# Exploring the Indoor Air Quality in the context of changing climate in a naturally ventilated residential Building using CONTAM

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**SUMMARY**

Indoor Air Quality (IAQ) of residential buildings is a crucial field of study as it aims important subjects: providing healthy indoor air to inhabitants, avoiding high pollutants concentration and impacts of extreme heat events along with climate change and global warming concerns. In order to set up a performance-based method, a critical question has to be answered: What are the relevant IAQ performance parameters that are mostly affected in the context of climate change? To address this, a measurement campaign was carried out in summer of 2021 at south of Belgium. Indoor temperature, relative humidity, CO, Particulate Matters ($PM_{2.5}$, $PM_{10}$), Volatile Organic Compounds (VOCs), NO, $NO_2$ and $O_3$ concentrations were measured with fabricated monitoring devices of low-cost sensors, as well as the corresponding outdoor values. In the first step of this study, IAQ parameters are computed using designed model with CONTAM software for the test house. In the next step, the validation of the developed model is investigated.

**KEYWORDS**

*IAQ, Residential Buildings, CONTAM Model Validation, Climate Change, Natural Ventilation.*

## 1 INTRODUCTION

Mostly inspired with EU Commission's proposal to cut greenhouse gas (GHG) emissions by at least 55% by 2030, European countries are being set on a responsible track to becoming climate neutral by 2050 (EC, 2019). In Belgium, the Climate Change Department of the FPS (Federal Public Service Health) launched an initiative entitled "A low-carbon Belgium by 2050" in 2012. The built environment is one of the main energy consuming sectors in Belgium, about 34% of the overall final energy consumption in 2010 (CLIMAT, 2013). GHG emissions in the built environment increased significantly by 18% over the period 1990-2010 which was mainly caused by the +13% growth of the number of households and +35% output growth of the services sector (CLIMAT, 2013). Hence, the current dwellings, mainly naturally ventilated, are projected to account for approximately more than 80% of the housing stock till 2050. To reach 2050 climate neutral targets, current policies propose existing dwellings must undergo extensive retrofitting, with the implementation of insulation and more efficient HVAC systems combined with an increase in air tightness (Wilkinson et al., 2009). Though, such measures to air tightness and ventilation systems are expected to result in variations of IAQ and personal exposure to airborne pollutants which will have direct influence on population health. Concentrations of chemical contaminants and airborne pollutants in residential buildings are related to the infiltration of outdoor compounds, emissions from indoor sources (activities, building materials, ventilation systems, etc.) and the removal from the internal air by deposition, filtration and exfiltration, though some re-suspension also occurs largely related to domestic activities. Indoor emissions include transient emissions from internal sources such as building materials, fixtures and appliances, as well as intermittent emissions such as burning fuel and candles, smoking, cooking, heating and human household activities. (Shrubsole et al., 2012).

This study investigates the validation of a “Poly-contaminant CONTAM model” of a natural ventilated studio house as part of the “OCCUPANT” project which aims the climate change effects on IAQ. The contaminants include CO, $PM_{2.5}$, $PM_{10}$, VOCs, NO, $NO_2$ and $O_3$. To the best knowledge of authors this is the first model validation of a design in CONTAM for IAQ assessment from the point of contaminants number, and time duration (7 contaminants for 73 days).

## 2 MATERIAL/METHODS

### 2.1 Multi-Zone Simulation

CONTAM is a multizone IAQ and ventilation analysis computer program designed by National Institute of Standards and Technology (NIST) (Dols and Polidro 2020). The multizone approach is implemented by constructing a building model as a network of elements describing the flow paths (doors, windows, cracks, HVAC etc.) between the zones (primarily rooms) of a building. The network nodes represent the zones, which are modelled with a hydrostatically varying pressure, and uniform temperature and pollutant concentration within each zone. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations to the zones. CONTAM has frequently been used to study a variety of residential IAQ issues in past simulation studies (Emmerich and Persily, 1996; Paralovo et al., 2021). From wide range of its applications, the prediction of contaminant concentrations can be used to investigate the IAQ performance of buildings for future environmental variations as well as impacts of measures going to be applied in buildings. Predicted contaminant concentrations can also be used to estimate personal exposure based on occupancy patterns.

In this research, the simulations were performed for the test building using CONTAM Outdoor Contaminant files (CTM), Weather files (WTH) and Continuous Value Files (CVF).

