Indoor Air Quality Analysis of Commercial Reference Buildings

Lisa Ng[1]
Amy Musser[2]
Andrew K. Persily[1]
Steven Emmerich[1]

[1]Indoor Air Quality and Ventilation Group, Energy and Environment Division
Engineering Laboratory, National Institute of Standards and Technology
100 Bureau Drive Gaithersburg, MD 20899

[2] Vandemusser Design PLLC

Content submitted to and published by:
Building and Environment
Volume 58: 179-187

U.S. Department of Commerce
Dr. Rebecca M. Blank, Acting Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Director

NIST National Institute of Standards and Technology • U.S. Department of Commerce

DISCLAIMERS

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

Any link(s) to website(s) in this document have been provided because they may have information of interest to our readers. NIST does not necessarily endorse the views expressed or the facts presented on these sites. Further, NIST does not endorse any commercial products that may be advertised or available on these sites.

Abstract

Sixteen commercial reference buildings were created in the multizone airflow and contaminant transport program CONTAM in order to support airflow and indoor air quality (IAQ) analyses, which are not possible using the existing EnergyPlus input files for these buildings. Annual airflow and contaminant simulations were performed in CONTAM for six of the buildings. Contaminant analyses were performed for occupant-generated carbon dioxide (CO_2), volatile organic compounds (VOC) from indoor sources, outdoor particulate matter, and outdoor ozone. In all of the selected buildings and zones, the simulated indoor ozone and PM2.5 concentrations did not exceed indoor limits set by the World Health Organization. For CO_2 and VOC, for which no similarly relevant indoor concentration standards or limits exist, the simulated concentrations were within expected ranges based on published field measurements in commercial buildings. The results of this study provide a baseline for subsequent use of these models to investigate approaches to building ventilation and other technologies that are intended to simultaneously reduce building energy consumption while maintaining or improving indoor air quality.

Keywords: indoor air quality; CONTAM; reference buildings

1. Introduction

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to provide thermally comfortable conditions and to maintain acceptable indoor air quality (IAQ). Sixteen commercial reference buildings, previously defined by the National Renewable Energy Laboratory, were entered into the multizone airflow and contaminant transport program CONTAM in order to support IAQ analyses of these buildings and future evaluations of the IAQ impacts of building design and operation. The 16 reference buildings characterize more than 60 % of the commercial building stock in the U.S. [1]. These reference buildings include 15 commercial buildings and one multi-family residential building. There are three versions (or vintages) of each reference building: new, post-1980, and pre-1980 construction. The three vintages differ in insulation values, infiltration rates, lighting levels, and HVAC system types. The new construction models were developed to comply with the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 [2], the post-1980 models to comply with the minimum requirements of ASHRAE/IES Standard 90.1-1989 [3], and the pre-1980 models to comply with requirements from previous standards and studies of construction practices.

The reference buildings were created to assess new technologies and support the development of energy codes and standards, and therefore their definitions are focused on capturing energy performance, not IAQ. Many discussions of building energy efficiency neglect potential impacts on IAQ or view acceptable IAQ as being in conflict with energy efficiency [4]. However, saving energy at the expense of IAQ has the potential to negatively impact the health, comfort, and productivity of building occupants. Therefore, there is a need to evaluate the IAQ impacts of energy efficiency measures as well as a need for improved modeling capabilities to assess a range of IAQ issues in buildings.

Multizone airflow and contaminant transport models exist and have been used to examine the IAQ impacts of energy efficiency technologies. Persily et al. [5] used CONTAM to show that the use of DCV resulted in 10 % to 80 % energy savings without necessarily compromising certain aspects of IAQ. Carpenter [6] used an airflow-thermal model to show that the use of DCV resulted in 20 % to 30 % energy savings, reduced CO_2 levels, and 50 % to 100 % reduction in formaldehyde concentrations.

The studies above demonstrate the application of multizone airflow and IAQ analyses in in evaluating energy efficiency technologies and other issues. To support airflow and IAQ analyses of the reference buildings, models of the 16 buildings were created (including new, post-1980, and pre-1980 versions) in CONTAM (version 3.0). The availability of the CONTAM models will support the study of technologies and approaches that can simultaneously reduce building energy consumption while maintaining or improving IAQ as well as future studies of a range of commercial building IAQ issues. This paper gives a description of the CONTAM building models and the contaminant simulations performed. The contaminant results are then compared to relevant IAQ guidelines and published field measurements.

2. Building descriptions

This section provides a brief description of the reference buildings; detailed descriptions are available in Deru et al. [1] and Ng et al. [7]. In this paper, contaminant simulations were performed for six of the sixteen reference buildings, representing each type of occupancy covered by the commercial reference buildings. The buildings simulated were: Full Service Restaurant, Hospital, Medium Office, Primary School, Small Hotel, and Stand-Alone Retail. Table 1 lists the six simulated reference buildings and their floor area, number of floors, and number of zones in the CONTAM models. The CONTAM models employ the occupancy and outdoor air ventilation requirements that were defined in the EnergyPlus input files. Details on occupancy schedules and ventilation requirements are found in Ng et al. [7]. In general, the buildings are occupied when the HVAC system is scheduled to be on. Except for the Primary School and Small Hotel, the occupancy in the other buildings is similar among all the zones except for the peak number of occupants. For instance, though the Full Service Restaurant the Kitchen and Dining zones are occupied at the same time, the Dining zone has about 40 times more peak occupants. In contrast, the Primary School has zones with relatively low occupancy for most of the operating day (classrooms), but high occupancy in other zones for a short period of the day (Cafeteria). The differences in occupancy are shown to have an effect on peak and average contaminant concentrations.

3. Modeling approach

CONTAM simulations were performed for the "new" vintages of the reference buildings listed in Table 1 using typical meteorological year, version 2 (TMY2) weather data for Chicago, IL [8]. Building exterior envelope leakage was modeled using an effective leakage area (A_L) of 5.27 cm^2/m^2 at a reference pressure difference (ΔP_r) of 4 Pa, a discharge coefficient (C_D) of 1.0, and a pressure exponent (n) of 0.65 for all three vintages of the reference buildings. The effective leakage area of partitions between floors and between zones used the same value as the exterior wall leakage. The connections between zones that would not have a physical partition, such as within an open office or retail space, were modeled as large openings with discharge coefficient $C_D = 0.6$ and $n = 0.5$. Transfer grilles and door undercuts were modeled between restrooms and adjacent zones. Wind effects were calculated using a wind pressure profile calculated using wind pressure coefficient (C_P) relationships found in Swami and Chandra [9]. A wind speed modifier of 0.36, which corresponds to "suburban" terrain [10], was applied to all exterior leakage paths. This parameter is used in CONTAM to account for the effects of local terrain on the variation of wind speed with height above ground level. For openings on roofs, C_P was -0.5 for all wind directions [11].

The minimum amount of outdoor ventilation air for each zone (or HVAC system) was specified in the EnergyPlus models using ASHRAE 62.1-1999 for all vintages [12], and these values were included in the CONTAM models. Note that the minimum ventilation requirements in the different building vintages may be expected to vary based on the version of ASHRAE 62.1 required by relevant building code at the time. The common design goal of pressurizing commercial buildings was accounted for in the CONTAM models by returning 90 % of the supply airflow rate to the HVAC system. When the outdoor air quantity to a zone was less than 10 % of the supply, the return airflow rate was equal to the supply minus the outdoor airflow rate. For buildings with large exhaust fans, i.e., the two restaurants, the total outdoor air intake was approximately equal to the total exhaust. Details on the supply, return, and outdoor ventilation rates in the CONTAM models can be found in Ng et al. [7].

