Data analysis

3.1.1. Penetration factor and deposition rate

The indoor PM2.5 concentration estimated by Eq. (5) was compared with the values measured in real-time (with 1-min time intervals) (Fig. 4). The coefficient of determination (R^2) equal to 0.96 indicates a high correlation between the estimated and observed values, which confirms the estimation of K and P.

Previously published papers have emphasized that P for a specific building and K for uninhabited spaces (without indoor particulate sources) under natural ventilation can be considered constant [15,43]. Therefore, we considered P and K constants during the study period.

The best estimates for P and k are 0.9 and 0.3, respectively. Chen and Zhao, 2011 reviewed previously published studies and found values between 0.2 and 1 for the penetration factor of PM2.5 in naturally ventilated buildings, which is consistent with our findings [18].

3.1.2. Air exchange rate and indoor and outdoor concentrations

The air exchange rate for the bedroom in closed-door conditions for the measurement period (20–28 February) varied from 0.25 to 0.96 (0.52 ± 0.18). For the whole apartment, ACH was (0.92 ± 0.21). In contrast to preceding research, the mean air changes per hour (ACH) within the examined apartment were found to be significantly higher than the threshold advocated by the ASHRAE standard., i.e., 0.35/hour [42]. The results of Hou et al.'s study on China's urban bedrooms [44] and another study on an experimental house [45] showed the mean values of ACH lower than the ASHRAE recommended level. This high ACH can be attributed to the elevated levels of building leakage present within Iran. This phenomenon is due to energy cheapness within the country, resulting inadequate compliance with the stipulated national building regulations related to energy efficiency and airtightness.

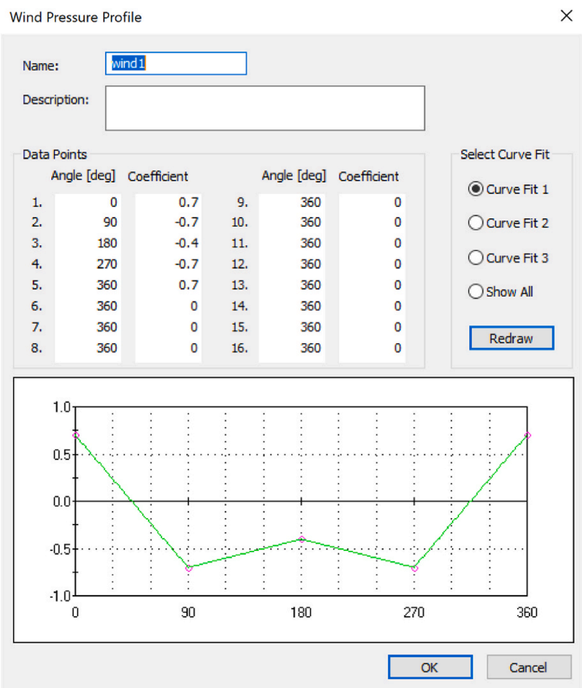

Fig. 3. Wind pressure profile introduced to the CONTAM model.

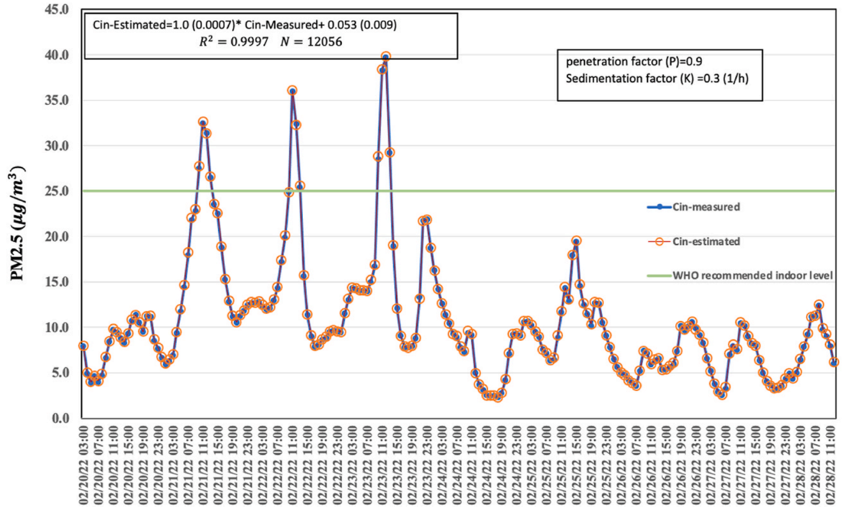

Fig. 4. Estimated and measured values of indoor PM2.5 concentration and their regression relationship. *(The numbers in parentheses are the standard error of the model coefficients).

