Climate and occupancy based investigation of air pollutants in office spaces

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Abstract. Indoor air quality (IAQ) has long been a matter of public concern as many people are spending a large portion of their time indoors. The concentration of some pollutant in offices and other work places can often be 2 to 5 times higher than typical outdoor concentrations. This study investigates the relationship between office space available per employee and outside weather condition with indoor pollutants level at 25 office locations of a large international architecture and design firm. Air pollutants measured in this study included carbon dioxide (CO₂), particulate matter (PM₂.₅), and volatile organic compounds (VOCs). They have been monitored for a three-month period from December 1st, 2017 to February 28th, 2018 in 23 offices located in the U.S., one office in China, and one office in Dubai. The first phase of this study analyzed the hourly average levels of mentioned pollutants at these offices during working and non-working hours. Then those levels were correlated to the number of employees at all of the locations. The second phase observed the difference in CO₂ level, as the most important indoor air pollutant, related to outside weather condition (temperature and humidity) at three locations in the U.S. The initial result of phase one proved the linear relationship between the number of employees and CO₂ levels in office buildings. It concluded, that the low area per employee rate will cause the high CO₂ concentrations. Moreover, a comparison between indoor CO₂ level and outside weather conditions (temperature and humidity) in the second phase at three office shows that CO₂ level are affected directly by outdoor conditions during working hours. Based on the building climate zone, when temperature and humidity are far from the comfort zone and mechanical ventilation system are operated, CO₂ concentration could variously change during working hours.

1. Introduction
Indoor Air Quality (IAQ) refers to the air quality within buildings and structures. IAQ directly affect occupant health, comfort and productivity in which poor indoor quality causes building-related illness, such as sick building syndrome [1]. It has been proven by several studies that indoor air pollution can trigger asthma attacks and can be detrimental to respiratory health status including lung cancer from radon exposure, and carbon monoxide (CO) poisoning [2], [3], [4]. Today, people are spending about 90 percent of their times indoors, thus, the level of indoor air pollutants may be of particular concern in both developing and developed countries. Indoor pollutants which significantly affect the indoor air quality has different sources. In general, those sources are fuel-burning combustion appliances, tobacco products, products for household cleaning and maintenance, central heating and cooling systems and humidification devices, excess moisture, and outdoor sources [5], [6]. Sources of air pollution release pollutants into the environment in different forms such as Carbon Dioxide (CO₂), Carbon Monoxide (CO), Nitrogen Dioxide (NO₂), Indoor Particulate Matter (PM₂.₅ and PM₁₀), Volatile Organic Compounds (VOCs) among others [7].

Despite the fact that a growing fraction of the active population worldwide is working in office buildings, little is known about IAQ in these office buildings [8]. In this research, the level of three indoor pollutants (CO₂, PM₂.₅, and Total VOCs) have been monitored for a three-month period,
December 1st, 2017 to February 28th, 2018 in selected 25 office buildings (23 offices in the U.S., one in Shanghai, China, and one in Dubai, UAE). The offices are architecture and design firms equipped with mechanical ventilation systems and located at different climate zones (shown by different color in Figure 1). Indoor air pollutants have been measuring on a continuous basis at the selected offices from 2017 and have been provided by the DLR Group Inc. [9]. Professionally calibrated IAQ Tongdy (certified to ISO 9001) sensors have been used to measure Temperature, Relative Humidity, CO₂, TVOC, and PM inside the offices at every 450 m² of regularly occupied spaces [10].

![Figure 1](image.png)

**Figure 1.** Under study offices regarding their climate zone, Reference: Author

Investigating the sources of measured air pollutants at these offices is beyond the scope of this study; however, routine sources for each pollutant with the focus on office spaces can be listed as below:

- **Carbon Dioxide (CO₂);** Indoor occupant density, in other word, metabolic activity and respiration of the building occupants combined with low fresh air change rate.

- **Particulate Matter (PM₁₅ and PM₁₀);** Human activities including electronics equipment usage, indoor walking, floor cleaning, and cigarette smoking are main sources of PM in offices [11].

- **Volatile Organic Compounds (VOCs);** liquid-process photocopiers and plotters, interior finish materials, cleaning products, and furnishings [12].

Among the factors that influence the production of indoor air pollution, the level of activity plays a fundamental role. The studied office spaces are occupied by a diverse number of full-time employees from 4 to 154. The size of the offices varies from 130 to 3,700 m². The total area for all the locations is 30,770 m² and the total number of full-time employees is 1193. In order to provide the density of occupation in each office, the indoor areas were divided by the number of employees at each office. The Offices’ area per employee show a range between 9 to 86 m² per person and average area per employee for all offices was calculated at 31 m². There are some offices with the density of occupation under 15 m² per person namely, Chicago, Cleveland, New York, Shanghai, and Washington DC. Diversity of area and density of occupation at each office is illustrated in Figure 2.
Phase One: levels of indoor air pollutants regarding occupant densities

2.1. Average level of pollutants for three months in all locations

The first phase of this study considers the average level of three pollutants at 25 offices in relation to the number of employees at each office. The level of three indoor pollutants (CO₂, PM₂.₅, and Total VOCs) have been monitored minutely for a three-month period from December 1, 2017 to February 28, 2019 at all the locations. The goal of the study was to detect anomalies regarding the high number of occupations and consequently the low rate of area per employee. The hourly average level of pollutants during three months were calculated from the minutely recorded data. It has to be noted that air pollutants have been measured at more than one location in some offices like, Omaha and Minneapolis with five sub locations.