Contaminant simulations were performed for four contaminants: carbon dioxide (CO_2), ozone, particulates less than 2.5 µm in diameter (PM 2.5), and a generic volatile organic compound (VOC). The VOC is not intended to represent any specific compound or compounds, but rather to represent a generic indoor source associated with materials and occupant activities. PM 2.5 is simulated using a diameter of 0.3 µm, which impacts the deposition rates and filtration efficiency. Outdoor concentrations of ozone and PM 2.5 were downloaded from the U.S. Environmental Protection Agency (EPA) Air Quality Standard (AQS) database [13].

Table 2 lists the minimum, maximum, mean, and standard deviation of the outdoor concentration of ozone and PM 2.5 for Chicago, IL. Based on the 2010 ozone data from the EPA database for Chicago, there were only 4 hours during the year for which the outdoor ozone level exceeded the National Ambient Air Quality Standards (NAAQS) limit of 150 $\mu g/m^3$ averaged over 8 hours

[14]. Based on the 2010 PM 2.5 data, there were 868 hours during the year for which the outdoor PM 2.5 level exceeded the NAAQS limit of 35 μg/m^3 averaged over 24 hours [14]. The outdoor concentrations of CO_2 and VOC were assumed to be constant at 648 mg/m^3 and zero respectively.

Indoor contaminant sources included occupant-generated CO_2 and VOCs from materials and occupant activities. A CO_2 source was defined in all occupied zones, with an assumed generation rate of 0.3 L/min per person [15]. The CO_2 source strengths in the CONTAM models varied with occupancy based on schedules in the EnergyPlus models. Detailed occupancy schedules for each building are found in Ng et al. [7]. An area-based VOC source was defined in all occupied building zones. In occupied zones, a 0.5 mg/m^2•h source was included during system-on hours and reduced by 50 % during system-off hours [5]. Note that this VOC source strength is not intended to characterize emissions in any specific building but rather to serve as a reasonable value for the purposes of these simulations, providing the ability to compare predicted VOC levels for different cases of building configuration and ventilation system design and operation. Nevertheless, the assumed source strength is consistent with experimental studies in an office building where total VOC source strengths of 0.2 mg/m^2•h to 0.4 mg/m^2•h from building materials, and 0.1 mg/m^2•h to 1.5 mg/m^2•h from occupant activities, were estimated from measured VOC concentrations and ventilation rates [16]. Levin [17] reported total VOC emission rates of 0.5 mg/m^2•h to 1.5 mg/m^2•h for several typical, i.e., not designed with low-emitting materials, buildings. In the CONTAM reference building models, zones that were assumed to be always unoccupied, such as restrooms and stairwells, had no VOC source. Deposition rates of 0.5 h^{-1} for PM 2.5 [18-20] and 4.0 h^{-1} for ozone [21-24] were included in every zone, whether occupied or unoccupied. No indoor sources were included for ozone or PM 2.5.

A constant efficiency filter was placed in both the outdoor and recirculation air streams of all HVAC systems in the CONTAM models to represent a filter placed in the mixed air stream. The filter removed ozone at 5 % efficiency [25] and removed PM 2.5 at 25 % efficiency, corresponding to filters with a Minimum Efficiency Reporting Value (MERV) of 6 as required in ASHRAE Standard 62.1-2010 [15, 26]. A penetration factor of one was assumed for both ozone [21, 27] and PM 2.5 [18, 28, 29], i.e., there was no removal of these contaminants as they entered the building through the exterior envelope.

4. Contaminant simulation results

This section presents the contaminant simulation results for system-on hours only.
Table 3 lists the building zones for which contaminant results are presented, including the maximum occupancy in each. The total zone occupancy divided by the zone floor area and the average outdoor air intake per person for the zones are also listed. The zones were selected to represent different occupancy types and densities within the building. Zones were also selected based on their being exposed to different weather-induced pressures and thus having different

airflows. For instance, in the Medium Office, the West and South Perimeter zones were selected since each is facing a different cardinal direction, and thus may be exposed to different weather-induced pressures. In the Medium Office and Small Hotel, similar zones were selected on different floors in order to observe the differences in contaminant concentrations due to different weather-induced pressures and airflow. As seen in Table 3, the highest occupancy density is in the Full Service Restaurant, with the values in the Hospital and Medium Office almost a factor of ten lower. The outdoor air intake rates per person are similar for all the buildings, except for the Hospital, for which they are much higher due to the higher ventilation requirements in healthcare facilities.

The results of the contaminant simulations are summarized in Table 4, which lists the minimum and maximum daily average and daily peak concentration for each contaminant considering only the zones listed in Table 3. Thus, the values in Table 4 are not overall building minimum and maximum concentrations but only reflect the selected zones. It should also be noted that the daily averages are calculated for the system-on hours, which are different among the buildings. Detailed minima, maxima, means and standard deviations of the indoor concentrations for each zone in each building can be found in Ng et al. [7]. Figure 1 to Figure 3 show the frequency distributions of CO_2 concentration for the Full Service Restaurant, Medium Office, and Primary School for the zones in Table 3 for an entire year. Similar plots for CO_2, ozone, PM 2.5, and VOC for the other buildings can be found in Ng et al. [7]. Figure 4 shows the time-variation of VOC concentration in two zones of the Medium Office.

Table 4 shows that among the simulated buildings, the indoor CO_2 concentrations are similar except in the Full Service Restaurant where CO_2 concentrations are noticeably higher. The Full Service Restaurant has the highest CO_2 concentrations among the simulated buildings primarily because it has the lowest value of outdoor air intake per floor area as reflected by the ratio of the outdoor airflow per person to the occupant density (based on the last two columns of Table 3). The Full Service Restaurant is the only building for which a daily system-on peak value exceeds 1800 mg/m^3, which is a common benchmark for CO_2 though is not an actual guideline value based on health concerns [30]. Note that while this benchmark value can be useful for evaluating outdoor air ventilation rates per occupant, its use and interpretation must be done with care and an appreciation of the relationship bettween indoor CO_2 levels and ventilation [30]. In a study of 41 office buildings, Apte et al. [31] found that the 95th percentile indoor-outdoor CO_2 concentration difference to be 604 mg/m^3 averaged over a "workday", which was a different number of hours among the buildings. Adding the assumed outdoor CO_2 concentration of 648 mg/m^3 in the current study to this value yields a concentration of 1252 mg/m^3. The California Energy Commission (CEC) study of 37 small and medium-sized commercial buildings reported an average 95th percentile CO_2 concentration of 1500 mg/m^3 [32].

The frequency distributions of CO_2 concentration for the Full Service Restaurant, Medium Office, and Primary School are discussed below. Figure 1 shows the frequency distributions of CO_2 concentration for the Full Service Restaurant. Similar plots for the other buildings can be found in Ng et al. [7]. Although the peak occupancy of the Kitchen in the Full Service Restaurant is 40 times less than that of the Dining zone, Figure 1 shows that the CO_2 concentrations differ by a much smaller fraction. This is due to the large amount of air transferred from the Dining zone to the Kitchen. Figure 2 shows that for the Medium Office, the daily averages and peaks of CO_2 concentrations are more similar among the selected zones than in the Full Service Restaurant and Primary School. The highest CO_2 concentrations in the Medium Office tend to occur in the zones on the third (or top) floor, though the differences in concentrations with the zones on the first and second floors are not large, only 100 mg/m^3 to 200 mg/m^3. Figure 3 shows that for the Primary School, there is greater spread in CO_2 concentrations among the selected zones than in the Full Service Restaurant and Medium Office due to wider variations in occupant density and schedule in the Primary School. For instance, the Cafeteria has some of the highest peak CO_2 concentrations but among the lowest average CO_2 concentrations. This is because the Cafeteria is highly occupied only a few hours of the day. In contrast, the other zones are more regularly occupied throughout the day so that the daily averages and peaks are more similar to each other. The daily average and peak CO_2 concentrations are higher in the Mult Class 1 zone than the Corner Class 1 zone because the Mult Class 1 zone has about five times the peak number of occupants.