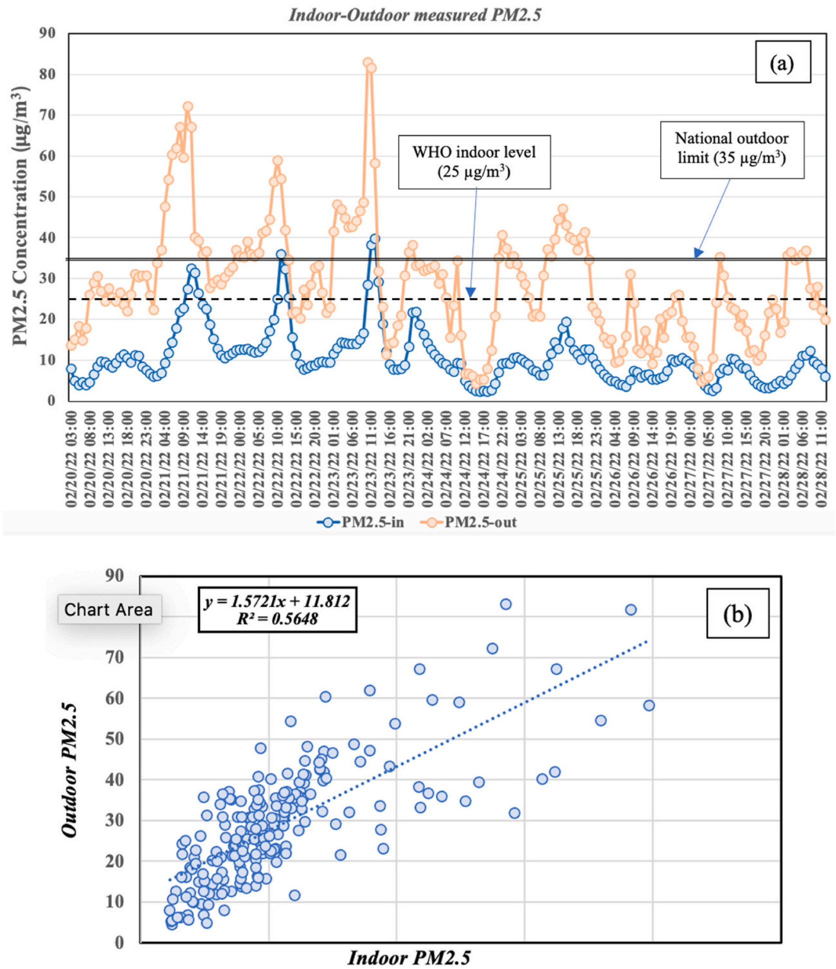

Fig. 5. Indoor and outdoor PM2.5 mass concentration (a) and correlation (b) for the measurement period (February 20 to 28).

The ACH50 for the whole apartment was 11.11 h^{-1} (Table 1), which is far from the mandatory EC category of 3 h^{-1}. This number represents the leakage rate of old buildings in Tehran, which is higher than the US study (7 h^{-1}) for homes built since 2000 [46], South Korea 8 h^{-1} [47], and cold areas of China (between 3.8 and 5.2 h^{-1}) for public buildings [2]. The leakage test results are summarized in Table 1.

In the conducted experiments, the trend of indoor PM2.5 was similar to the outdoor trend, indicating the significant effect of outdoor particles on indoor particle levels in the absence of indoor sources (Fig. 5a), consistent with other published research [48–50]. The results show a relatively high correlation between indoor and outdoor PM2.5 (P-Value≅ 0, $R^2 = 0.6$) (Fig. 5b).

From February 20 to 28, the average formaldehyde concentration was 66 (66 ± 45) $\mu g/m^3$ within WHO limits, conforming with previously published investigations. Menteşe & Güllü (2006) conducted a study for 24 buildings in Turkey, and a mean of 67.1 $\mu g/ m^3$, was obtained, which is close to the value observed in this study [51].

The World Health Organization recommends a guideline value of 100 μg/m3 for 30 min of exposure in non-occupational settings to protect sensory irritations against formaldehyde [52].

Dehghani et al. (2020) determined the formaldehyde levels in newly decorated houses in Iran, showing indoor levels in the range of 21–360 $\mu g/m^3$ (mean of 149.3 $\mu g/m^3$), much higher than the current study results, which can be attributed to the strong sources in new homes.

The box chart is presented in Fig. 6. These data will be used to validate the modeling results.

