IAQ and Energy Impacts of Ventilation Strategies and Building Envelope Airtightness in a Big Box Retail Building

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IAQ and Energy Impacts of Ventilation and Source Control in a Big Box Retail Building

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ABSTRACT

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to provide thermally comfortable conditions and to maintain acceptable indoor air quality (IAQ). At the same time, the operating costs of HVAC systems are often a large percentage of the total energy consumption of buildings, which constitutes 40 % of the primary energy consumed in the U.S. As efforts are pursued to reduce building energy use, some of which may include reductions in outdoor air ventilation rates, it is important to consider the impacts of these measures on IAQ. To better understand the IAQ and energy trade-offs of various approaches to reduce the indoor concentrations of CO_2, formaldehyde, ozone, particulate matter, and a generic volatile organic compound (VOC), a series of simulations was performed using the multizone airflow model, CONTAM, for a big box retail store in two different climates. Simulations included ventilating at the minimum outdoor airflow rate prescribed by ASHRAE 62.1 and at a lower rate for 24 hours a day. Additional cases included increasing the base outdoor air intake rates by 50 %, as well as a leakier building envelope. Annual airflow and contaminant simulations were performed using emission rates estimated from previous studies of retail buildings. The impact of changes in ventilation rates and building airtightness on contaminant concentrations and energy use were evaluated to investigate how both energy and IAQ goals can be met. This study demonstrated that ventilating at a lower rate for 24 hours a day saved energy compared with ventilating at the higher prescribed 62.1 rate during occupied periods without indoor contaminant concentrations exceeding several common benchmarks or health guidelines. Nevertheless, when considering different energy-saving measures, tightening the building envelope could significantly save more energy than reducing ventilation rates alone.

Keywords: ASHRAE Standard 62.1, CO_2, CONTAM, contaminants, energy, EnergyPlus, formaldehyde, indoor air quality, ozone, PM2.5, retail buildings, ventilation, volatile organic compounds

1. INTRODUCTION

Building owners, designers and operators are challenged to reduce the environmental impacts of buildings, including energy consumption and associated greenhouse gas emissions, while maintaining indoor environments that are conducive to occupant health, safety, and productivity. Forty percent of the primary energy consumed in the U.S. is from operating buildings, and 13 % of that energy use occurs in retail buildings (PNNL, 2011). While energy is critically important, it is only one aspect of building performance and should not be pursued to the neglect of IAQ and other indoor environment factors that affect that affect building occupants (Persily and Emmerich, 2012). When considering IAQ in the context of energy efficiency, one fundamental strategy is to reduce indoor contaminant sources through the careful selection of indoor materials and furnishings (ASHRAE, 2010). Source control also offers the potential to reduce outdoor air ventilation rates, which can save energy for space conditioning. Such reductions are allowed under the IAQ Procedure (IAQP) of ASHRAE Standard 62.1-2013 (ASHRAE, 2013). However, application of the IAQP presents several challenges, including the identification of the contaminants of concern for use in design, the adequacy of contaminant source data, and relevant concentration limits (Mendell and Apte, 2010; Dutton et al., 2013).

Recent field studies of retail and other commercial buildings have investigated indoor contaminant concentrations, ventilation rates and the connections between the two. Bennett et al. (2011) conducted a study of 37 commercial buildings, including six retail and two grocery stores. They found that the levels of most contaminants were below regulatory or recommended health levels, but formaldehyde (HCHO) consistently exceeded the 8-h reference exposure level (REL) of 9 μg/m^3 issued by the California Office of Environmental Health Hazard Assessment (OEHHA, 2012). Exposure limits of HCHO and other contaminants simulated in this study are listed in Table 1. Most buildings in the Bennett et al. (2011) study also did not meet California's Title 24 minimum requirements for ventilation on a per area basis. Chan et al. (2012, 2014) conducted a study of retail stores in California, which showed that HCHO exceeded the OEHHA REL, and that acetaldehyde and acrolein levels exceeded the reference concentration for chronic inhalation exposure (RfC) issued by the EPA (2014) while meeting, or exceeding, the Title 24 minimum ventilation requirement of 7 L/s•person or 1 L/s•m^2. The highest levels of HCHO were measured in apparel stores, and the highest acetaldehyde and acrolein were in grocery stores. The indoor levels of PM2.5 (particulate matter <2.5 μm) and PM10 (particulate matter <10 μm) were below federal and state 24-h ambient air quality standards for the particulate matter (35 μg/m^3 for PM2.5 (EPA, 2012) and 50 μg/m^3 for PM10 (CEPA, 2005)) in all stores. Another study of California retail stores explored the impact of ventilating at the prescribed minimum rate in Title 24 and at a rate determined using the IAQP on indoor contaminant concentrations (Dutton et al., 2013; Dutton et al., 2014). They found that the levels of volatile organic compounds (VOCs) and aldehydes all exceeded reference exposure levels (OEHHA, 2012; EPA, 2014) when ventilated at the Title 24 minimum required rate. In some stores, the ventilation rate determined using the IAQP was higher than the Title 24 required minimum. In other stores, it was lower. The IAQP-based ventilation rates were driven by acetaldehyde in the grocery stores, and by HCHO in the furniture, apparel, and big box retail stores. The indoor levels of PM2.5 and PM10 were both below the EPA 24-h ambient air quality standard but not the CA annual ambient air quality standard. Bridges et al. (2013) utilized the IAQP to lower ventilation rates by 70 % (compared with the rates prescribed by ASHRAE 62.1) in three big box retail stores while maintaining indoor levels of HCHO and TVOC (total VOC) below reference levels (USGBC, 2009; WHO, 2010; EPA, 2011b). It should be noted that there is insufficient evidence that TVOC measurements are an accurate predictor of health or comfort effects (ASHRAE, 2013).