The Full Service Restaurant and Primary School are among the buildings with the highest indoor ozone and PM 2.5 concentrations based on trends in the concentration distribution that are not completely reflected in Table 4, but which are described in detail in Ng et al. [7]. The only source of ozone and PM 2.5 is the outdoor air, making the outdoor air change and interior depostion rates the key parmaters in determining the indoor concentrations. Note that the modeled indoor deposition rates are related to zone size. The higher indoor ozone and PM 2.5 concentrations in these two buildings occur primarily due to the higher mean system-on air change rates, 4.83 h^{-1} and 1.88 h^{-1} respectively, that bring in more ozone and PM 2.5 faster. Thus, there tend to be more hours of the year in which high ozone and PM 2.5 concentrations exist in the Full Service Restaurant and Primary School. In contrast, the Hospital and Medium Office are among the buildings with the lowest indoor ozone and PM 2.5 concentrations. This is due primarily to the lower mean system-on air change rates, 0.91 h^{-1} and 0.68 h^{-1} respectively. The World Health Organization (WHO) indoor guideline for ozone is 100 μg/m^3 over an average of eight hours [33]. More recently, an ASHRAE Emerging Issue brief reported that levels as low as 40 μg/m^3 have been shown to increase mortality [34]. There were no hours for which the indoor ozone level exceeded 100 μg/m^3 in any of the selected zones. Table 4 shows that of the selected zones in the simulated buildings, the maximum daily peak ozone concentration was 98 μg/m^3. However, the number of hours the indoor ozone level exceeded 40 μg/m^3, was different in each simulated building. It ranged from five hours in the Medium Office to 1776 hours in the Meeting Room in the Small Hotel.

The WHO indoor guidelines for PM 2.5 are given as multiple levels to steadily reduce PM 2.5 to 10 μg/m^3 over time, based on exposure studies of long-term health effects. Currently, the maximum allowable level of PM 2.5 is 35 μg/m^3 for an annual mean [33]. Table 2 shows that for Chicago, the annual mean outdoor PM 2.5 concentration is 18 μg/m^3. The annual mean indoor PM 2.5 concentration in all buildings was less than 18 μg/m^3. The Cafeteria in the Primary School had the highest annual mean PM 2.5 concentration of 16 μg/m^3. The number of individual hours the indoor PM 2.5 level exceeded 35 μg/m^3 was different in each simulated building. It ranged from no hours (Medium Office and Hospital) to 220 hours (Cafeteria zone in the Primary School). The number of hours the indoor PM 2.5 level exceeded 10 μg/m^3 was different in each simulated building. It ranged from over 200 hours in the Medium Office to over 4000 hours in the Full Service Restaurant and Small Hotel. For comparison, Bennett et al. [32] reported the PM 2.5 concentrations in the BASE study to be between 2 μg/m^3 and 24 μg/m^3, and in the CEC study to be between 3 μg/m^3 and 21 μg/m^3 [32].

Considering general trends in the concentration distribution (details in Ng et al. [7]) that are not completely reflected in Table 4, the Hospital and Medium Office have the highest indoor VOC concentrations (243 μg/m^3 and 812 μg/m^3, respectively). Because the VOC sources are area-based, the primary factor in determining the indoor concentrations are the outdoor air intake rates per unit floor area, with the Hospital and Medium Office have the lowest values of the outdoor air intake per floor area. In contrast, the Primary School, Small Hotel, and Stand-Alone Retail have higher outdoor air intake rates per floor area, leading to lower indoor VOC concentrations (15 μg/m^3 to 20 μg/m^3 daily averages). Persily et al. [16] measured VOC concentrations in a two-story office building using a measurement method that yielded a total VOC conentration calibrated with toluene. The researchers measured concentrations as high as 700 μg/m^3 where the VOC emission rates, estimated from VOC concentrations and measured ventilation rates, were similar to the ones assumed in this paper. In the BASE study, 48 indivdiual VOCs were measured in 56 buildings with concentrations ranging from 0.2 μg/m^3 to 450 μg/m^3 [35]. Note that the maximum VOC concentrations shown in Table 4 occur during system-off hours as seen in Figure 4 for two zones in the Medium Office. These figures show that there is a build-up of VOC during the system-off hours. Once the system is on and the building is occupied, the ventilation system reduces the VOC concentration up to one-fifth the maximum concentration.

5. Discussion

The development of the CONTAM models of the reference buildings and their application to airflow and contaminant transport analyses described in this paper will support future studies of ventilation and IAQ. However, their development presented a number of issues and presented a number of challenges that merit discussion and should be addressed in the future.

One key issue is that building models developed for performing airflow and IAQ analyses employ different building representations and require different data than those used for energy analyses. CONTAM, and other multizone airflow and IAQ models, consider buildings as networks of interconnected zones. Airflow rates are then calculated based on physical relationships between flow and pressure analogous to the relationship between heat transfer and temperature differences in energy models. Thus, it is important that multizone building airflow models capture the pressure network of buildings, which are a function of building geometry, exposure to the outdoors, interzone leakages, and HVAC system airflows. In contrast, building models for energy analysis are focused on accounting for thermal loads of different building zones, system efficiencies in meeting these loads, and selecting equipment types and sizes. While building geometry, exposure to the outdoors, and HVAC system flows are also important in energy calculations, the zones modeled are based on the similarity and differences between their thermal loads. Therefore, these thermal zones may not be the same as the zones needed for properly modeling building airflow, as was the case in this effort. When performing IAQ simulations, the building models need to include zones containing key contaminant sources and need to capture important airflow paths for contaminant transport in the building.

In addition, there are a number of limitations to the CONTAM models that need to be considered and potentially addressed in the future. To simplify CONTAM modeling, the maximum supply airflow rates calculated by EnergyPlus were used in the CONTAM models. Therefore, variable-air volume (VAV) system effects were not included. Also, the CONTAM simulations maintained a constant indoor temperature and used the minimum amount of outdoor ventilation air specified in EnergyPlus for each zone (or HVAC system) with no economizer cycle. Thus, future applications of these models would likely benefit from more complete HVAC system modeling, given the importance of HVAC operation in relation to contaminant concentrations.

When using multizone models to conduct IAQ simulations for evaluating different buildings and design approaches, the manner in which to present the simulation results is challenging. IAQ simulations conducted over a year, or any significant period of time, in a multizone building produce a large amount of data. Running such simulations for different conditions of building operation, source strengths, weather conditions and/or other parameters quickly multiplies the amount of data produced. Converting these data into understandable formats and drawing useful conclusions is difficult, and there are no standard approaches for doing do.

Another challenging aspect of analyzing IAQ simulation results is the comparison of the predicted concentrations to meaningful reference values, given the lack of such reference or limit values for most indoor contaminants. As discussed in Section 4, two of the simulated contaminant concentrations (ozone and PM 2.5) were compared with the NAAQS outdoor air limits and WHO indoor air guidelines. However, the other contaminants simulated, CO_2 and VOCs, do not have guidelines for comparison, let alone formalized, health-based limits. The same lack of concentration limits is also the case for many other indoor air contaminants. As noted in Persily and Emmerich [4], the diversity of occupants and contaminants and the lack of guidelines for exposure limits to the numerous contaminants present in buildings means that IAQ cannot not be judged as good or bad in terms of contaminant concentration(s) alone. Unlike energy consumption or thermal comfort, which can be quantified in terms of well-defined parameters, the complex interaction of ventilation rates, contaminant sources, interaction and removal mechanisms, and occupant behavior make the evaluation of IAQ extremely challenging.