3.2. Simulation results

In order to verify the model, the simulated trends of PM2.5 and formaldehyde in the indoor environment were compared with the recorded ones (Figs. 7 and 8).

The results of correlation analysis show a high correlation between simulated and measured concentrations, especially for PM2.5 ($R^2 = 0.83$).

The average predicted and measured concentrations differ by less than 5%, which indicates the correctness of the entered data for the flow paths and their leakage rates. In addition, the average air exchange rate calculated by the model was compared with the corresponding measured value, which shows that the difference is less than 10%, confirming the model's accuracy.

In the next step, in order to determine the sensitivity of the model, the meteorological parameters, outdoor trend of PM2.5, formaldehyde emission rate, and the PM2.5 deposition rate were altered by ±20% compared to the baseline scenario, and the variations of indoor pollutants were checked. The relevant results are shown in Table 2. Regarding indoor PM2.5, the highest sensitivity of the model is to the deposition rate and the outdoor concentration of PM2.5. The indoor formaldehyde levels are most sensitive to its emission rate. Among the meteorological parameters, wind speed and then relative humidity between 4.5 and 10% affected the indoor concentration of selected pollutants.

After verification of the model, different airtightness levels, along with Various user behavior scenarios, including window fully open, window fully closed, window open at 20% during the day and night, and window open at 20% for 8 h (from 8:00 a.m. to 4:00 p.m.) and otherwise closed, were applied in different combinations of scenarios. Since the concentration levels of the outdoor environment were not at a critical level during the measurement period, it is expected that indoor PM2.5 levels will be lower than the recommended limit of the WHO (25 μg/mˆ3) in all scenarios. To examine the results of critical atmospheric PM2.5 pollution conditions in seasonal inversion, simulations have therefore been carried out for outdoor PM2.5 scenarios that are 2 or 3 times higher than the baseline scenario. These 16 scenarios for actual outdoor air pollution conditions are briefly presented in Table 3. In order to investigate the exposure of different people based on the amount and location of their presence inside and outside the building, two occupants were introduced to the model. The timing and place of their presence are listed in Table 4.

In addition, the CO2 generation rate was assumed equal to 0.0042 l/s which is the average ventilation rate for an average-sized adult while doing passive activities and being a non-smoker [53]. The Outdoor CO2 was considered as 400 ppm, in the model.

So, the carbon dioxide accumulation was checked in different combined scenarios and compared with the permissible level of 1000

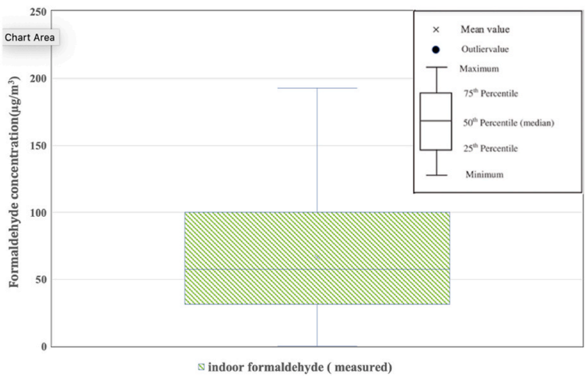

Fig. 6. Indoor measured formaldehyde box plot.

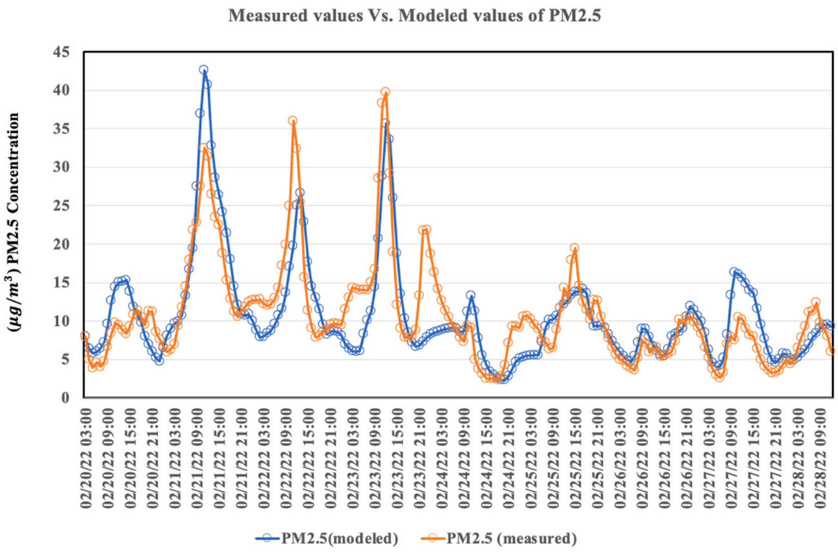

Fig. 7. Comparison of PM2.5 values simulated by CONTAM with measured data.