Table 1 Summary of indoor exposure guidelines for contaminants studied

Contaminant	Limit	Source
CO_2	1800 mg/m^3	Note 1
	1280 mg/m^3 above the outdoor CO_2 concentration	(USGBC, 2014)
HCHO	9 μg/m^3 (chronic REL)	OEHHA (2012)
	20 μg/m^3 (40-h REL)	NIOSH (2010)
	33 μg/m^3	USGBC (2009)
	100 μg/m^3 (30-min)	WHO (2010)
Ozone	100 μg/m^3 (8-h)	WHO (2005)
PM2.5	35 μg/m^3 limit for outdoor PM2.5 (24-h) 12 μg/m^3 limit for outdoor PM2.5 (annual)	EPA (2012) CEPA (2005)

1. A common benchmark for indoor CO_2 concentrations though not a guideline value based on health concerns (Persily, 1997).

Another study of retail stores in Pennsylvania and Texas showed no statistical relationship between outdoor air change rates and indoor contaminant concentrations among all the buildings in the study due to differences in building characteristics and indoor and outdoor contaminant sources (Siegel et al., 2012). Nirlo et al. (2014) found that in these same stores, levels of HCHO and acetaldehyde exceeded the OEHHA REL. VOC concentrations varied up to three orders of magnitude between stores, showing that the results from any single study of indoor contaminants are not easily generalized to other buildings. Zaatari and Siegel (2014) studied the effects of using varying ventilation rates and higher efficiency filters on controlling indoor levels of PM2.5 and PM10. For stores where the outdoor concentration of particulates was less than indoors, increasing the ventilation rate proved to be an effective method of maintaining indoor levels below the outdoor PM2.5 ambient air quality standard set by EPA (Table 1). For stores where the outdoor concentration of particulates was greater than indoors, decreasing the ventilation rate did not always maintain indoor levels below a reference level. Further, decreasing the ventilation rate had adverse effects on the levels of other contaminants. Increasing filtration efficiency did not always maintain indoor levels below a reference level since particulates entering the building envelope through infiltration could not be controlled. These studies highlight the need for minimum ventilation requirements to be related to building-specific contaminant sources and the need for improved source control.

These studies also show that HCHO is a critical contaminant of concern for retail buildings and as such a prime candidate for considering the impacts of source control. Formaldehyde emissions have historically been associated with a wide range of building products and HCHO is of interest in terms of its impact on occupant health (OEHHA, 2012). Any effort to control indoor contaminant sources with the goal of potentially reducing outdoor air ventilation rates, including implementation of the ASHRAE Standard 62.1 IAQP, likely will need to consider HCHO emissions in addition to other contaminants of concern.

The objective of this study was to simulate indoor CO_2, HCHO, ozone, PM2.5 and VOC concentrations as a means of investigating the interactions between IAQ, ventilation, and energy use. In addition, it served as a demonstration of the utility of multizone airflow and contaminant transport simulations in conjunction with energy modeling tools (Ng et al., 2013). Historically, ventilation and energy analyses have been performed in isolation, with energy simulations treating ventilation rates as an input without considering its variation due to weather effects and the physical coupling between air and energy flows. IAQ impacts are rarely analyzed during design and more rarely linked to energy analysis. However, addressing the challenges of designing, building and operating low energy buildings with good IAQ requires more complete design and analysis approaches that integrate airflow, IAQ and energy simulations. In this study, the concentrations of the five contaminants were simulated in a big box retail store using the CONTAM simulation model (Walton and Dols, 2013) at various outdoor air ventilation rates, including ASHRAE 62.1-2013 prescribed rates and rates calculated by Bridges et al. (2013). Contaminant concentrations were also predicted for ventilation rates that were 50 % higher than both of these rates and for a lower value of building airtightness. Annual energy simulations were also performed in EnergyPlus in order to estimate the effects of outdoor air ventilation and building airtightness on energy use.

2. BUILDING DESCRIPTION

A one-story, 16 100 m^2 (173 500 ft^2) big box retail building was simulated in both CONTAM, a multizone airflow and contaminant transport modeling program (Walton and Dols, 2013), and EnergyPlus, a building energy simulation program (DOE, 2011). The retail building consisted of 12 zones, including a bakery, vestibules, grocery, sales, and office (Figure 1). Each zone was supplied conditioned air with a separate rooftop unit (RTU) that was either constant-air-volume (CAV) or variable-air volume (VAV). The maximum design supply flow rates for these units were calculated by EnergyPlus based on design weather conditions, internal loads, and desired setpoints. These values were used in the CONTAM model regardless if the supply rate changed in the energy simulation based on the specific demand of the building, i.e., VAV effects were not modeled. Exhaust fans were included for the restroom, food service areas, pharmacy, and stock room in both the CONTAM and EnergyPlus models.