### 2.2 DATA

For the CONATM model data input, outdoor contaminant records were downloaded from ISSeP (Institut Scientifique De Service Public) air pollution and meteorological station, located in Southern Wallonia (ISSeP, 2021). Outdoor meteorological data such as direct solar radiation and wind speed were provided from RMI (Royal Meteorological Institute of Belgium). With the aim of CONTAM model validation, we measured indoor temperature and contaminant concentrations in parallel to reference data sources (our measurements were performed in both indoor and outdoor). The measurement duration was 3 months (20Jun- 31Aug 2021) for monitoring seven contaminants indoor and outdoor, as well as the temperature, relative humidity and pressure. Figure 1 shows the fabricated measuring device in the SAM-LAB, based on low-cost electrochemical and light scattering sensors. Table 1 represents their main specifications. The data logging was set to measure the parameters all together in each minute.


Figure 1. Schematic of OCT IAQ measuring devices.

Table 1. Specification of sensors included in OCT devices.

| Sensors | Provider | Concentration | Temp ˚C |
|---|---|---|---|
| $PM_{2.5}/PM_{10}$ | Light scattering Sensirion SPS30 | 0-1000 µg/m3(±10) | 10 - 40 |
| $O_3$ | EC -Alphasense OX-B431 | 1-20 ppm (±2) | -30 - 40 |
| NO | EC Alphasense B4 | 2-20 ppm (±2) | -30 - 40 |
| $NO_2$ | EC Alphasense B43F | 2-20 ppm (±2) | -30 - 40 |
| CO | EC Alphasense B4 | 2-1000 ppm (±2) | -30 - 50 |
| VOC | PID -AMETEK MOCON – Blue | 0.5 ppb - 2 ppm | -20 - 60 |

Moreover, a detailed questionnaire was developed in order to log the occupancy pattern, activity behaviours (sleeping, cooking, cleaning) and the opening of windows in order to define the schedules in the software. Based on the presence of suitable data, various schedules were defined in the library of software for window openings, doors and occupants' emissions for the domestic activities. The whole-house indoor emission rate of pollutants (sources/sinks) were calculated by mass balance method (Dacunto et al., 2013). Table 2 presents the defined air flow paths for the designed model. The detailed values and other set parameters for flow path elements were gathered from ASHRAE Handbook (ASHRAE, 2015).

Table 2. Air flow element characteristics in the CONTAM model design.

| Element | Model Summary | Formula | Model Parameter |
|---|---|---|---|
| Exterior wall leakage | One-way flow using power law | Leakage area per unit length | 15 $cm^2$/m |
| Interior wall leakage | One-way flow using power law | Leakage area per unit length | 20 $cm^2$/m |
| Windows Close | One-way flow using power law | Leakage area per item | 2 $cm^2$ |
| Doors Closed (old) | One-way flow using power law | Leakage area per item | 150 $cm^2$ |
| Windows Open | Two-way flow | One opening | Cross section area |
| Doors Open | Two-way flow | One opening | Cross section area |

A total floor area of 100 $m^2$, net volume of 320 $m^3$, floor-to-ceiling height of 3.2 m are considered based on the test house geometry. The envelope effective leakage area (ELA) of this case study is considered at a pressure of 4 Pa, exponent of 0.65 and discharge coefficient of 1. The exhaust fan (bathroom/kitchen) with the flow rates of 24 L/s is operated in an on or off mode by introducing an AHS (Air Handling System) component in the design. The number of zones and envelope airflow paths are 8 and 34, respectively. Envelope airflow paths represent doors, windows, cracks and leakages, and exhausts. The apartment (Figure 2) was modelled to be on the ground floor, with no adjustments for either change in wind speed. The transient indoor temperature (measurements) was fed to the model by (CVF) files.

## 2.3 VALIDATION

For the validation of the model, the contaminant concentrations recorded during the measuring campaign was used according to ASTM D5157-19 Standard Guide for Statistical Evaluation of IAQ Models (ASTM, 2019). The data sets gathered during this project satisfy the ASTM D5157 criteria for model assessment, as they are totally independent of the data employed to develop the model and to estimate model inputs. Also, the data details are sufficient detail to evaluate the CONTAM predictions of individual zonal pollutant concentrations. Three elements suggested by ASTM D5157 to evaluate the accuracy of a model includes: correlation coefficient ($r$), regression slope ($M$) and intercept ($b$), and normalized mean square error ($NMSE$). For evaluation of adequate model performance, the normalized fractional bias ($FB$), and absolute fractional bias of variance ($FS$) are advised. Table 3 presents the equations of aforementioned parameters as well as the proposed limits and satisfactory ranges by ASTM D5157.