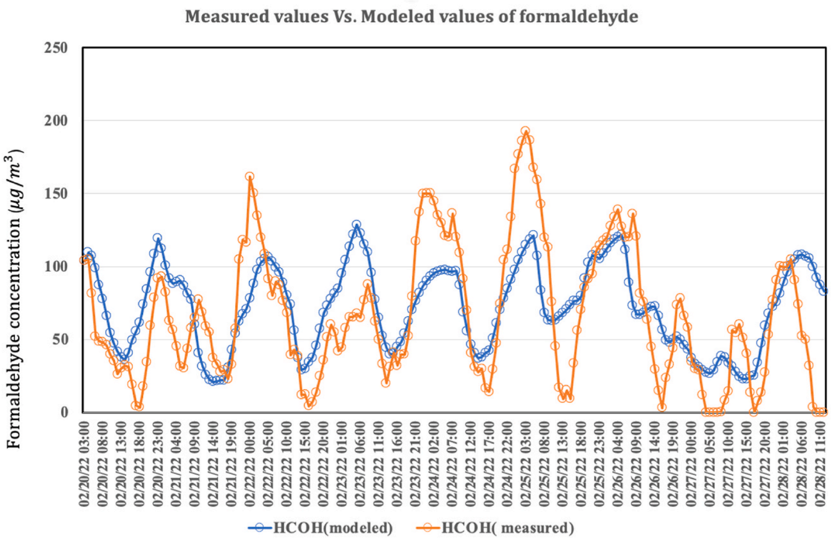

Fig. 8. Comparison of Formaldehyde values simulated by CONTAM with measured data.

Table 2
The results of sensitivity analysis for input variables.

Variable	Percentage changes compared to the baseline scenario	Average changes in formaldehyde	Average changes in indoor PM2.5
Temperature	+20%	−3%	+4.3%
	−20%	+3%	−4.5%
Wind speed	+20%	−9%	+8%
	−20%	+10%	−8%
The outdoor concentration of PM2.5	+20%	0%	+19.8%
	−20%	0%	−19.8%
Formaldehyde emission rate	+20%	+20%	0%
	−20%	−20%	0%
PM2.5 deposition rate	+20%	0%	−11.7%
	−20%	0%	+14.7%
Relative humidity	+20%	+4.5%	−5.1%
	−20%	−4.6%	+5.0%

Table 3
The scenarios for simulation.

Combined scenario	airtightness	Window opening status	Window opening schedule
1 (Baseline Scenario)	11.1/hr @50pa[a]	Completely closed	all the time
2	11.1/hr @50pa	open window	all the time
3	11.1/hr @50pa	Aperture by 20%	all the time
4	11.1/hr @50pa	Aperture by 20%	Opening for 8 h (from 8 to 16)
5	3/hr @50pa	Completely closed	all the time
6	3/hr @50pa	open window	all the time
7	3/hr @50pa	Aperture by 20%	all the time
8	3/hr @50pa	Aperture by 20%	Opening for 8 h (from 8 to 16)
9	1.5/hr @50pa	Completely closed	all the time
10	1.5/hr @50pa	open window	all the time
11	1.5/hr @50pa	Aperture by 20%	all the time
12	1.5/hr @50pa	Aperture by 20%	Opening for 8 h (from 8 to 16)
13	0.75/hr @50pa	Completely closed	all the time
14	0.75/hr @50pa	open window	all the time
15	0.75/hr @50pa	Aperture by 20%	all the time
16	0.75/hr @50pa	Aperture by 20%	Opening for 8 h (from 8 to 16)

[a] The airtightness of the baseline scenario is 11.1/hr at a pressure difference of 50 Pa, measured by the blower door test.

Table 4
Time Schedule and location of residents.

Residents	Time	Location
resident No.1 (employee)	0 to 7	bedroom 1
	7 to 16	outdoor
	16 to 24	living room
resident No.2 (housewife)	0 to 8	bedroom1
	8 to 24	Living room and kitchen

ppm.

The simulation results of combined scenarios and the average concentrations of selected pollutants plus CO2 in the indoor environment are reported in Table 5.

Also, the results of Table 5 are presented as percentage changes compared to the baseline scenario in Table 6.

According to Table 6, the highest increase of particles compared to the baseline scenario occurs in scenario 2, where the windows are open all the time, and the lowest occurs in scenario#13, where the only path of air penetration is through the leaks in the highest level of airtightness (0.75/hr@ 50pa). The highest accumulation of formaldehyde also occurs in the same scenario 13.