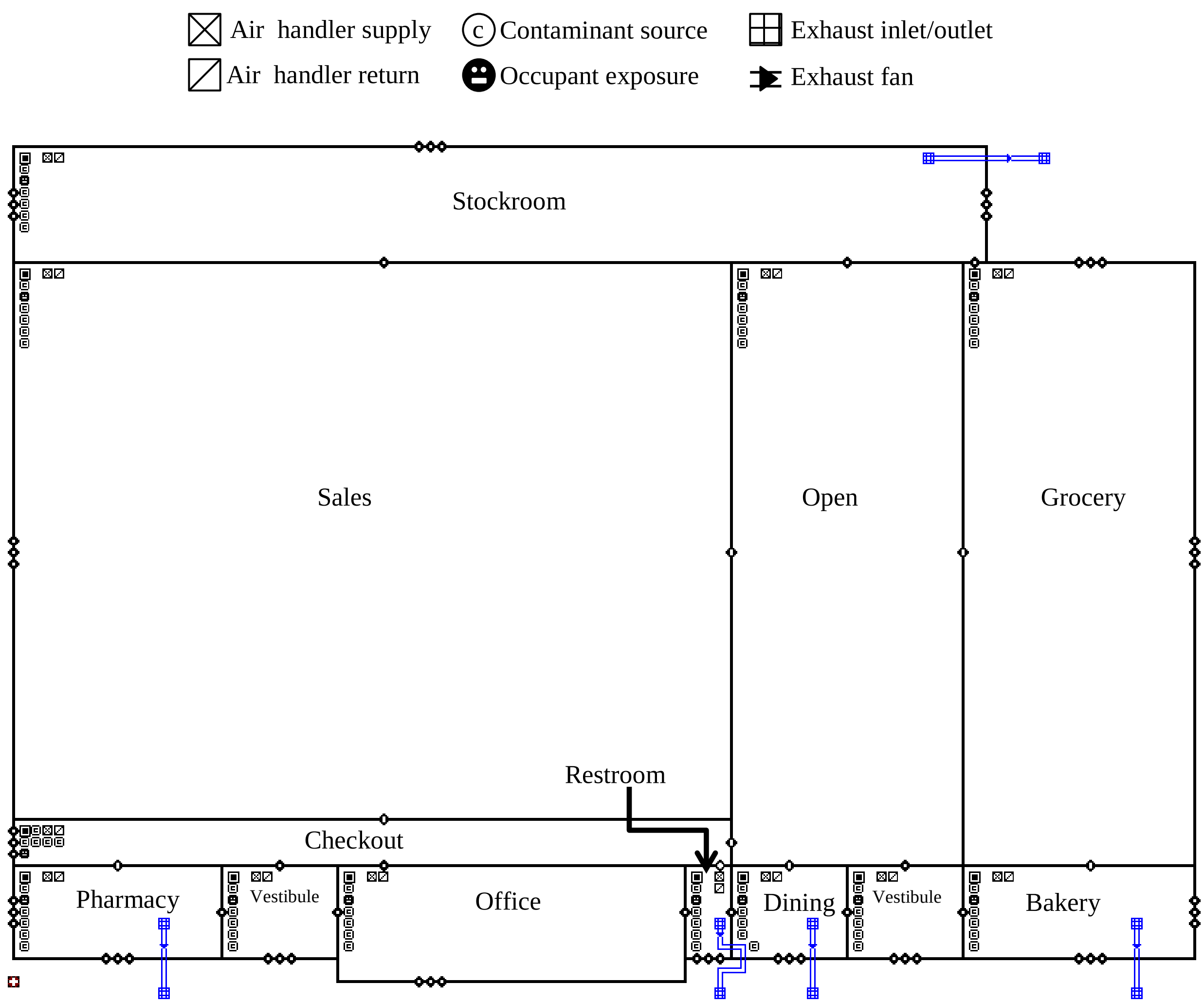


Figure 1. CONTAM model showing floor plan of retail building in this study.

The common design goal of over-supplying air in commercial buildings was accounted for in the CONTAM models by returning the greater of (a) 90 % of the supply airflow rate and (b) supply airflow rate minus the minimum required ventilation rate. If an exhaust fan was located in a zone, the return airflow rate was further reduced by the exhaust airflow rate. If the return airflow rate plus the minimum required outdoor airflow rate was less than the required supply airflow rate, additional outdoor air was supplied in the CONTAM model. In the EnergyPlus models, over-supply was accounted for by providing 8 m^3/s more outdoor air than the volume of air exhausted, i.e., 12 m^3/s outdoor air minus 4 m^3/s of exhausted air.

Two ventilation strategies were modeled: (1) 1.2 L/s•m^2 of outdoor air during occupied hours, which is the prescribed ventilation rate in ASHRAE 62.1-2013 (ASHRAE, 2013) for retail buildings (referred to as the "62.1 prescribed ventilation case") assuming approximately 9 occupants per 100 m^2, and (2) 0.4 L/s•m^2 24 hours a day based on the IAQP analysis performed by Bridges et al. (2013) (referred to as the "24-h ventilation case"). In Bridges et al. (2013), the concentration of HCHO, selected VOCs, and carbon monoxide (CO) were measured over 48-h periods. Measurements were made in retail stores in three climates (FL, MD, MN). The 0.4 L/s•m^2 ventilation rate was based on the minimum calculated ventilation rate required to maintain HCHO below 100 μg/m^3, TVOC below 1000 μg/m^3, and CO below 10 mg/m^3 assuming steady state conditions.

For both ventilation strategies, the 12 RTUs supplied outdoor air ventilation from 7 a.m. to 12 a.m., which were the hours when over 90 % of the occupants were present. For the 62.1 prescribed ventilation case, all 12 RTUs were set to operate between 12 a.m. and 7 a.m. only when indoor temperature setpoints were not met. For the 24-h ventilation case, 3 of the 12 RTUs continued to supply outdoor ventilation between 12 a.m. and 7 a.m. The remaining 9 RTUs were set to operate without outdoor air and only when indoor temperature setpoints were not met between 12 a.m. and 7 a.m.

Constant infiltration rates were input into the EnergyPlus models, with infiltration in the two vestibules scheduled to be zero when the building was unoccupied. These inputs resulted in an annual mean infiltration rate of 0.21 h^{-1}. Normalizing by exterior wall and roof area, this equated to a building exterior leakage rate of 0.000 332 m^3/s•m^2 at 4 Pa. For use in CONTAM, this leakage rate was converted to an effective leakage area (A_L) of 1.284 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. This A_L is about 10 % tighter than the values collected by Emmerich and Persily (2014) for 79 new buildings designed and constructed with attention to airtightness. These buildings include those identified by the building tester as having an air barrier, buildings participating in the Efficiency Vermont building performance program, those known to have used a building envelope consultant, and those in Washington State which has a code requirement for an air leakage test.

It should be noted that the indoor-outdoor pressure difference across the exterior envelope is actually calculated in CONTAM rather than assumed to be a constant as in the EnergyPlus models. Assuming a constant pressure difference does not reflect known dependencies of infiltration on indoor-outdoor pressure differences due to ambient conditions and system operation.

The effective leakage area of partitions between floors and between zones used the same value as the exterior wall leakage (1.284 cm^2/m^2 at 4 Pa). The connections between zones that would not have a physical partition, such as between the Sales and Checkout zones, were modeled using the two-way, two-openings model in CONTAM with a discharge coefficient C_D=0.78. The size of such openings was 75 % of the wall area between zones. In EnergyPlus, between zones for which no physical partition would actually exist (such as between the Sales and Checkout zones), a physical wall (two layers of ½” gypsum) was modeled. The walls were modeled in this way to produce temperature differences between the zones.