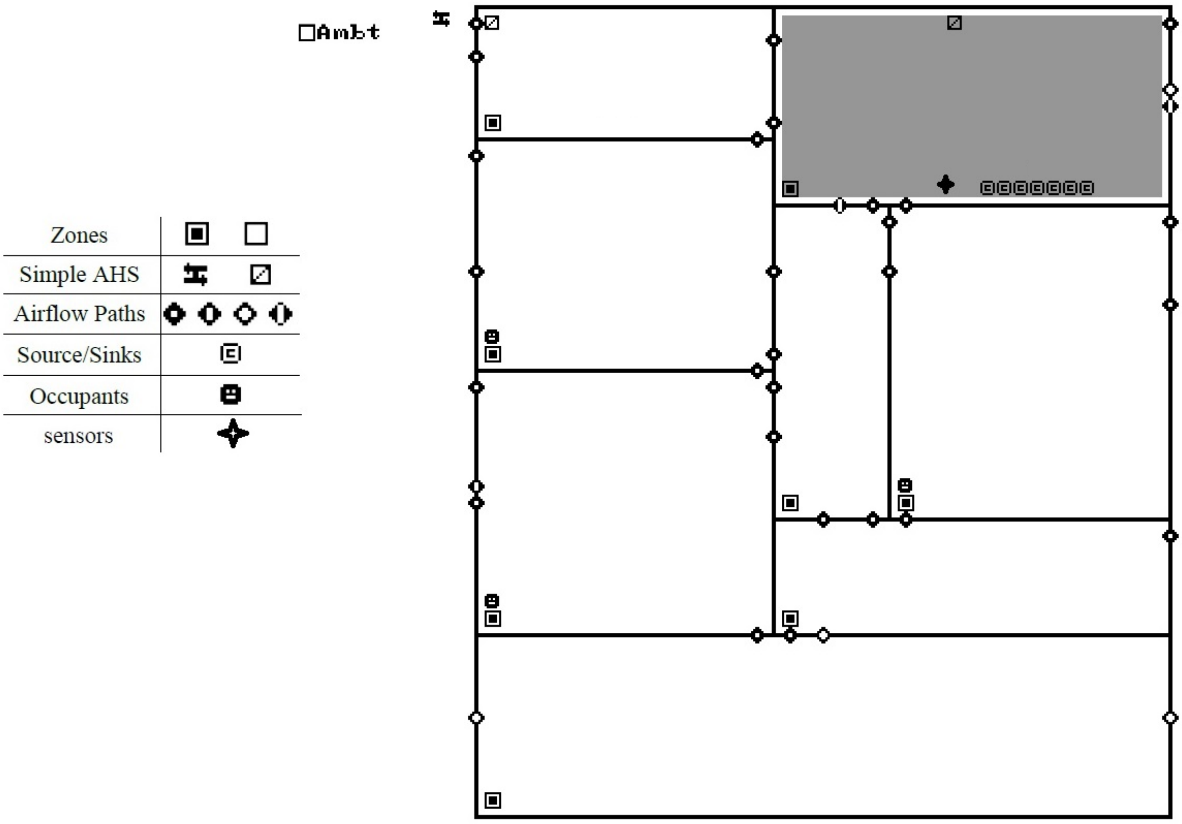


Figure 2. CONTAM sketchpad representation of the test house (The top of the figure is due north).

Table 3. ASTM D5157 criteria for IAQ model validation.

| Evaluation Parameter | Parameter Definition | D5157 Acceptable Values |
|---|---|---|
| Correlation Coefficient | $r = \frac{\sum(M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum(M_i - \bar{M})^2 \sum(O_i - \bar{O})^2}}$ | $r \geq 0.9$ |
| Regression Slope | $M$ | $0.75 \leq M \leq 1.25$ |
| Regression Intercept | $b$ | $\lvert b \rvert \leq 0.25\bar{O}$ |
| NMSE | $NMSE = \sum \frac{(M_i - O_i)^2}{2\bar{M}\bar{O}}$ | $NSME \leq 0.25$ |
| FB | $FB = \frac{2(\bar{M} - \bar{O})}{(\bar{M} + \bar{O})}$ | $FB \leq 0.25$ |
| FS | $FS = \frac{2(\sum(M_i - \bar{M})^2 - \sum(O_i - \bar{O})^2)}{\sum(M_i - \bar{M})^2 + \sum(O_i - \bar{O})^2}$ | $FS \leq 0.5$ |

*The *M* and *O* stands for predicted and observed concentrations of each pollutant, respectively.