2.2. Average levels in comparison to standards

After calculating the average level of pollutants for all locations, they were compared to standards. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has set standards and guidelines for acceptable indoor air quality. ANSI/ASHRAE Standard 62.1-2004 [13] provides the acceptable levels of common indoor air pollutants for occupant comfort and the avoidance of irritation caused by odors. By comparing the measured average level of pollutants for offices found at section 2.1 and standards, the offices with exceeding levels of pollutant have been found. New York office with the average of 760 ppm for CO₂, the Second East Office in Omaha with the average of 687 ppm for CO₂, and the Shanghai office with the average of 31.09 for µg/m³ PM₂.₅ had the highest recorded pollutants concentration at this section.

2.3. The level of pollutant during working and non-working hours

In order to better understand the role of occupants in the production and distribution of indoor air pollutants, the average level of pollutants has been analyzed during working and non-working hours at random office locations. Working hours are considered from 8 am to 7 pm and others as non-working hours. This grouping strategy has been also used for holidays and the weekends for the three months from December 2017 to February 2018 at chosen offices.

Table 1. Total, working and non-working hours average level of indoor pollutants at Charlotte office.

| Charlotte-Open Office | CO₂ (ppm) | PM₂.₅ (µg/m³) | Total VOCs (mg/m³) |
|-----------------------|-----------|---------------|-------------------|
| Total average         | 467       | 9.65          | 0.35              |
| Average in working hours | 490       | 9.13          | 0.32              |
| Average in non-working hours | 444       | 10.18         | 0.38              |

The analysis was conducted for 7 locations namely Charlotte, Chicago, Cleveland-location 1 and 2, Colorado Springs, Dallas, and Dubai. Table 1 shows a sample of the analysis done at the Charlotte office.
3. Results from Phase One

Results in this phase indicate that the low rate of area per employee in the offices will cause the high CO₂ concentration in offices like New York. Among 25 offices, the minimum area per employee belonged to New York with 9 m² for each employee while the maximum average of CO₂ concentration with 760 ppm was also recorded at the New York office. The value is higher than 600 ppm, standard level for high thermal comfort and close to the allowable value for CO₂ concentration in air. Moreover, the average level of CO₂ at the Omaha-2nd East Office exceeded standard amount with 687 ppm. Although the total area per employee for the entirety of the building at this location is 23 the rate for specified location i.e. 2nd East Office is not clear. It could be assumed that the space has high occupant density similar to New York office. In addition, considering the concentration of air pollutants for different hours of a day, working and non-working hours (see section 2.3), concluded that the average concentrations of CO₂ and PM ₂.₅ during working hours is clearly higher than the average level during non-working hours for all 7 offices. Although the impact of occupant density on the concentration of CO₂ at some offices could be verified, some offices with high rate of area per employee (spaces are not dense) also showed high concentrations of CO₂.

At the Shanghai office, average of PM₂.₅ concentration was recorded at 31.09 µg/m³, which is more than twice the recommended ASHRAE standard of 15 µg/m³ for a year average. The Shanghai office with 13 m² area per employee ranked as the fourth lowest amount among the 25 offices. Of course, the rate is not the main and only reason for this high PM₂.₅ concentrations but informed a high-level of human activity at the location.

Nevertheless, the average level of total VOCs shows diverse trends during working and non-working hours at 7 of the studied offices. In offices like Cleveland-Locations 1and 3, Colorado Springs-Open Office, and Dubai-Open Office, VOCs concentration during working hours is higher than non-working hours while in the Chicago-Open Office and Dallas-Location 2 it is the reverse.

4. Phase Two: levels of indoor air pollutants regarding outside weather conditions

Given the results of Phase One, the second phase of this study investigated the effect of outside weather conditions (temperature and relative humidity) on indoor CO₂ levels as the most indicative indoor air pollutant. Indoor CO₂ levels are an indicator of the adequacy of outdoor air ventilation relative to indoor occupant density and metabolic activity. Basically, using ASHRAE Standard 55 and the PMV (Predicted Mean Vote) model, the zone in which most people are comfortable can be calculated. For people dressed in normal winter clothes, thermal comfort zone maintains effective temperatures of 20°C to 23.3°C measured at 50% relative humidity, which means weather conditions outside of the mentioned range cause the need of mechanical ventilation systems indoors.

Therefore, as the first step of this phase of the study, the average amount of CO₂ concentration for a week (December 1 to 7, 2017) was calculated at three offices. The selected offices are located in two different climate zones based on the Köppen–Geiger climate classification system and are listed below:

- Des Moines, IA which is located in humid continental climate with hot summers and cold winters.
- Houston, TX and Charlotte, NC are classified as humid subtropical climate with hot and humid summers and mild winters.