In CONTAM, 0.186 m^2 transfer grilles were modeled between the Restroom and Checkout to allow airflow between the two zones since there was an exhaust fan modeled in the Restroom (Figure 1). In EnergyPlus, to makeup for the air extracted from the Restroom to the outdoors via an exhaust fan, the same amount of air was artificially transferred from Checkout to the Restroom. This does not, however, reflect what happens in actual buildings, where the pressure induced by the systems and weather determine how much air flows between zones and between the building and the outside.

Contaminant simulations were performed for five contaminants in CONTAM: CO_2, HCHO, ozone, PM2.5, and a generic VOC. The outdoor concentration of CO_2 was assumed to be 732 mg/m^3, that of the generic VOC was zero, and that of HCHO was 4 $\mu g/m^3$ (EPA, 2006). Outdoor concentrations of ozone and PM2.5 were downloaded from the EPA Air Quality Standard (AQS) database (EPA, 2011a). Table 2 lists the minimum, maximum, mean, and standard deviation of the outdoor concentration of ozone and PM2.5 for Atlanta, GA and Chicago, IL.

Table 2 Summary of outdoor contaminant concentrations for Atlanta and Chicago

Outdoor contaminant	**Daily average contaminant concentrations**				**Daily peak contaminant concentrations**			
	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
Atlanta								
Ozone, $\mu g/m^3$	76	28	137	19	93	38	160	20
PM 2.5, $\mu g/m^3$	9	1	25	5	16	3	54	8
Chicago								
Ozone, $\mu g/m^3$	47	6	106	21	80	12	155	29
PM 2.5, $\mu g/m^3$	18	1	57	10	30	4	94	14

A constant efficiency filter was placed in both the outdoor and recirculation airstreams 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 (Bekö et al., 2006) and removed PM2.5 at 69 % efficiency, corresponding to filters with a Minimum Efficiency Reporting Value (MERV) of 8 as required in ASHRAE Standard 62.1-2013 (Kowalski and Bahnfleth, 2002; ASHRAE, 2013). A penetration factor of one was assumed for both ozone (Weschler et al., 1989; Liu and Nazaroff, 2001) and PM2.5 (Thornburg et al., 2001; Allen et al., 2003; Tian et al., 2009), i.e., there was no removal of these contaminants in the exterior leakage paths.

Indoor contaminant sources included occupant-generated CO_2 and VOCs from materials and activities. A CO_2 source was defined in all occupied zones. Though a mixed population (adults of various ages, children) and a wide range of activities (cashiers, shoppers, employees on the sales floor and in the stock room) are present in retail buildings, a CO_2 generation rate of 0.3 L/min per person was assumed based on adults at moderate activity levels (ASHRAE, 2013). The occupant schedule in the EnergyPlus and CONTAM models was the same. The CO_2 source strength thus varied with the occupancy. Area-based VOC and HCHO sources were defined in all zones. Table 3 lists several whole building emission rates (WBER) in the literature, and shows that HCHO WBERs measured across various types of buildings, climates, and year of construction were similar (average 0.065 mg/m^2•h, standard deviation 0.008 mg/m^2•h). In contrast, for the two studies that reported TVOC (total VOC) WBERs, the difference was tenfold. A 0.074 mg/m^2•h source of HCHO and 0.54 mg/m^2•h of a generic VOC were included as constant sources in the CONTAM model. These values were taken from Bridges et al. (2013) since that study focused on big box retail, whereas the other studies gathered data from a variety of different types of retail stores (grocery, hardware, furniture). Deposition rates of 0.5 h^{-1} for PM2.5 (Riley et al., 2002; Allen et al., 2003; Howard-Reed et al., 2003) and 4.0 h^{-1} for ozone (Weschler et al., 1989; Nazaroff et al., 1993; Weschler, 2000; Kunkel et al., 2010) were included in every zone. No indoor sources were included for ozone or PM2.5.

Annual simulations were performed in both CONTAM and EnergyPlus using Typical Meteorological Year (TMY2) weather data for Atlanta and Chicago (NREL, 1990). The timestep for the CONTAM and EnergyPlus simulations were 1 hour. There were three days out of the year that the building was unoccupied (holidays) but HVAC systems still ran as usual.

Table 3 Whole building emission rates from literature

HCHO (mg/m^2•h)	TVOC (mg/m^2•h)	Source
0.073	N/A	Bennett et al. (2011)
0.071	N/A	Estimated from Chan et al. (2012)
0.069	6.4	Seigel et al. (2012)
0.074	0.54	Bridges et al. (2013)
0.057	N/A	Dutton et al. (2013)
0.056	N/A	Nirlo et al. (2014)

3. AIRFLOW SIMULATION RESULTS

Outdoor air change rates were calculated as the total flow of outdoor air into the building (including both air leakage through the exterior envelope and outdoor air intake via the mechanical ventilation system) divided by the building volume. As described in Sec. 2, two ventilation strategies were modeled: (1) 1.2 L/s•m^2 during occupied hours (62.1 prescribed ventilation case), and (2) 0.4 L/s•m^2 24 hours a day (24-hr ventilation case).

Table 4 and Table 5 lists the number of hours under each condition (occupied or unoccupied), as well as the corresponding minimum, maximum, mean, and standard deviation of the total outdoor air change rates calculated by CONTAM and EnergyPlus for each ventilation strategy for Atlanta. The term “occupied” refers to the hours between 7 am and 11 pm, when over 90 % of the occupants are present. “Total outdoor air change rate” is the sum of mechanical ventilation and infiltration. Table 4 and Table 5 shows that the mean outdoor air change rates input into

EnergyPlus were 25 % to 100 % higher than those calculated by CONTAM. These differences were similar for Chicago but not shown for brevity. Though the building envelope airtightness was the same for both the CONTAM and EnergyPlus models, the resulting infiltration rate for EnergyPlus was a constant value while infiltration was calculated by CONTAM based on indoor-outdoor pressures induced by temperature differences, wind speed and system operation. The constant infiltration rate specified in the EnergyPlus model resulted in a mean outdoor air change rate of 0.19 h^{-1} (unoccupied, 62.1 prescribed and 24-h ventilation case) whereas the mean infiltration rate calculated by CONTAM was only 0.02 h^{-1} (62.1 prescribed ventilation case) and 0.01 h^{-1} (24-hr ventilation case). The low infiltration rates predicted by CONTAM may not be typical of actual buildings since the building envelope airtightness assumed was about four times tighter than the airtightness data from 50 new retail buildings (Emmerich and Persily, 2014). This highlights the need for pressure testing of commercial buildings and more physically-based infiltration modeling in energy models due to the large discrepancy between the calculated infiltration and its subsequent impact on energy use. One such method has been proposed by Ng et al. (2014a; Ng et al., 2014b), which utilizes building characteristics to calculate EnergyPlus inputs for infiltration. These inputs allow for system operation and weather to affect infiltration rates in EnergyPlus.