## 3 RESULTS

Hourly results of CONTAM contaminants simulations in the kitchen zone (most challenging zone) in 3 months (20 Jun - 31 Aug 2021) are presented in Figure 3. The simulated data is extracted by CONTAM Results Export Tool (Polidoro et al., 2021) to be compared with the real measured indoor data.

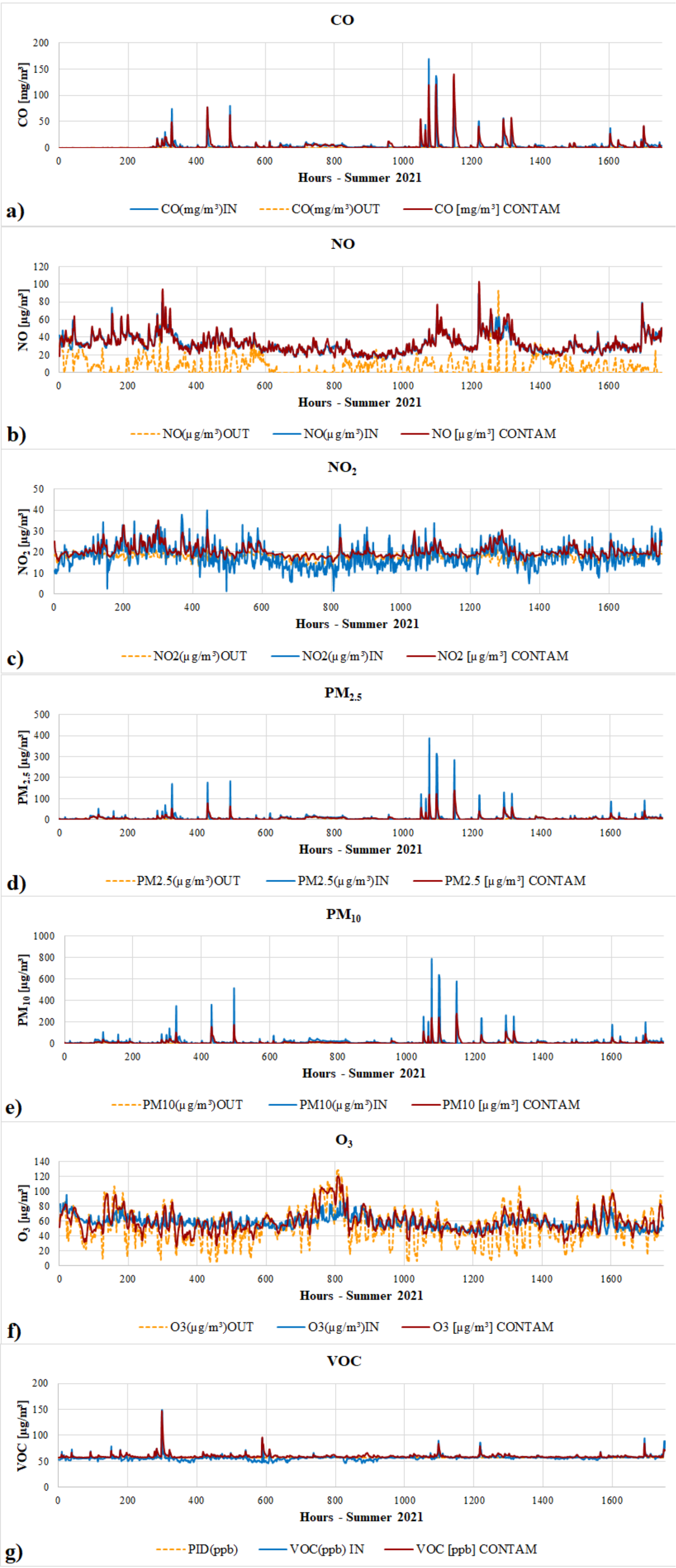


Figure 3. CONTAM simulation results (hourly average) in comparison with indoor and outdoor.