The need for IAQ metrics has been considered previously but no set of metrics has been accepted. TenBrinke et al. [36] correlated results of occupant surveys with total VOC levels. Hollick and Sangiovanni [37] developed a metric that accounted for the effects of human health and comfort on individuals by various contaminants. Sofuoglo and Moschandreas [38] aggregated the concentrations of eight contaminants and correlated the resulting metric with occupant surveys to determine an Indoor Air Pollution Index (IAPI). Jackson et al. [39] based their assessment of IAQ on the potential health risk of VOC exposure to occupants. Catalina and Iordache [40] proposed an index that incorporated energy consumption, visual comfort, acoustics, and air change rate, but did not consider contaminant concentrations. It is not yet possible to say which IAQ metric is most useful based on their limited application and fundamentally because each situation is different. Thus, the development of an IAQ metric, or perhaps multiple metrics, that is widely applicable to a range of buildings is still a major need.

5.1. Future work

The EnergyPlus and CONTAM models of the reference buildings serve as baseline cases, which can be used in future analyses to support the design and implementation of strategies to simultaneously reduce building energy use while maintaining or improving IAQ, such as alternative ventilation approaches (heat recovery, demand control ventilation, economizers), enhanced filtration and contaminant source control. However the analysis of these and other approaches can be limited by the inability of current simulation tools to model building airflow and contaminants in a physically reasonable fashion.

Given that this study considered a limited set of contaminants, future work should include additional contaminants, including those that are unique to specific building types. For example, particles from cooking in the Full Service Restaurant and infectious biological agents in the Hospital both merit attention. There are also numerous other contaminants that are known to affect occupant health and comfort, such as carbon monoxide, formaldehyde and individual VOCs [33, 41] that were not simulated in this study. In addition, future simulations would likely benefit from more accurate consideration other transport mechanisms, such as particle deposition and absorption/desorption of VOCs.

6. Conclusion

Sixteen commercial reference buildings were created in the multizone airflow and contaminant transport program CONTAM to support physically-based airflow calculations, as well as IAQ analyses, that are not possible using the existing EnergyPlus input files. Six of the reference buildings, representing each type of occupancy covered by the 15 commercial reference buildings (excluding the Midrise Apartment building), were selected for annual airflow and contaminant simulations.

In all of the selected buildings and zones, the simulated indoor ozone concentrations did not exceed limits set by WHO. No simulated buildings exceeded the WHO annual indoor limit of 35 μg/m^3 for PM 2.5, though this limit was exceeded in less than 5 % of the individual hours in a year. For CO_2 and VOC, for which no similarly relevant indoor concentration standards or limits exist, the simulated concentrations were within expected ranges based on published field measurements of commercial buildings. Note that the IAQ simulations in this study only used a limited set of contaminants and relatively constant source strengths. Additional simulations of other contaminants and source strengths, as well as IAQ control technologies, are needed to better understand a range of important IAQ issues.

The EnergyPlus and CONTAM models of the reference buildings serve as baseline cases, which will be useful in future analyses to support the design and implementation of alternative ventilation and IAQ control approaches that can simultaneously reduce building energy use while maintaining or improving IAQ.

7. Acknowledgements

The authors would like to thank Michael Deru, Brent Griffith, and Kristin Field from the National Renewable Energy Laboratory for their support in understanding the EnergyPlus files of the reference buildings. The authors would also like to thank Barney Burroughs and Charles Weschler for their support in determining inputs for the contaminant simulations.

8. References

[1] Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, Liu B, Halverson M, Winiarski D, Rosenberg M, Yazdanian M, Huang J, Crawley D. U.S. Department of Energy Commercial Reference Building Models of the National Building Stock. NREL/TP-5500-46861. Colorado: National Renewable Energy Laboratory; 2011.

[2] ASHRAE. ANSI/ASHRAE/IESNA Standard 90.1-2004: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2004.

[3] ASHRAE. ASHRAE/IES Standard 90.1-1989: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 1989.

[4] Persily AK, Emmerich SJ. Indoor Air Quality in Sustainable, Energy Efficient Buildings. HVAC&R Res 2012;18(1):1-17.

[5] Persily AK, Musser A, Emmerich SJ, Taylor AW. Simulations of Indoor Air Quality and Ventilation Impacts of Demand Controlled Ventilation in Commercial and Institutional Buildings. NISTIR 7042. Gaithersburg: National Institute of Standards and Technology; 2003.

[6] Carpenter SC. Energy and IAQ Impacts of CO_2-based Demand-Controlled Ventilation. ASHRAE Tran 1996;102(2):80-88.

[7] Ng LC, Musser A, Emmerich SJ, Persily AK. Airflow and Indoor Air Quality Models of DOE Reference Commercial Buildings. Technical Note 1734. Gaithersburg, MD: National Institute of Standards and Technology; 2012.

[8] DOE. Commercial Reference Buildings. 2011 [cited 2011; Available from: http://www1.eere.energy.gov/buildings/commercial_initiative/reference_buildings.html.

[9] Swami MV, Chandra S. Procedures for calculating natural ventilation airflow rates in buildings. FSEC-CR-163-86. Florida: Florida Solar Energy Center; 1987.

[10] Walton GN, Dols WS. CONTAM User Guide and Program Documentation. NISTIR 7251. Gaithersburg: National Institute of Standards and Technology; 2005.

[11] ASHRAE. ASHRAE Handbook Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2009.

[12] ASHRAE. ASHRAE Standard 62-1999: Ventilation For Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 1999.

[13] EPA, Air Quality System Data Mart. 2011, U.S. Environ. Prot. Agency.

[14] EPA. National Ambient Air Quality Standards (NAAQS). Washington: U.S. Environmental Protection Agency; 2011.

[15] ASHRAE. ANSI/ASHRAE Standard 62.1-2010: Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2010.

[16] Persily A, Howard-Reed C, Nabinger SJ. Transient analysis of volatile organic compound concentrations for estimating emission rates. Atmos Environ 2003;37(39):5505-5516.

[17] Levin H, Emissions Testing Data and Indoor Air Quality, in Proceedings of 2nd International Conference on Indoor Air Quality, Ventilation, and Energy Conservation in Buildings, F. Haghighat, Editor. 1995: Montreal, Canada. p. 465-482.

[18] Allen R, Larson T, Sheppard L, Wallace L, Liu LJS. Use of Real-Time Light Scattering Data To Estimate the Contribution of Infiltrated and Indoor-Generated Particles to Indoor Air. Environ Sci Technol 2003;37(16):3484-3492.

[19] Howard-Reed C, Wallace LA, Emmerich SJ. Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse. Atmos Environ 2003;37(38):5295-5306.

[20] Riley WJ, McKone TE, Lai ACK, Nazaroff WW. Indoor Particulate Matter of Outdoor Origin: Importance of Size-Dependent Removal Mechanisms. Environ Sci Technol 2002;36(2):200-207.

[21] Weschler CJ, Shields HC, Naik DV. Indoor Ozone Exposures. J Air Pollut Control Assoc 1989;39(12):1562-1568.

[22] Weschler CJ. Ozone in Indoor Environments: Concentration and Chemistry. Indoor Air 2000;10(4):269-288.