Table 4 Summary of calculated outdoor air change rates (62.1 prescribed ventilation case) (Atlanta)

Retail building	**Occupied hours – total outdoor air change rates, h^{-1}**					**Occupied hours – infiltration rates, h^{-1}**			
	Hours	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
CONTAM	5840	0.72	0.72	0.77	0.00	0.00	0.00	0.05	0.00
EnergyPlus	5840	0.97	0.91	1.57	0.03	0.22	0.18	0.26	0.02
	Unoccupied hours – total outdoor air change rates, h^{-1}					**Unoccupied hours – infiltration rates, h^{-1}**			
	Hours	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
CONTAM	2800	-	-	-	-	0.02	0.00	0.08	0.01
EnergyPlus	2800	-	-	-	-	0.19	0.18	0.21	0.01

Note: Values “0.00” are not zero but very small values. “Total outdoor air change rate” is the sum of mechanical ventilation and infiltration.

Table 5 Summary of calculated outdoor air change rates (24-h ventilation case) (Atlanta)

Retail building	**Occupied hours – total outdoor air change rates, h^{-1}**					**Occupied hours – infiltration rates, h^{-1}**			
	Hours	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
CONTAM	5840	0.33	0.33	0.38	0.01	0.00	0.00	0.06	0.01
EnergyPlus	5840	0.58	0.51	1.31	0.05	0.22	0.18	0.26	0.02
	Unoccupied hours – total outdoor air change rates, h^{-1}					**Unoccupied hours – infiltration rates, h^{-1}**			
	Hours	Mean	Min.	Max.	StdDev	Mean	Min.	Max.	StdDev
CONTAM	2800	0.14	0.13	0.20	0.01	0.01	0.00	0.07	0.01
EnergyPlus	2800	0.32	0.31	0.34	0.01	0.19	0.18	0.21	0.01

Note: Values “0.00” are not zero but very small values. “Total outdoor air change rate” is the sum of mechanical ventilation and infiltration.

4. CONTAMINANT SIMULATION RESULTS

Table 6 and Table 7 list the building minimum, maximum, mean, and standard deviation of the daily averages and daily peaks of the five contaminants simulated in CONTAM for each ventilation strategy using Atlanta weather. These values were calculated by taking the product of each zone's concentration and its volume, summing them, then dividing by the total building volume (i.e., volume-weighted). These values are for the occupied hours only. The mean daily averages and mean daily peaks of CO_2 were on average 32 % higher for the 24-hr ventilation case when compared to the 62.1 prescribed ventilation case. The maximum daily peak CO_2 concentration was 36 % higher for the 24-hr ventilation case and reached about 1470 mg/m^3. Nevertheless, the daily peak CO_2 concentration never exceeded a common benchmark for indoor CO_2 concentrations (1800 mg/m^3) as listed in Table 1. Since the results for Chicago were similar to those for Atlanta, only Atlanta results were presented and discussed.

The mean daily average of HCHO was 46 % higher for the 24-hr ventilation case when compared to the 62.1 prescribed ventilation case, however the mean daily HCHO peak was 12 % lower. The maximum daily peak was also lower (17 %) for the 24-hr ventilation case and reached about 59 μg/m^3. This was below the WHO exposure guideline but not those from the OEHHA and other organizations (see Table 1). The range of hourly HCHO concentrations in this study was 22 μg/m^3 to 71 μg/m^3, considering both ventilation strategies, which is within the range of the indoor concentrations reported in studies of other retail and commercial buildings (Table 8). The simulated range was lower than that measured by Bridges et al. (2013) even though the HCHO building emission rate used in this study was taken from that study. This difference was most likely due to assumptions made when calculating the building emission rate, and the differences between the actual and simulated operation of HVAC systems. Modeling assumptions were also made about building envelope airtightness, which could not be compared to the actual airtightness of the three retail buildings in Bridges et al. (2013) because it was not measured.

The mean daily average of VOC was 54 % higher for the 24-hr ventilation case when compared to the 62.1 prescribed ventilation case, however the mean daily VOC peak was 13 % lower. The maximum daily peak was also lower (18 %) for the 24-hr ventilation case and reached about 400 μg/m^3. The predicted range of the VOC concentrations in this study were similar to those reported by Seigel et al. (2012) and lower than those reported by Bridges et al. (2013).

The mean daily averages and mean daily peaks of ozone were an average 42 % lower for the 24-hr ventilation case when compared to the 62.1 prescribed ventilation case. The maximum daily peak was 41 % lower for the 24-hr ventilation case and reached about 12 μg/m^3. This was below the WHO 30-min exposure guideline of 100 μg/m^3 as listed in Table 1.

Similarly, the mean daily averages and mean daily peaks of PM2.5 (ratio of indoor to outdoor concentration, I/O) are an average 47 % lower for the 24-hr ventilation case when compared to the 62.1 prescribed ventilation case. The maximum daily peak was 34 % lower for the 24-hr ventilation case, and the I/O ratio reached 0.06. The reason for the reduction in indoor PM2.5 was due to the ventilation rate being lower for the 24-h ventilation case, and there were only outdoor sources of ozone and PM2.5. The I/O ratio of PM2.5 simulated in this study were smaller than those in the literature, likely due to the differences in the type of filters, outdoor concentration of PM2.5, ventilation rates simulated in this study and those present in the published field studies, and there were no indoor sources of PM2.5 simulated in this study. There are no guidelines for indoor exposure to PM2.5, but ambient air quality standards are set by EPA and CEPA and are summarized in Table 1. For the whole building, neither the daily average nor the daily peak indoor PM2.5 concentration exceeded the EPA ambient air quality standard or the CEPA standard for both the Atlanta and Chicago cases.