Increasing the airtightness from the baseline scenario (ACH50 = 11.11/h) to 3, 1.5, and 0.75 per hour in closed window conditions reduces PM2.5 by 15%, 38%, and 58%, respectively. It also causes an increase in formaldehyde by 23%, 77%, and 169%, respectively, compared to the baseline scenario.

The occupants' behavior in opening the windows influences the indoor pollutants in the opposite direction of airtightness. Variations of openings status from closed to open in different scenarios increase the concentration of PM2.5 from about 8 to 23% and reduce formaldehyde from about 4.5 to 25%.

In the existing conditions of building airtightness and outdoor PM2.5 levels, senario#1 to #4, PM2.5 and formaldehyde remain acceptable. However, in scenarios 1 and 4 (closed window and 20% aperture in 8 h), the CO2 is higher than the permissible limit.

Under critical outdoor PM2.5 conditions in all combined scenarios, at least one pollutant exceeds the international recommended limits, which requires alternative solutions (Fig. 9).

Table 7 indicates residents 1 (employee) and 2 (housewife) exposure to selected pollutants under existing PM2.5 conditions outdoors. Generally, in different scenarios, the exposure of resident No. 2 to formaldehyde and CO2 and the exposure of resident No. 1 to PM2.5 is more than another inhabitant.

Increasing the time spent indoors in all scenarios causes an average 28% increase in formaldehyde exposure and a 25% decrease in PM2.5 exposure in indoor environments.

The results indicated that the health burden from the investigated air pollutants was mainly dependent on (a) the airtightness and user behavior in manipulating the building air leakage and (b) the duration of stay indoors or outdoors. These results are consistent with the CONTAM(W)-doses model by Temenos & Nikolopoulos (2015), which confirmed the dependence of the concentration distribution inhaled by the occupants on the exposure duration and the size of the openings in the dwelling [22].

The maximum indoor concentration of PM2.5 is due to a combination of low airtightness in the open window status, high wind speeds, and critical outdoor pollution for PM2.5. For example, in scenario#2, indoor PM2.5 increases by 269% compared to the baseline scenario, and for every 1% increase in wind speed, 0.4% is added to the PM2.5 average concentration.

The highest concentration of formaldehyde in the indoor environment is due to the coincidence of high airtightness with fully closed windows, high formaldehyde emissions, and low wind speed. For example, in scenario number#13, formaldehyde elevates by

Table 5
The average concentration of selected pollutants in the indoor environment in different scenarios.

Combined scenario	Average indoor PM2.5 ($\mu g/m^3$) Existing) outdoor conditions)	Average indoor PM2.5 ($\mu g/m^3$) (Doubling the outside concentrations)	Average indoor PM2.5 ($\mu g/m^3$) (Tripling the outside concentrations)	Average indoor HCOH ($\mu g/m^3$)	Average Indoor CO2 concentration (ppm)
1	10.78	21.56	32.34	81.39	1304.29
2	13.26	26.52	39.78	61.36	982.07
3	13.23	26.45	39.68	61.59	985.76
4	11.70	23.39	35.09	77.84	1374.26
5	9.13	18.25	27.38	100.39	1478.41
6	13.00	26.00	39.00	64.42	1054.77
7	12.99	25.98	38.97	64.49	946.90
8	9.78	19.55	29.33	99.18	1587.24
9	6.64	13.29	19.93	144.49	1918.57
10	12.69	25.37	38.06	68.62	924.01
11	12.67	25.35	38.02	68.71	924.95
12	7.10	14.19	21.29	139.76	1867.47
13	4.51	9.02	13.53	218.88	2704.95
14	12.42	24.84	37.27	72.72	916.07
15	12.41	24.82	37.23	72.82	917.02
16	5.61	11.21	16.82	180.14	2036.20

Values higher than the WHO recommended limit ($25\boldsymbol{\mu g/m^3}$)
Values higher than the WHO recommended limit ($100\ \boldsymbol{\mu g/m^3}$)
Values higher than 1000 ppm

169% (equivalent to 219 g/m^3) compared to the baseline scenario, and with every 1% decrease in the average wind speed, it will escalate by about 0.5%.

3.3. *Suggested solution*

Considering that the minimum fresh air required for different building spaces is determined in the 16th topic of the National Building Regulations, mechanical installations, the fresh air supply system is defined in the model accordingly.

The results show that although this system reduces the average concentration of formaldehyde and CO2 to an acceptable level, it augments the infiltration of outdoor particles.