Figures 3a, b, c, d, e, f, g, h, illustrates the indoor, outdoor and simulated concentrations for, CO, NO, $NO_2$, $PM_{2.5}$, $PM_{10}$, $O_3$ and VOCs, respectively.

The Table 4 presents the summarized evaluation results for each contaminant. Acceptable values by the D5157 criteria are made bold and cells are highlighted in green colour. Correspondingly, the Figure 4a, b, c, d, e, f, g, depicts the scatter plots of simulated and measured values of CO, $NO_2$, NO, $O_3$, $PM_{2.5}$, $PM_{10}$ and VOCs respectively, as well as the regression lines and equations.

Table 4. Statistical analysis of simulated result for validation of CONTAM model.

| Parameter | CO | NO | $NO_2$ | $PM_{2.5}$ | $PM_{10}$ | VOC | $O_3$ |
|---|---|---|---|---|---|---|---|
| *r* | 0.74 | 0.92 | 0.72 | 0.75 | 0.74 | 0.65 | 0.55 |
| *M* | 0.82 | 0.99 | 0.41 | 0.38 | 0.37 | 0.6 | 1.04 |
| *b* | 1.14≥1.04 | 0≤8.13 | 12.68≥5.03 | 4.88≥1.93 | 6.2≥2.97 | 25.16≥14.22 | 0.26≤14.97 |
| *NMSE* | 3662 | 14.32 | 40 | 36222 | 5083 | 6.17 | 41 |
| *FB* | 0.2 | -0.01 | 0.11 | 0.03 | 0.25 | 0.04 | 0.04 |
| *FS* | 0.33 | 0.15 | -1.1 | -1.18 | -1.2 | -0.15 | 1.12 |