The previous discussion of Table 6 and Table 7 were based on the building as a whole. There are differences on a zone level that are worth discussing. For all of the contaminants except HCHO and VOC, the distribution of contaminant concentration among the zones was similar for the 62.1 prescribed and 24-h ventilation cases. For example, the distribution of CO_2 within the building was similar between the two ventilation cases as seen in Figure 2. The CO_2 concentration in the offices and stock room were lower than the other three zones shown because their outdoor air requirements (normalized by zone volume and by the number of occupants) were higher.

For HCHO and VOC, the distribution of daily average concentration was similar between the two ventilation cases. In contrast, there was a wider spread between the concentrations in the zones for the 62.1 prescribed ventilation case compared to the 24-h ventilation case. For example, there was about 20 $\mu g/m^3$ difference between the HCHO concentrations in the office and stockroom, and the checkout, grocery, and sales areas in Figure 3a. In contrast, for the 24-h ventilation case, there was more uniform distribution of HCHO, as well as a reduction in daily peak concentration, as shown in Figure 3b. This was also seen for VOC though not shown for brevity.

Table 6 Summary of volume-weighted calculated contaminant concentrations (62.1 prescribed ventilation case, Atlanta)

Retail building	Daily average contaminant concentrations			Daily peak contaminant concentrations		
	Mean ± SD	**Min.**	**Max.**	**Mean ± SD**	**Min.**	**Max.**
CO_2, mg/m^3	1347 ± 54	766	1364	1452 ± 44	954	1467
HCHO, μg/m^3	29 ± 2	26	30	64 ± 3	52	71
Ozone, μg/m^3	10 ± 3	4	18	12 ± 3	5	21
PM2.5, I/O	0.08 ± 0.01	0.04	0.10	0.07± 0.01	0.03	0.09
VOC, μg/m^3	180 ± 4	160	189	436 ± 20	351	486

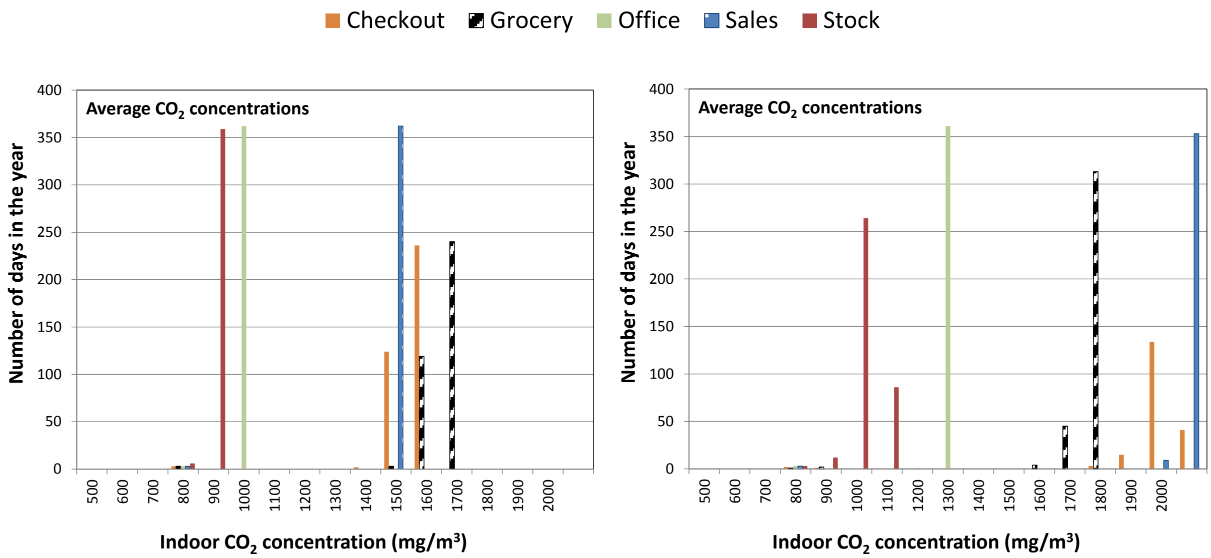
Table 7 Summary of volume-weighted calculated contaminant concentrations (24-h ventilation case, Atlanta)

Retail building	Daily average contaminant concentrations			Daily peak contaminant concentrations		
	Mean ± SD	**Min.**	**Max.**	**Mean ± SD**	**Min.**	**Max.**
CO_2, mg/m^3	1742 ± 93	775	1776	1962 ± 101	913	2000
HCHO, μg/m^3	42 ± 1	37	43	56 ± 2	47	59
Ozone, μg/m^3	6 ± 2	2	11	7 ± 2	3	12
PM2.5, I/O	0.04 ± 0.01	0.02	0.06	0.04 ± 0.01	0.02	0.06
VOC, μg/m^3	277 ± 6	242	283	380 ± 14	311	398

Table 8 Simulated indoor contaminant concentrations in this study relative to values in the literature