[23] Kunkel DA, Gall ET, Siegel JA, Novoselac A, Morrison GC, Corsi RL. Passive reduction of human exposure to indoor ozone. Build Environ 2010;45(2):445-452.

[24] Nazaroff WW, Gadgil AJ, Weschler CJ. Critique of the use of deposition velocity in modeling indoor air quality. Proceedings of Modeling of Indoor Air Quality and Exposure. Pittsburgh, PA, USA: American Society for Testing and Materials; 1993.

[25] Bekö G, Halás O, Clausen G, Weschler CJ. Initial studies of oxidation processes on filter surfaces and their impact on perceived air quality. Indoor Air 2006;16(1):56-64.

[26] Kowalski WJ, Bahnfleth WP. MERV filter models for aerobiological applications. Air Media 2002;Summer(2002):13-17.

[27] Liu D-L, Nazaroff WW. Modeling pollutant penetration across building envelopes. Atmos Environ 2001;35(26):4451.

[28] Tian L, Zhang G, Lin Y, Yu J, Zhou J, Zhang Q. Mathematical model of particle penetration through smooth/rough building envelope leakages. Build Environ 2009;44(6):1144-1149.

[29] Thornburg J, Ensor DS, Rodes CE, Lawless PA, Sparks LE, Mosley RB. Penetration of Particles into Buildings and Associated Physical Factors. Part I: Model Development and Computer Simulations. Aerosol Sci Technol 2001;34(3):284 - 296.

[30] Persily AK. Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. ASHRAE Tran 1997;103(2):193-204.

[31] Apte MG, Fisk WJ, Daisey JM. Associations Between Indoor CO_2 Concentrations and Sick Building Syndrome Symptoms in U. S. Office Buildings: An Analysis of the 1994-1996 BASE Study Data. Indoor Air 2000;10(4):246-257.

[32] Bennett DH, Apte M, Wu XM, Trout A, Faulkner D, Maddalena RL, Sullivan DP. Indoor Environmental Quality and Heating, Ventilating, and Air Conditioning Survey of Small and Medium Size Commercial Buildings: Field Study. CEC-500-2011-043. California Energy Commission; 2011.

[33] WHO. Air Quality Guidelines: Global Update 2005. Denmark: World Health Organization Europe; 2005.

[34] ASHRAE. Environmental Health Committee (EHC) Emerging Issue - Ozone and Indoor Chemistry. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2011.

[35] Girman JR, Hadwen GE, Burton LE, Womble SE, McCarthy JF. Individual Volatile Organic Compound Prevalence and Concentrations in 56 Buildings of the Building Assessment Survey and Evaluation (BASE) Study. Proceedings of Indoor Air 1999; 1999.

[36] Brinke JT, Selvin S, Hodgson AT, Fisk WJ, Mendell MJ, Koshland CP, Daisey JM. Development of New Volatile Organic Compound (VOC) Exposure Metrics and their Relationship to "Sick Building Syndrome" Symptoms. Indoor Air 1998;8(3):140-152.

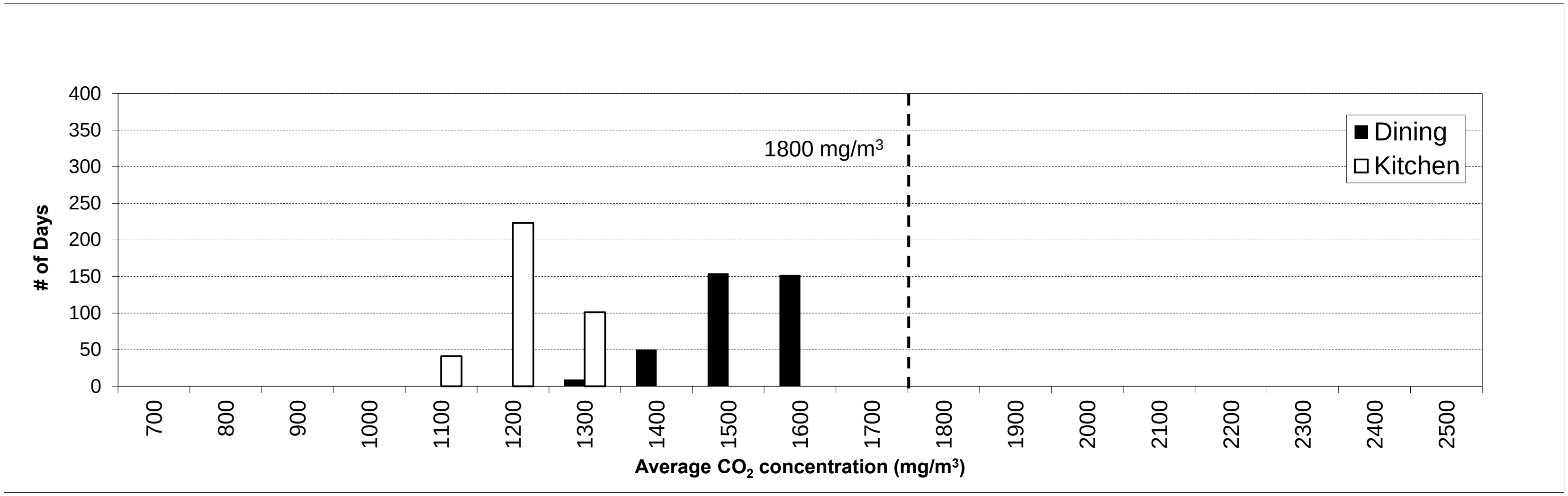
[37] Hollick HH, Sangiovanni JJ, A Proposed Indoor Air Quality Metric for Estimation of the Combined Effects of Gaseous Contaminants on Human Health and Comfort, in Air Quality and Comfort in Airliner Cabins, ASTM STP1393, N.L. Nagda, Editor. 2000, American Society for Testing and Materials: Philadelphia. p. 319.

[38] Sofuoglu SC, Moschandreas DJ. The link between symptoms of off ice building occupants and in-office air pollution: the Indoor Air Pollution Index. Indoor Air 2003;13(4):332-343.

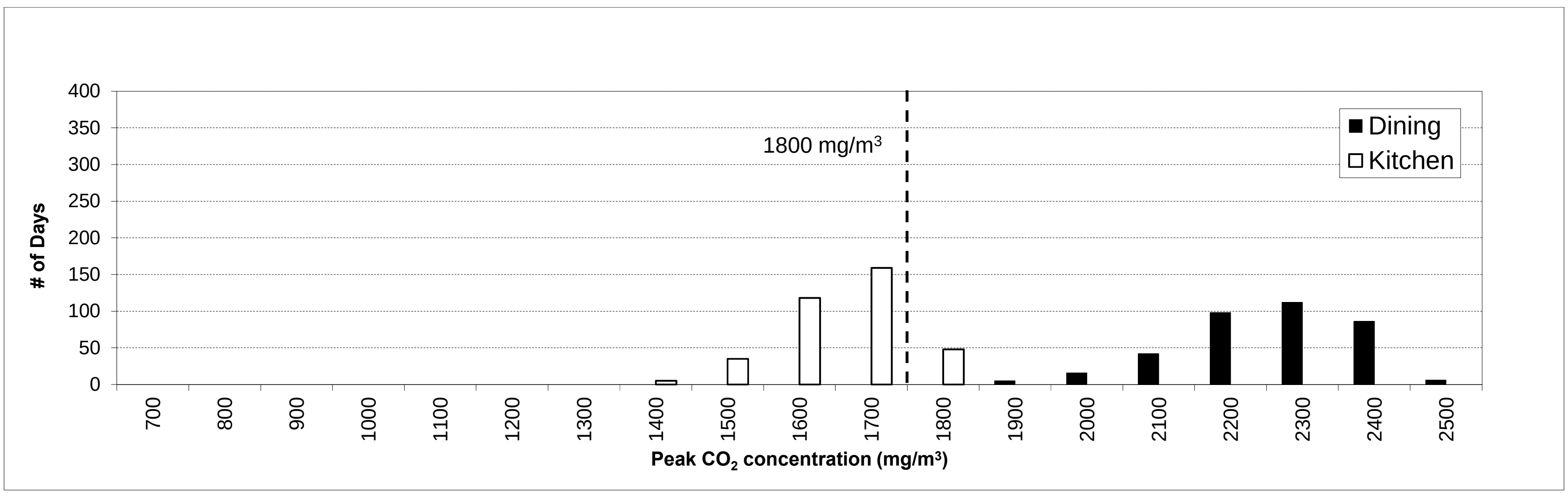
[39] Jackson MC, Penn RL, Aldred JR, Zeliger HI, Cude GE, Neace LM, Kuhs JF, Corsi RL, Comparison of metrics for characterizing the quality of Indoor air, in Indoor Air 2011, I.S.I.A.Q. Clim., Editor. 2011, International Society of Indoor Air Quality and Climate: Austin, TX.