In this condition, the average concentration of particles increases sharply, so that in scenario#13 and critical conditions of outdoor air pollution, it reaches 70.7 $\mu g/m^3$ (Fig. 10). If a particle filter with 70% efficiency is used in this system, the average indoor PM2.5 will become 21.6 g/m^3 , following the WHO guidelines (Fig. 11). Efficient air filtration was identified as an effective strategy for improving indoor air quality [54], based on the CONTAM model developed within the U.S. Healthy Home Initiative.

Suppose we do not consider the fresh air supply system and only use a formaldehyde absorber with an efficiency of 60%. The results show that this has no impact on other indoor pollutants, even when reducing the concentration of formaldehyde to the recommended level. For example, CO2 concentrations remain at critical levels (Fig. 12).

In the conditions of closed windows and high airtightness of the envelope, where the only ventilation mechanism is through leaks, the use of a fresh air supply, along with the removal of outdoor pollutants with critical concentrations, is a suitable solution to reduce both internal and external originated pollutants to the recommended limits.

4. Conclusion

This study has developed and applied a series of field measurements and model simulations in CONTAM for a typical old building in Tehran in order to quantify the impact of increased building airtightness, based on the objectives of the new Energy Conservation Code,

Table 6
Changes in the average concentration of pollutants in the indoor environment in different scenarios compared to the baseline scenario.

	$(\mu g/m^3)$	$(\mu g/m^3)$	
1 (Baseline Scenario)	·	·	·
2	+23%	-25%	-25%
3	+22.7%	-24.3%	-24.4%
4	+8.5%	-4.4%	+5.4%
5	-15%	+23%	+13%
6	+21%	-21%	-19%
7	+20.5%	-20.8%	-27.4%
8	-9.3%	+21.8%	+21.7%
9	-38.4%	+77.5%	+47.1%
10	+17.7%	-15.7%	-29.1%
11	+17.5%	-15.6%	-29.1%
12	-34.1%	+71.7%	+43.2%
13	-58.2%	+169%	+107%
14	+15.2%	-10.7%	-29.8%
15	+15.1%	-10.5%	-29.7%
16	-48%	+121%	+156%

*The highlighted cells represent the maximum percentage of changes in pollutant concentration compared to the baseline Scenario

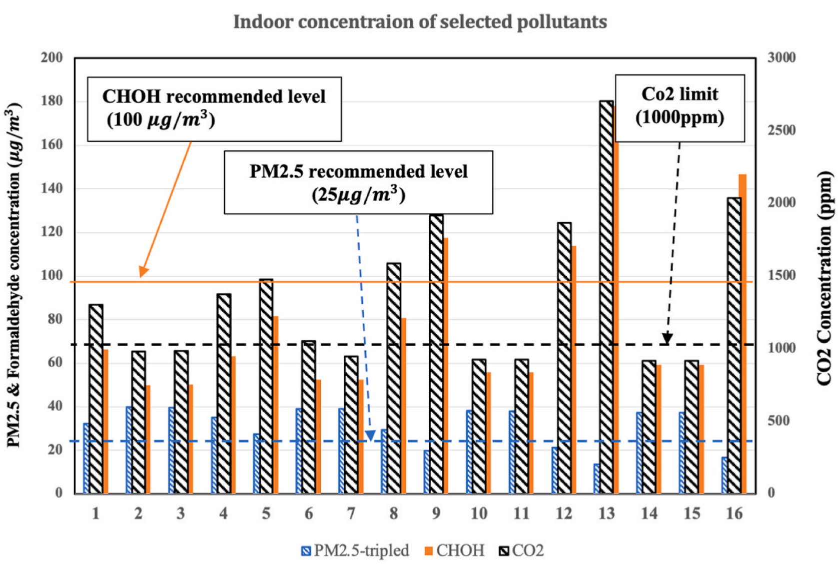

Fig. 9. The concentration of selected pollutants in the indoor environment for combined scenarios)In the condition of critical levels of outdoor PM2.5).

on the variations of indoor exposure to PM2.5 and formaldehyde.

The main parameters affecting IAQ and indoor exposure were quantified, and it was shown that airtightness, occupant factors, and source strength had significant effects, while meteorological parameters except for wind had a relatively smaller influence.

Our principal findings suggest, in the conditions of severe outdoor air pollution, significantly increased airtightness in naturally ventilated buildings, although substantially reduces infiltration of outdoor pollutants, but, increases indoor-sourced pollutants including formaldehyde and respiratory carbon dioxide. Consequently, indoor air quality is not guaranteed by any airtightness value under these circumstances.