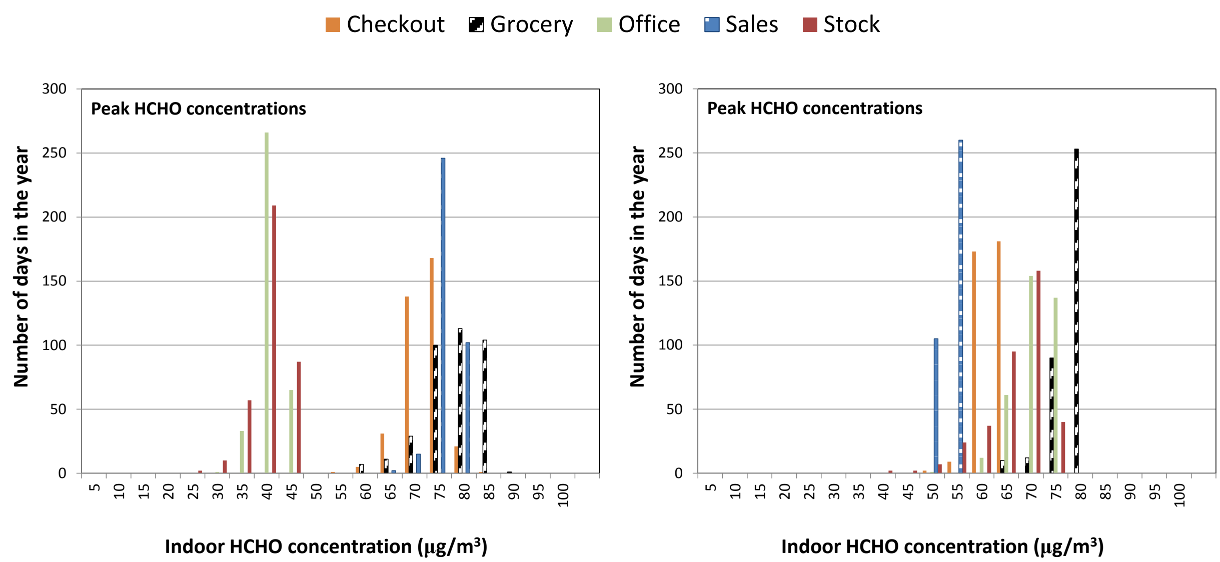
HCHO, $\mu g/m^3$ Mean±SD (Range)	TVOC, $\mu g/m^3$ Mean±SD (Range)	PM2.5 (I/O) Mean±SD (Range)	Source	Number of buildings[1]
29 ± 11 (22 to 71)	180 ± 80 (130 to 486)	0.08 ± 0.05 (0.05 to 2)	This study – 62.1 prescribed ventilation case	1
42 ± 5 (36 to 58)	277 ± 36 (231 to 395)	0.04 ± 0.02 (0.03 to 1)	This study – 24-h ventilation case	1
16 ± 2 (1 to 102)	N.R.[3]	0.9 ± 0.5[2] (0.2 to 5)	Bennett et al. (2011)	40
N.R. (5 to 54)[4]	N.R.	N.R. (0.5 to 1.9)	Chan et al. (2012; Chan et al., 2014)	HCHO, VOCs: 21 PM2.5: 9
14 ± 11 (2 to 54)	146 ± 163 (100 to 630)	1 ± 0.7 (0.1 to 4)	Seigel et al. (2012)	14
N.R. (30 to 100)	N.R. (100 to 1400)	Mean: 9 $\mu g/m^3$ (N.R.)	Bridges et al. (2013)	3
19 ± N.R. (5 to 58)	N.R.	N.R.	Dutton et al. (2013)	13
N. R. 4 to 67	N.R.	None	Nirlo et al. (2014)	14

1. All values reported are for all the buildings in a particular study unless researchers separately reported for retail buildings, which will be noted.
2. This value is for the seven retail buildings in the Bennett et al. (2011) study.
3. N.R. = not reported.
4. Reported range is actually 10^{th} to 90^{th} percentile.



(a) 62.1 prescribed ventilation case (b) 24-h ventilation case

Figure 2 Frequency distribution of simulated daily average CO_2 concentrations by zone (Atlanta)



(a) 62.1 prescribed ventilation case (b) 24-h ventilation case

Figure 3 Frequency distribution of simulated daily peak HCHO concentrations by zone (Atlanta)

5. ADDITIONAL TEST CASES

A higher value for building airtightness was also modeled in both CONTAM and EnergyPlus, i.e., A_L = 5.647 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. This leakage area value was based on consideration of airtightness data from 50 new retail buildings with varying levels of attention given to airtightness in design and construction, though the majority did not involve any serious efforts towards achieving an airtight building envelope (Emmerich and Persily, 2014). This envelope leakage was applied to all above-grade exterior walls, interior ceilings/floors, and roofs. For use in EnergyPlus, this A_L was converted to a leakage rate of 0.001 46 m^3/s•m^2. These values were approximately four times the original value discussed in Sec. 2. The increase in building leakiness resulted in infiltration increasing in the CONTAM models up to 32 times the value discussed in Sec. 2 (from 0.002 h^{-1} to 0.064 h^{-1}). The infiltration in the EnergyPlus models increased only about four times. Further, using a higher constant infiltration rate in EnergyPlus resulted in infiltration being larger than mechanical ventilation, which was never the case for the CONTAM model.

The increase in envelope leakage had the smallest effect on indoor CO_2 concentrations. There was on average (considering both ventilation cases) a 10 % decrease in average daily peak, average concentration, and maximum daily peak. For HCHO, there was on average an 18 % decrease (daily averages, daily peaks, maximum daily peak) in indoor concentrations for the increased envelope leakage. In contrast, for the increased envelope leakage, there was on average a 20 % increase (daily averages, daily peaks, maximum daily peak) in indoor concentrations of ozone and PM2.5. Nevertheless, even with a leakier building envelope, the indoor concentrations remained under relevant guidelines (Table 1), except for HCHO, which only met the WHO exposure guideline as was the case with the tighter building envelope (Sec. 4).

For another set of test cases, the ventilation rates for the building were increased 50 % in order to examine the ability of increased ventilation to control contaminant levels and the effect on energy use. The rates were increased to 1.8 L/s•m^2 for the 62.1 ventilation case and an average 0.7 L/s•m^2 for the 24-h case. For the building with an airtightness of 1.284 cm^2/m^2 at 4 Pa (“tight” building), the increase in ventilation resulted in an average 12 % decrease (daily averages, daily peaks, maximum daily peak) in indoor CO_2 concentrations and an average 21 % decrease in indoor HCHO and VOC concentrations. In contrast, there was an average 27 % increase in indoor ozone and PM2.5 concentrations, which was expected since the only source of ozone and PM2.5 was the outdoor air. For the building with the leakier building envelope, the increase in ventilation had a smaller impact on indoor concentrations but nonetheless resulted in a decrease in indoor CO_2, HCHO and VOC concentrations, and an increase in indoor ozone and PM2.5.