[40] Catalina T, Iordache V. IEQ assessment on schools in the design stage. Build Environ 2012;49(0):129-140.

[41] WHO. WHO guidelines for indoor air quality: selected pollutants. Denmark: World Health Organization Europe; 2010.



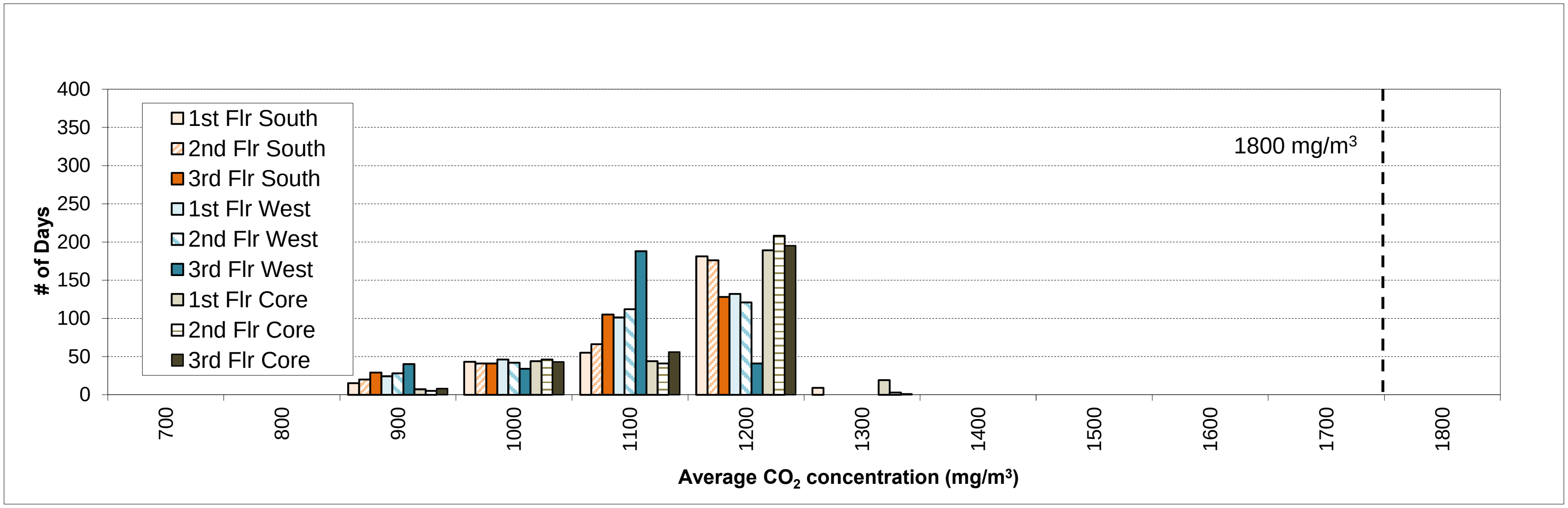
(a) Daily averages



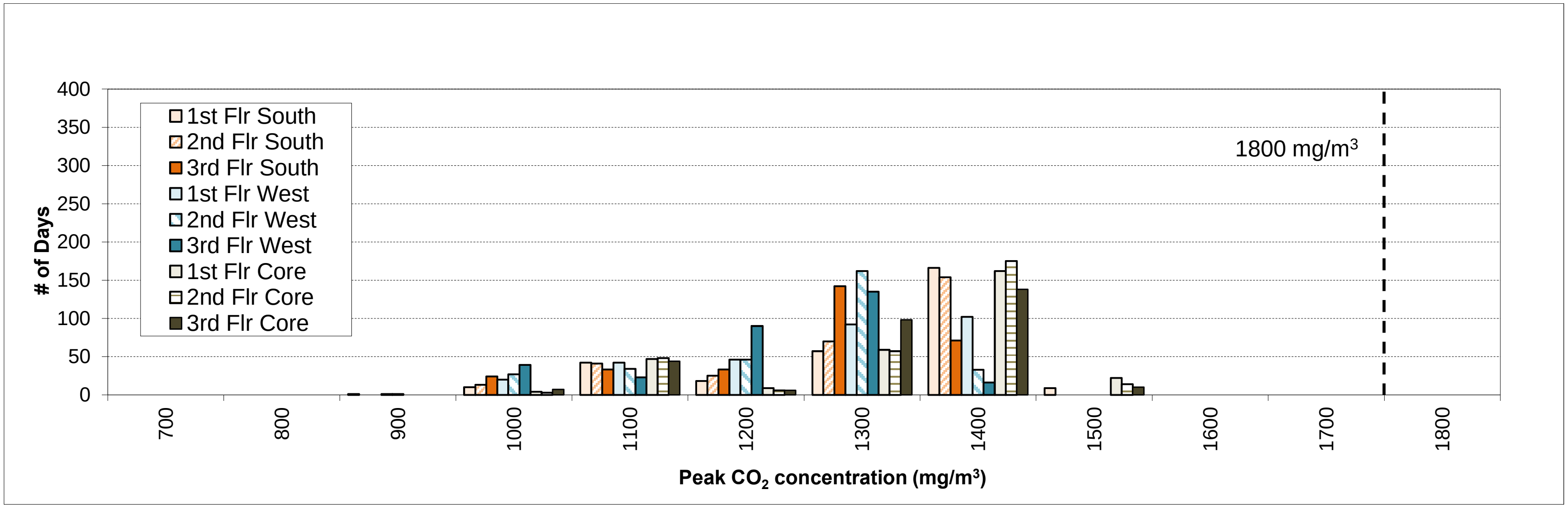
(b) Daily peaks

1800 mg/m^3 is a common benchmark for CO_2 though is not an actual guideline value based on health concerns [30]

Figure 1 Frequency distribution of simulated CO_2 concentration for Full Service Restaurant