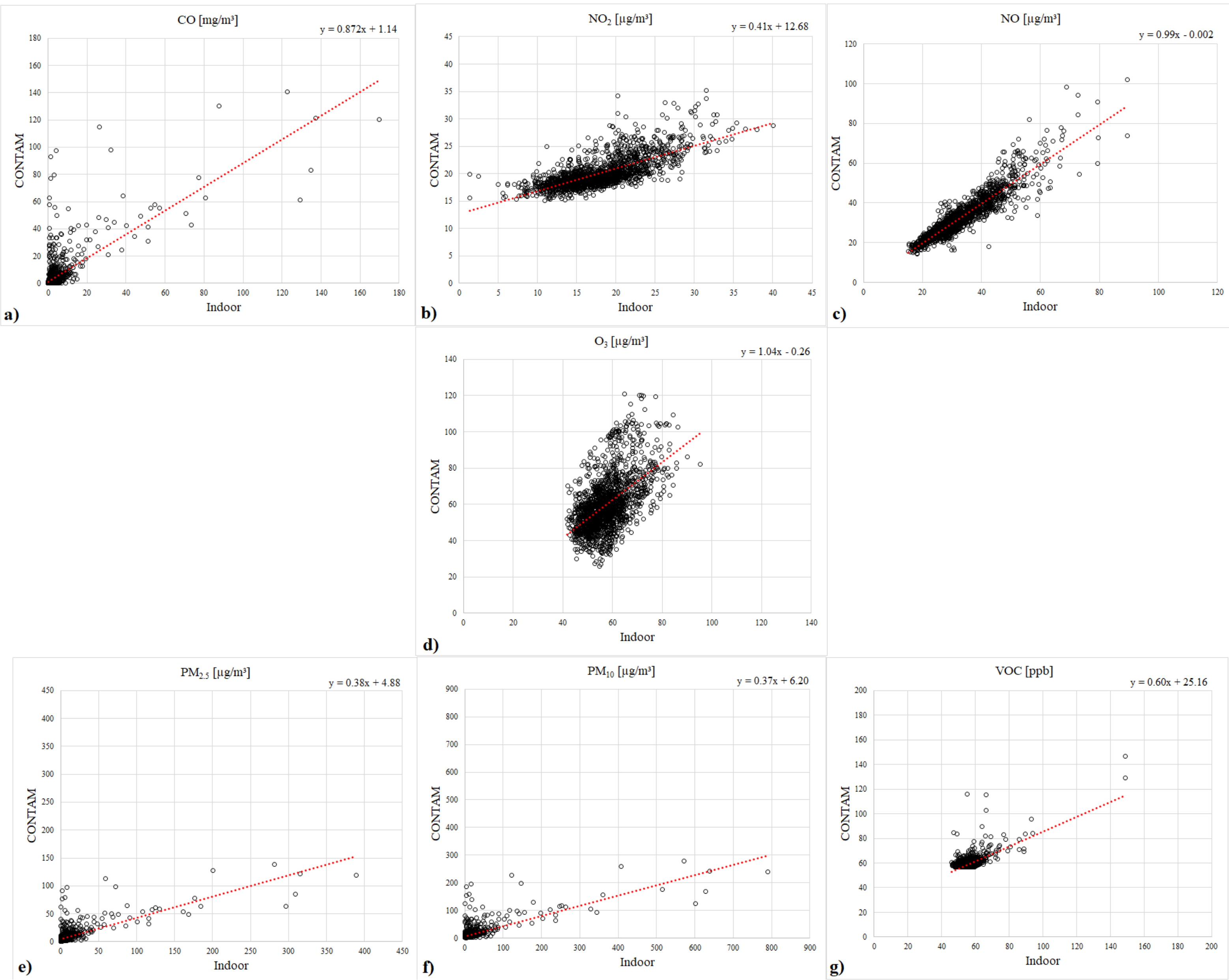


Figure 4. Scatter plots and regression line of the predicted concentration against experiments.

## 4 DISCUSSION

As it can be observed by the values summarized in Table 4, statistical agreement with ASTM-D5157 criteria varies for the individual contaminants. The agreement was generally better for CO, NOx and PMs, however VOCs and $O_3$ results showed the least satisfactory levels. Also, it is noteworthy that the average values for the simulated and measured pairs of VOCs and $O_3$ are (59.37, 56.78) ppb and (59.88, 57.52) µg/m³ respectively, indicating a highly close average values. In other words, while the data analysis of contaminant is helpful to realize strengths and weaknesses of the model, an additional critical statistical evaluation can be the comparison of the entire set of contaminants. This overall evaluation indicates that the model's ability to predict the relative outcome when individual parameters are changed, has a consistent agreement (e.g., door/window open vs. closed, or presence vs. absence of one type of source/sink/exposure element). Regarding the adequate model performance, it could be observed based on FB, the model has a satisfactory level of precision (average *FB* of 0.094). As it is discussed earlier in the literature (Emmerich and Nabinger, 2001; Emmerich and Dols, 2016), absolute validation of a complex model, such as CONTAM, is impossible as there are countless possible designs that can be developed by a user for a single case of study. However, the main goal of this experimental validation is to evaluate the performance of the CONTAM model simulations for OCCUPANT project applications, to detect large sources of error, and to assess the level of confidence that is obtainable in the predictions for future weather and pollution scenarios in the context of climate change. For the simulation performed by the developed design in this study, no substantial errors in the CONTAM performance were detected, specially from the average point of view of concentrations in the analysis time range. Furthermore, some of the disagreements between model results and experimental measurements can be due to experiment data limitations in identification of occupants' behavior patterns, and definition of sources, sinks and exposures, instead of model insufficiencies. Yet, there are additional measurements and test regarding the building itself that would have been more beneficial for the model design development. Also, uncertainties in experimental measurements include more than simply the instrument accuracy. Recorded measurements are a single point that was employed to characterize an average zone concentration. The capacity of this single-point data to signify a whole zone volume might be a point of subject.

## 5 CONCLUSIONS

A series of experiments to characterize the temporal profiles of poly-contaminants concentrations from a test residential house was carried in the summer of 2021 in Belgium to support the validation process of a designed model in IAQ simulation software, CONTAM. Seven contaminates include CO, $PM_{2.5}$, $PM_{10}$, VOCs, NO, $NO_2$ and $O_3$. The outdoor measurement was used to create CONTAM CTM files. The long-term time span of the designed model considered to be 73 days in 3 months (20 Jun – 31 Aug). Absolute validation of a complex model, such as CONTAM, is impossible as there are countless possible designs that can be developed by a user for a single case of study. Nonetheless, for the simulation performed by the designed model in this study, no substantial errors in the CONTAM performance were detected, specially from the average point of view of concentrations in the examination time range. The agreement between the measurements and predictions of the CO, NOx and PMs concentrations in the kitchen zone was very good. Between one to four of the calculated statistical values met the ASTM D5157 criteria for each contaminant. The agreement, however, was not satisfactory in terms of *NMSE*. But the average values of simulated and measured concentrations for each contaminant in the whole summer time were identical at the level of 83% for CO, 77% for $PM_{10}$ and +90% for other contaminants.

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