The week average of CO₂ concentration recorded 525 ppm at Des Moines office, 475 and 465 ppm at Charlotte and Houston offices respectively. Then, the hourly indoor CO₂ levels over the week were plotted in relation to outdoor temperature and relative humidity. Due to the lack of exact weather data for temperature and humidity instantly around the offices, local climate data mainly recorded at airport locations [14] close to each office have been used. Various external factors cause differences in actual temperature around the buildings; however, local climate data satisfy the aim of this phase of the study. The major impact of occupant density on CO₂ concentration has been verified in the previous section. Thus, it was confirmed that the indoor CO₂ concentration during working hours, when buildings were occupied and mechanical ventilation were in operation, were higher than the average amount for the entire week. At the second step, after removing the non-working hours, CO₂ concentration recorded during working hours were plotted in relation to outdoor temperature and humidity in order to observe
any impact of the outdoor conditions on indoor CO\textsubscript{2} level. The aim was to observe how outdoor weather condition changed during the hours in which the recorded CO\textsubscript{2} concentration was higher than the average concentration at each office. Figure 3 shows a sample of this analysis, changes in CO\textsubscript{2} concentration during a work day (Wednesday, December 6 2017) in relation to changes of outdoor humidity at Open Office, Charlotte, NC. Overall, six similar plots were created to study the existing relationship between three offices CO\textsubscript{2} and outdoor temperature and humidity.

![Figure 3. CO\textsubscript{2} Level and Outdoor Humidity at Open Office, Charlotte, NC](image)

5. Results from Phase 2
As a major result of this section, it has been found that indoor CO\textsubscript{2} concentration were directly affected by outdoor weather conditions during a work day at the three selected offices when buildings were occupied and HVAC systems were operated.

For a typical working day at Charlotte office, from 9 am to 4 pm when outdoor temperature fluctuated between 12 and 14 °C and outdoor humidity was higher than 90%, CO\textsubscript{2} concentration showed a range from 550 to 570 ppm. In other words, at the average outdoor temperature of 13 °C from 9 am to 4 pm, 20% increase in outdoor humidity caused 17% rise in CO\textsubscript{2} concentration. On Monday, December 4, outdoor temperature was recorded between 21 and 26 °C, pretty close to comfort zone at the Houston office while minimum relative humidity was recorded at 72% at 2 pm and maximum amount of 100% at 5 pm. In a similar way, the minimum and maximum amounts of CO\textsubscript{2} were recorded at 485 ppm and 520 ppm at 2 and 5 pm respectively. It has been calculated that with the average temperature of 24 °C, moving from 100% to 72% outdoor humidity, every 5% drop caused 4% decrease in CO\textsubscript{2} concentration during working hours at the Houston office. For both offices located in humid subtropical climate, outdoor humidity played a major role in the changes of CO\textsubscript{2} concentrations and higher amount of humidity caused higher indoor CO\textsubscript{2} accumulation.

Over the first week of December 2017, the average temperature was recorded at 5 °C and humidity was 58% in Des Moines. Although humidity around the Des Moines office fluctuated narrowly around the comfort zone, low temperature was obviously playing a major role in manipulating indoor CO\textsubscript{2} level. During working hours on December 4, the minimum amount of CO\textsubscript{2} was recorded at 403 ppm (at 2 pm) when outdoor condition was close to thermal comfort zone i.e. temperature of 21 °C and humidity at 53%. On the same day, the maximum CO\textsubscript{2} concentration was recorded at 482 ppm (at 5 pm) with outdoor temperature of 8 °C and humidity of 58%. It is noticeable that 13 °C drop in outdoor temperature (humidity changes were only 5%) during three hours resulted 79 ppm growth in CO\textsubscript{2} level. While this relationship between outside weather conditions and CO\textsubscript{2} concentration cannot be observed for all days, non-working hours in particular; however, by plotting CO\textsubscript{2} with outside weather conditions sensible impacts of the outside conditions on inside CO\textsubscript{2} concentration can be concluded. In fact, when outdoor conditions differed significantly from comfort zones the CO\textsubscript{2} concentration was influenced as a result of increasing use of Air Conditioning (AC) and higher ventilation rate to provide occupants comfort. Moreover, based on the building climate zones, the impact of temperature and humidity on CO\textsubscript{2} concentration could be different. Humidity changes at locations like Houston and Charlotte offices during a humid and mild December showed significant impacts on CO\textsubscript{2} concentration while during a
slightly cold December at the Des Moines office, temperature could be detected as a major driver of changes in CO2 levels.

6. Conclusion and Future Work
In order to find the source of CO2 in all 25 offices, in addition to occupant density, secondary factors like outside weather conditions need to be considered. In this study, the period of analysis was during cold months, December to February, when heating equipment were operated in all offices. In order to reach more comprehensive results regarding the impact of outdoor weather conditions at different climate zones on indoor pollutants during warm months should be studied next. Moreover, expanding the investigation of the impact of outside weather conditions on CO2 and other air pollutants to other offices will support conclusions from section 5 more accurately.

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