Table 7
The average exposure of residents to the selected pollutants in the indoor environment in different scenarios.

Combined Scenario	Average Exposure to PM2.5 ($\mu g/m^3$) (resident No.1)	Average Exposure to PM2.5 ($\mu g/m^3$) (resident No.2)	Average Exposure to Formaldehyde ($\mu g/m^3$) (resident No.1)	Average Exposure to Formaldehyde ($\mu g/m^3$) (resident No.2)	Average Exposure to CO2 ($\mu g/m^3$) (resident No.1)	Average Exposure to CO2 ($\mu g/m^3$) (resident No.2)
1	17.74	14.36	66.51	82.31	826.51	851.55
2	18.78	15.78	54.22	67.23	994.70	1044.66
3	18.76	15.76	54.38	67.42	998.05	1048.40
4	17.56	14.47	70.26	84.75	1380.76	1466.65
5	16.95	12.77	78.61	100.64	1358.49	1484.27
6	17.50	15.22	64.22	72.49	1053.79	931.45
7	18.55	15.21	57.18	72.56	959.30	1010.78
8	16.91	12.30	80.30	106.39	1366.21	1530.99
9	15.75	10.40	106.00	140.91	1580.95	1778.09
10	18.34	14.68	60.61	78.39	935.27	989.05
11	18.33	14.67	60.68	78.48	936.15	990.05
12	15.74	10.23	107.03	143.16	1588.71	1781.74
13	14.58	8.08	153.56	207.30	1885.46	2181.76
14	18.17	14.29	63.68	83.30	925.94	982.02
15	18.17	14.26	63.76	83.43	926.82	983.04
16	14.69	8.71	140.66	185.93	1815.71	2028.67

Values higher than the WHO recommended limit (100 $\boldsymbol{\mu g/m^3}$)
Values higher than 1000 ppm

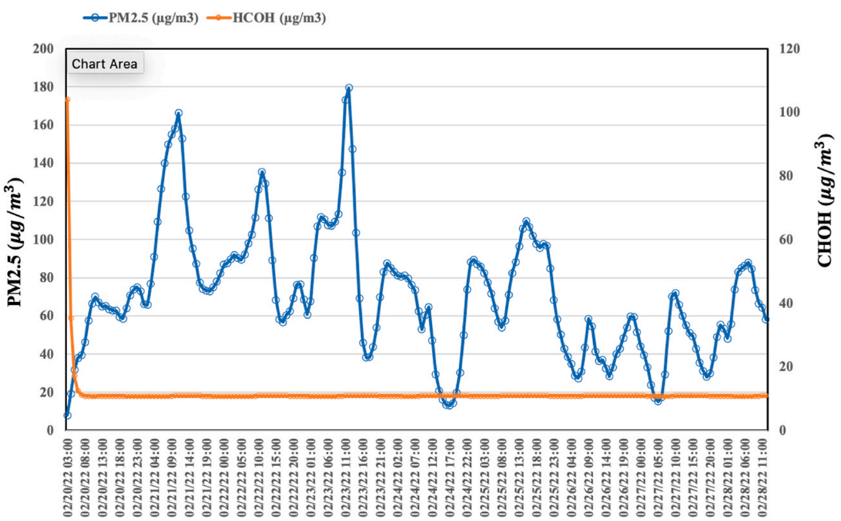

Fig. 10. Concentration of PM2.5 and formaldehyde in case of using a fresh air supply system without particle filtration.

In low and very low-energy buildings with high levels of airtightness, alternative solutions such as a fresh air supply system combined with the removal or filtering of critical concentrations of outdoor pollutants not only meet energy conservation targets but also support IAQ and occupants' health. These also help remove other indoor-generated contaminants such as tobacco smoke, which would be beneficial for non-smokers in such homes.

The combination of low airtightness in open window status, high wind speed, and elevated outdoor PM2.5 pollution creates the worst case of indoor PM2.5 concentration.