Table 9 compares the energy consumption for the different outdoor ventilation strategies and outdoor ventilation rates for the tight and leaky buildings. For both building tightness cases, there was an average 9 % energy savings when implementing the 24-h ventilation case instead of the 62.1 prescribed ventilation case in Atlanta. The energy savings was greater for Chicago, i.e., 12 %. When the outdoor ventilation rate was increased 50 %, there was average 6 % increase in energy use in Atlanta (8 % in Chicago). A larger difference in energy use was seen when comparing the tight and leaky buildings. For both ventilation strategies and ventilation rates, there was an average 31 % increase in energy use. The energy savings was greater for Chicago for the tighter building, i.e., 54 %. This is because the indoor-outdoor temperature differences in Chicago are greater than those in Atlanta.

Table 9 Summary energy usage for test cases (Atlanta and Chicago)

Building tightness	Ventilation strategy (prescribed or 24-h), rate (base or 1.5x)	Atlanta annual energy use (GJ)	Chicago annual energy use (GJ)
Tight	62.1 prescribed, base	14,650	18,000
Tight	24-h, base	13,460	15,630
Tight	62.1 prescribed, 1.5x	15,980	20,160
Tight	24-h, 1.5x	14,110	16,770
Leaky	62.1 prescribed, base	19,220	27,290
Leaky	24-h, base	17,930	25,050
Leaky	62.1 prescribed, 1.5x	20,590	29,530
Leaky	24-h, 1.5x	18,710	26,320

6. DISCUSSION

This study of the impact of ventilation strategy and building envelope airtightness on energy and IAQ demonstrates the need for the accurate determination of building airtightness and accurate accounting of infiltration in building energy models. There were large differences in the infiltration rates calculated by CONTAM and EnergyPlus, in large part because constant infiltration rates were modeled in EnergyPlus. If more accurate infiltration rates were incorporated into the EnergyPlus models, following the method described by Ng et al. (2014a; Ng et al., 2014b), the difference in infiltration rates relative to the CONTAM predictions could be as small as 4 %.

In addition, this study demonstrated that when considering different energy-saving measures, tightening the building envelope could save significantly more energy than reducing ventilation rates to the degree studied in this analysis and for the particular climates studied (Atlanta and Chicago). With regards to IAQ, envelope tightening reduced the mean daily average and mean daily peak concentrations of ozone and PM2.5 since the outdoors was the only source in this study. Even though there was an increase in indoor HCHO concentrations with improved airtightness, the level did not exceed the WHO exposure guideline. Increasing the ventilation rate by 50 % reduced HCHO concentrations but levels still did not meet the OEHHA REL of 9 $\mu g/m^3$ and resulted in an increase in energy use in both Atlanta and Chicago.

Lastly, ventilating 24 hours a day at a lower rate resulted in energy savings when compared to ventilating at the 62.1 prescribed ventilation rate during occupied hours only. Greater savings were realized in the leakier building and also in Chicago. Though there was an increase in daily average CO_2 and HCHO using the 24-h ventilation strategy, levels did not exceed common benchmarks and relevant guidelines. Further, the daily peak HCHO concentration actually decreased using the 24-h ventilation strategy for both Atlanta and Chicago. Thus, a reduced ventilation rate that is supplied 24 hours a day is a potential strategy to maintain IAQ and save energy in big box retail buildings.

The limitations of this study include the use of a single retail building with assumptions made about building airtightness, ventilation rates, HVAC system operation, filtration, contaminants, and contaminant source strengths. Constant emission rates were modeled in CONTAM, but in reality emissions may be episodic and vary with temperature, humidity, and other factors. Further, contaminant sources will vary among retail buildings because of differences in inventory. Thus, more analysis of other buildings is needed in order to support broader generalizations for retail buildings regarding ventilation operation schedules and recommended outdoor airflow rates, as well as the development of more specific, performance-based design approaches.

While progress is being made in implementing energy efficient design approaches that address IAQ concerns, more work is needed in several areas, including understanding contaminant sources and emission rates and establishing indoor contaminant benchmarks for HCHO, VOCs, and other airborne contaminants. Air filtration and air cleaning also may play important roles, with more information needed on installed contaminant removal rates over time. A key step in making progress toward building and ventilation system design based on indoor contaminant levels is the integration of airflow, IAQ and energy simulation tools, so the trade-offs between different design decisions can be better understood during the building design process.

7. CONCLUSION

The total energy consumption of buildings constitutes 40 % of the primary energy consumed in the U.S., with 13 % of that energy consumed by retail buildings. This study outlines an analysis approach that can be used to evaluate various energy saving measures, which takes into account ventilation rate and schedule, building envelope airtightness, weather, and contaminant sources. In this study, the concentrations of indoor CO_2, HCHO, PM2.5, ozone, and VOC, and were simulated under two different outdoor ventilation rates with different operating schedules. These cases were modeled for two buildings (tight, leaky) and two ventilation rates (base rate and 50 % greater than base rate). The 24-hr ventilation case required an average 9 % less energy per year than the 62.1 prescribed ventilation case for Atlanta and Chicago. The greatest energy savings, however, was realized by increasing the building envelope airtightness, with 31 % savings in Atlanta and 54 % savings in Chicago. Nevertheless, in all cases, the 24-hr ventilation case was able to maintain the daily average CO_2 concentration below a common benchmark of 1800 mg/m^3. The 24-hr ventilation case was also able to maintain the daily average HCHO concentration below the WHO exposure guideline of 100 μg/m^3. Increasing the ventilation rate by 50 % was not able to reduce HCHO to the OEHHA REL of 9 μg/m^3 and required an average 8 % increase in energy use. Thus, a reduced ventilation rate that is supplied 24 hours a day is a potential strategy to maintain IAQ and save energy in big box retail buildings when designed properly. Nevertheless, consideration should be given to improving building envelope airtightness as it has the potential to save more energy and reduce indoor concentrations of contaminants with outdoor source.

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