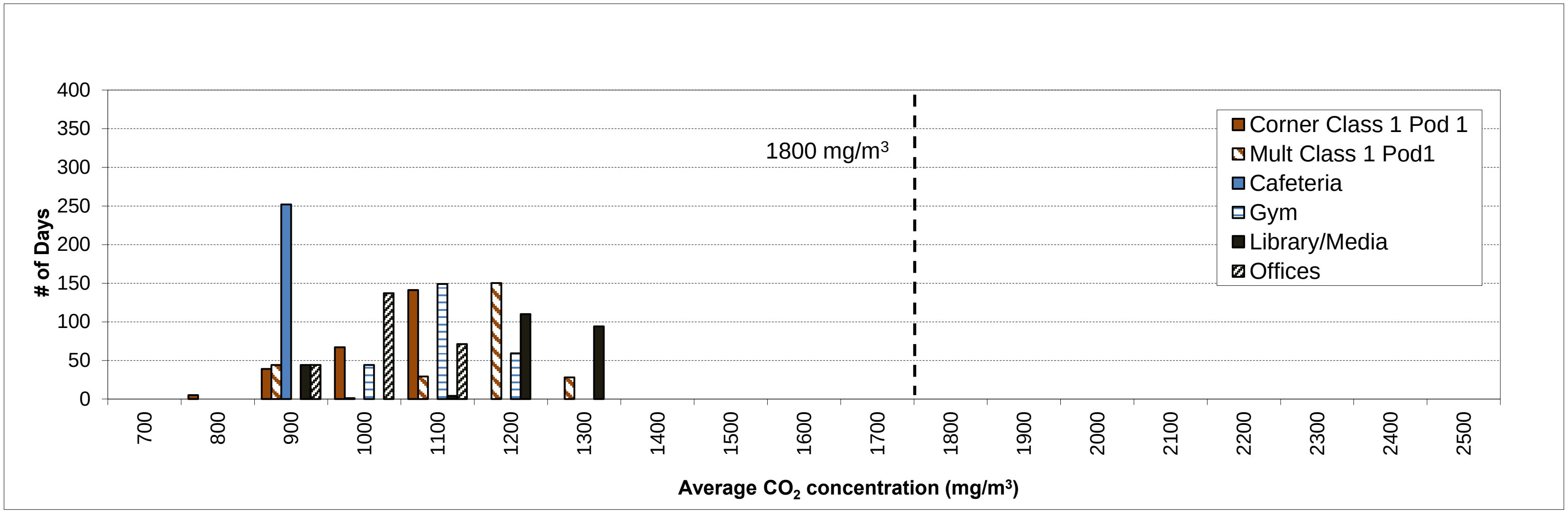
(a) Daily averages



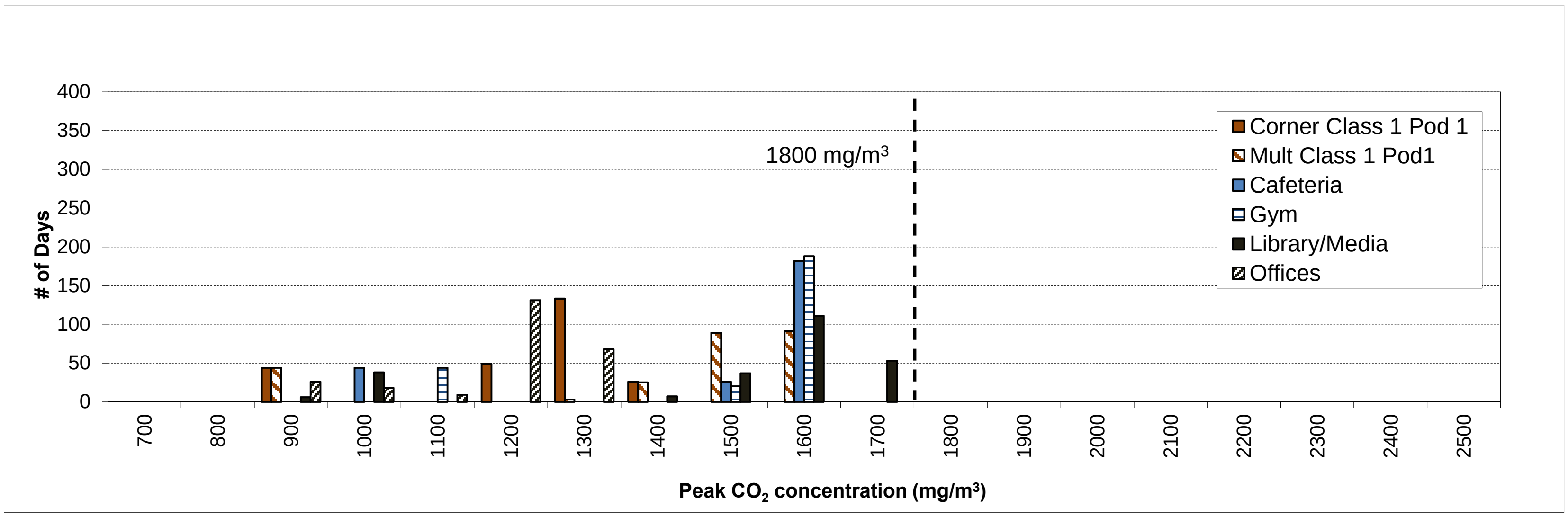
(b) Daily peaks

1800 mg/m^3 is a common benchmark for CO_2 though is not an actual guideline value based on health concerns [30]

Figure 2 Frequency distribution of simulated CO_2 concentration for Medium Office