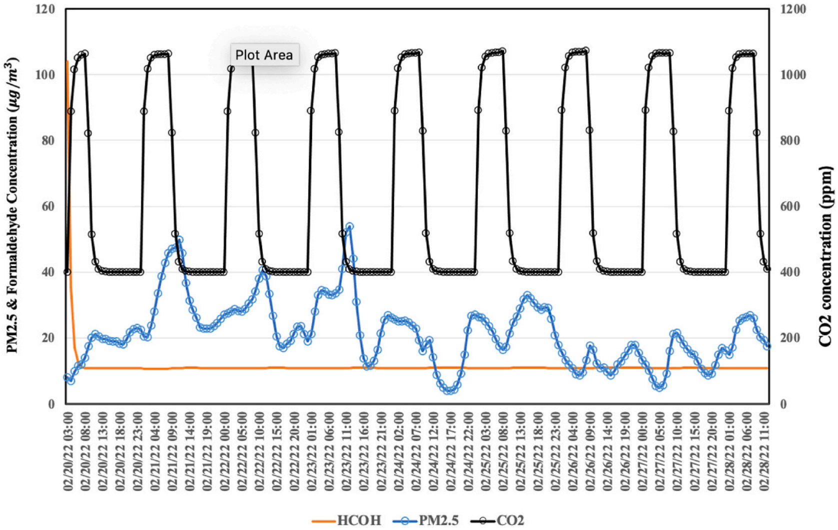

Fig. 11. Concentration of PM2.5 and formaldehyde if using a fresh air supply system with particle filter with 70% efficiency.

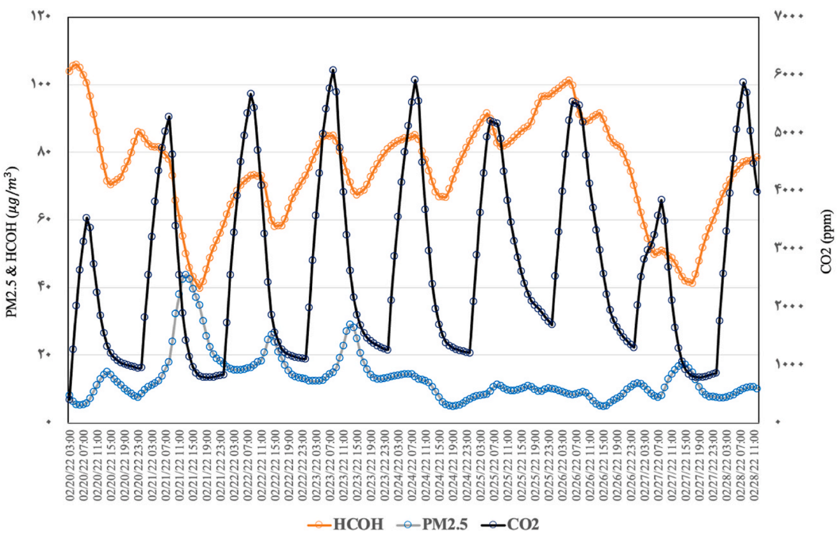

Fig. 12. Concentration of PM2.5 and formaldehyde and carbon dioxide in the indoor environment in case of using a formaldehyde absorber with 60% efficiency.

The worst indoor formaldehyde scenario is due to the coincidence of high airtightness with leakage-based ventilation (closed window), high formaldehyde emission rate, and low wind speed.

The sensitivity analysis results show that indoor PM2.5 is more sensitive to its deposition rate and outdoor levels, while indoor formaldehyde sensitivity depends on the formaldehyde emission rate. Among meteorological parameters, changes in wind speed and relative humidity by $\mp$ 20% affect the indoor concentration of selected pollutants between 4.5 and 10%.

In this work, several limitations have to be taken into account. Indoor sources contribute significantly to indoor PM2.5 concentrations but were not included. According to the scope of the study on the effect of airtightness on the infiltration of pollutants from the outside environment, measurements and simulations have been carried out in the absence of an internal source in order to eliminate its interfering effect.

In modeling the behavior of occupants, assumptions have also been required. Window-opening behavior is complex, based on people's physical conditions or climate situations, which indicates that by opening the window more frequently, occupants may temporarily increase their exposure to outside air pollutants. In this study, only the effect of some common behavior of users on the leakage conditions of the building is considered.

Air leakage paths were expected to be distributed across all openings of the building except for party walls, which had been assumed to be impermeable. Actually, at 50 Pa differential pressure in UK dwellings, partitions may contribute to as much as 30% of air leakage [10]. Moreover, some leakage paths, such as between suites and floors, are not taken into account in the models. Compared with the primary air flow paths, they are generally small [40]. In order to gain a better understanding of the permeability of different surface types in Iran's housing stock, further research is needed.

Further work is now needed to produce a large set of geometries, that are more representative of various building stock, and a wide variety of energy refurbishment strategies, differing pollutants and source emissions, and changes to occupant behavior.

Author contribution statement

Fatemeh Zahed: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Alireza Pardakhti; Behrouz mohammad Kari: Conceived and designed the experiments; Analyzed and interpreted the data.

Majid Shafiepour Motlagh; Azadeh Tavakoli: Analyzed and interpreted the data.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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