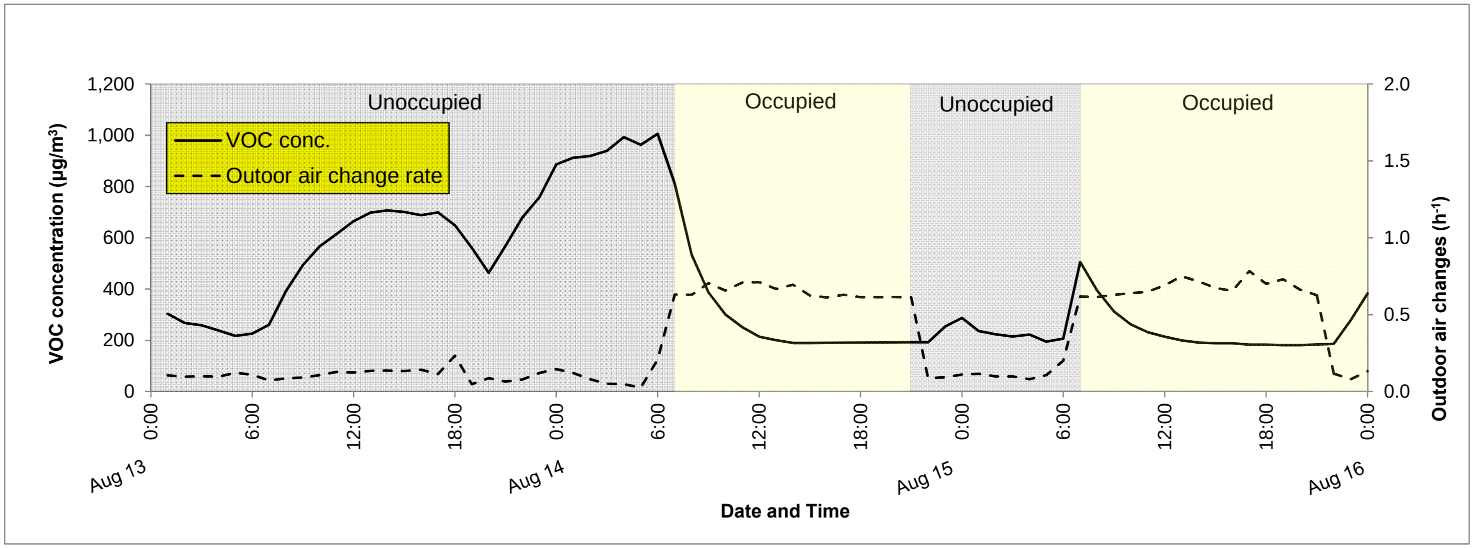
(a) Daily averages



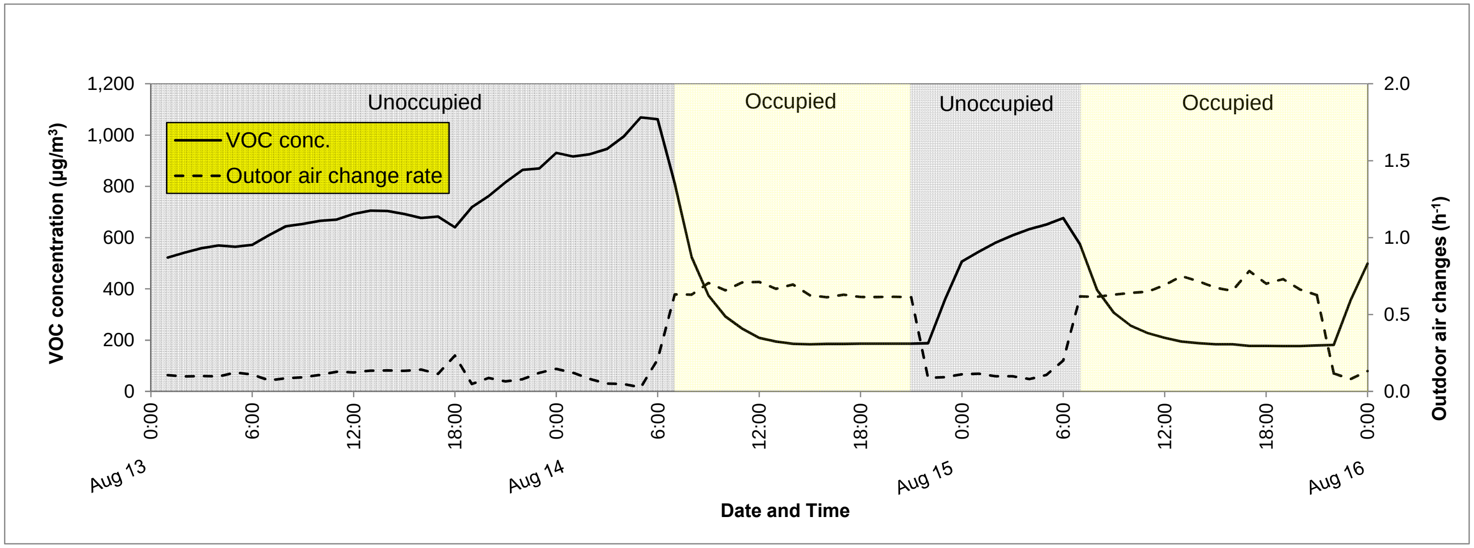
(b) Daily peaks

1800 mg/m^3 is a common benchmark for CO_2 though is not an actual guideline value based on health concerns [30]

Figure 3 Frequency distribution of simulated CO_2 concentration for Primary School



(a) First floor South zone



(b) First floor Core zone

Figure 4 Time variation of VOC concentration for Medium Office

Table 1 Summary of reference buildings

Building	Floor area (m^2)	No. of floors	No. of CONTAM zones
Full Service Restaurant	511	1	3
Hospital	22422	6	64
Small Hotel	4013	4	67
Medium Office	4982	3	23
Primary School	6871	1	25
Stand-Alone Retail	2294	1	6

Table 2 Summary of outdoor contaminant concentrations for Chicago

Outdoor contaminant	Daily average contaminant concentrations (μg/m^3)				Daily peak contaminant concentrations (μg/m^3)			
	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
Ozone	47	6	106	21	80	12	155	29
PM 2.5	18	1	57	10	30	4	94	14

Table 3 Selected zones for which contaminant concentration results reported

Building	Selected zones		Maximum occupancy in selected zones[1]	Maximum occupancy per floor area (per 100 m^2)[1]	Average outdoor air intake (L/s•person)[2]
Full Service Restaurant	Dining	Kitchen	274	55	10.0
Hospital	1F ER Exam 3 1F ER Nurse's Station 1F Lobby 2F ICU 2F ICU Patient Rm 3 2F Operating Rm 2	3F Lab 3F Nurse's Station Lobby 3F Patient Rm 3 3F Patient Rm 4 5F Dining 5F Office 2	259	4	27.1
Medium Office	1-3F Core Zone 1-3F West Perimeter	1-3F South Perimeter	213	6	11.9
Primary School	Cafeteria Gym Library/Media Classroom	Offices Pod 1 Corner Classroom 1 Pod 1 Multiple Classroom 1	591	29	9.4
Small Hotel	Front Lounge Meeting Room Guest 209-212 Guest 309-312	Guest 409-412 Guest 215-218 Guest 315-318 Guest 415-318	129	13	9.2
Stand-Alone Retail	Back Space Core Retail	Front Retail Point of Sale	321	14	9.8

Notes:

1. Maximum occupancy and occupancy per floor area are based only on the selected zones.
2. Values are sum of L/s supplied to all of the selected zones divided by the sum of the number of occupants in the selected zones.

Table 4 Summary of calculated contaminant concentrations

Full Service Restaurant	Daily average contaminant concentrations		Daily peak contaminant concentrations	
	Min.	**Max.**	**Min.**	**Max.**
CO_2, mg/m^3	1020	1579	1352	2433
Ozone, µg/m^3	3	62	5	86
PM 2.5, µg/m^3	1	42	2	61
VOC, µg/m^3	27	62	31	343
Hospital	**Daily average contaminant concentrations**		**Daily peak contaminant concentrations**	
	Min.	**Max.**	**Min.**	**Max.**
CO_2, mg/m^3	749	991	759	1145
Ozone, µg/m^3	1	40	1	58
PM 2.5, µg/m^3	<1	24	1	33
VOC, µg/m^3	38	242	42	243
Medium Office	**Daily average contaminant concentrations**		**Daily peak contaminant concentrations**	
	Min.	**Max.**	**Min.**	**Max.**
CO_2, mg/m^3	826	1219	887	1416
Ozone, µg/m^3	1	34	2	57
PM 2.5, µg/m^3	<1	23	1	32
VOC, µg/m^3	75	291	104	812
Primary School	**Daily average contaminant concentrations**		**Daily peak contaminant concentrations**	
	Min.	**Max.**	**Min.**	**Max.**
CO_2, mg/m^3	793	1279	820	1683
Ozone, µg/m^3	2	74	5	98
PM 2.5, µg/m^3	<1	52	1	68
VOC, µg/m^3	15	172	34	1186

Small Hotel	**Daily average contaminant concentrations**		**Daily peak contaminant concentrations**	
	Min.	**Max.**	**Min.**	**Max.**
CO_2, mg/m^3	759	1054	847	1363
Ozone, µg/m^3	1	61	1	89
PM 2.5, µg/m^3	<1	41	1	60
VOC, µg/m^3	16	282	22	306
Stand-Alone Retail	**Daily average contaminant concentrations**		**Daily peak contaminant concentrations**	
	Min.	**Max.**	**Min.**	**Max.**
CO_2, mg/m^3	741	1173	757	1486
Ozone, µg/m^3	1	43	2	68
PM 2.5, µg/m^3	<1	32	1	45
VOC, µg/m^3	20	180	24	436

Note: The "Min." and "Max." values only apply to the zones in each building for which contaminant concentrations are reported (see Table 3 for selected zones).