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Modeling impacts of dynamic ventilation strategies on indoor air quality of offices in six US cities

Adams Rackes, Michael S. Waring*

Department of Civil, Architectural and Environmental Engineering, Drexel University, 3141 Chestnut Street, Curtis 251, Philadelphia, PA 19104, USA

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ABSTRACT

A potential source of energy savings in buildings is demand controlled ventilation (DCV), or dynamic modulation of the ventilation rate based on current occupancy. The impact of DCV on indoor air quality (IAQ) has not been investigated over a large range of indoor air processes or under the revised ventilation rate procedure (VRP) introduced in ASHRAE Standard 62.1-2004, which reduced per-occupant rates and added a constant per-area rate. A transient, multi-contaminant model of an area-normalized US office was created, and best estimates for distributions of model inputs across the US office sector were developed and used in a six city Monte Carlo simulation of dynamic ventilation strategies, including DCV and morning flushes. DCV implementation had a very minor effect on concentrations of ozone, particles, and carbon dioxide. The greatest effect was on daytime mean and peak concentration of total volatile organic compounds (TVOC). TVOC daytime means increased by 7–10% and peaks increased by 10–14%, depending on city. Adding a medium intensity morning flush to DCV almost completely mitigated the increase in mean concentration and reduced the peak concentration below the fixed ventilation baseline in most cases. Differences among offices due to input variations were far greater than changes observed from implementing DCV, and a sensitivity analysis indicated that the TVOC emission rate was more influential than the ventilation strategy. The distribution-based, sector-wide Monte Carlo method developed here should also be useful for assessing other ventilation strategies and input parameter impacts and informing the development of IAQ guidelines.

1. Introduction

Ventilation plays a crucial role in promoting the comfort and health of building occupants by diluting the indoor concentration of contaminants. Since real-time concentrations of all contaminants of concern are not known, ventilation rates are typically set in advance according to a standard, most commonly ASHRAE 62.1. From 1989 to 2001, the ASHRAE 62 ventilation rate procedure (VRP) included only a per-occupant ventilation rate. Since the 2004 version, however, the minimum ventilation rate $\dot{V}_v$ (V_{bz} in ASHRAE nomenclature) has been specified as [1]

$$\dot{V}_v = R_a A_z + R_p P_z \tag{1}$$

This additive approach includes a per-area component intended to dilute non-occupant emissions and a per-occupant component to provide additional dilution of human b_ioeffluents. For offices, the revised VRP, when compared to the 1989–2001 procedure, increases ventilation when there are four or fewer occupants per 92.5 m^2 (1000 ft^2), and decreases it when the density is greater.

To save energy, demand controlled ventilation (DCV) dynamically adjusts the ventilation rate based on the actual zone population, rather than the design population. Under the occupant-only 1989–2001 VRP, both required ventilation and human CO_2 emissions were proportional to actual occupancy, so a constant CO_2 setpoint control could be used to implement DCV. This implementation has sometimes led to the misapprehension that controlling CO_2 is sufficient to guarantee good IAQ [2]. With the incorporation of the additive approach into the standard, the CO_2 concentration that results from the prescribed ventilation rate varies greatly with occupant density, so a constant setpoint CO_2 control (with zero minimum) is not appropriate. After 2004, a few initial industry articles addressed the need to revise control strategies [3,4], but few DCV simulations or case studies referred to the new standard or the need to verify rate compliance instead of controlling CO_2. More recently, DCV research has largely recognized the current rates and the area-minimum component, but much of it still regards CO_2 concentration as a sufficient indicator of IAQ [5–8].

* Corresponding author. Tel.: +1 215 895 1502; fax: +1 215 895 1363.
E-mail addresses: aer37@drexel.edu (A. Rackes), msw59@drexel.edu (M.S. Waring).

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Nomenclature

A_z	zone floor area, 92.5 m^2 (1000 ft^2)
C	concentration, $\mu g/m^3$ or ppb or ppm
E	emission rate, μg/h or μg/h-occ
f_f	flush factor intensity
G	conversion factor from ppb to $\mu g/m^3$
L	contaminant loss rate, h^{-1}
p	penetration factor
P_z	zone population, occ
R_a	per-area ventilation rate, l/s-m^2 (cfm/ft^2)
R_p	per-occupant ventilation rate, l/s-occ (cfm/occ)
S	contaminant source strength, $\mu g/m^3$-h
V	zone volume, 227 m^3 (8000 ft^3)
$\dot{V}_v$	breathing zone ventilation rate, l/s (cfm)
y	molar yield
β	deposition loss rate, h^{-1}
η	filtration efficiency
λ	air exchange rate, h^{-1}

Subscripts

ave	average
bm	building materials and furniture
da	daytime
des	design
fl	morning flush
frac	fraction (ratio of average to design)
i	infiltration
ni	nighttime
occ	occupant skin and clothing
op	off-peak
out	outdoor concentration
p	primary (recirculation + ventilation)
r	recirculation
v	ventilation

A comprehensive literature review in 2001 identified only two studies up to that point that had considered IAQ measures other than CO_2 concentration [2]. Both were simulation-based. One used a generic, constantly emitted contaminant whose concentration remained just below a theoretical threshold under fixed ventilation; with DCV the contaminant did not remain below the threshold, but could be kept below it by incorporating a morning and midday purge of building air [9]. The other found that DCV was not as effective as fixed ventilation at controlling formaldehyde, and suggested a purge strategy but did not pursue the approach [10]. Chao and Hu implemented one of the few case studies that measured non-CO_2 contaminants [11]. They controlled ventilation in an auditorium using two static setpoints, one for CO_2 and one for radon, in combination with a purge cycle to reduce radon that accumulated overnight. Their baseline was DCV with CO_2 setpoint control only (i.e., no radon control). They also measured TVOC and formaldehyde concentrations, which were, respectively, in the range of 2500 $\mu g/m^3$ and 50 $\mu g/m^3$ with CO_2 only control, and 2000 $\mu g/m^3$ and 35 $\mu g/m^3$ with combined CO_2 and radon control.

The IAQ impacts of DCV under the additive VRP of Equation (1) have not been thoroughly explored, and a motivation for the present study was the need to better understand the IAQ effects of implementing DCV under the current standard. The switch to the additive VRP, with its per-area-minimum ventilation rate, means that the differences between fixed and DCV strategies are likely to be reduced, particularly in relatively low density occupancy classes like offices. A 2003 modeling study in advance of the 2004 revision did include both fixed and dynamic simulation with the updated rates [12], and it found that the concentration of a generic, constantly emitted VOC in an office was about 13% greater under DCV than under fixed ventilation with the updated rates. Also, since the literature often accounts for IAQ solely in terms of CO_2 concentration, a second important objective of this work was to model a wide range of indoor air processes based on realistic distributions of input parameters. An average reduction in the ventilation rate may increase the concentration of contaminants that are emitted indoors, while decreasing those generated outdoors, such as humidity in hot, humid summer months [13]. No study has taken all these effects (and others) into account.

To meet these identified needs, we developed a transient, multi-contaminant model of an area-normalized US office, and best estimates for distributions of model inputs across the office sector were developed and used in Monte Carlo simulations of dynamic ventilation strategies for six major US cities. This model and the input distributions are useful in this work as well as for other researchers evaluating the relative importance of different indoor air processes and the sensitivity of indoor contaminant concentrations to changes in ventilation strategies and other influential building-related input parameters. Specifically, these distributions are used to examine DCV impacts on IAQ in offices under ASHRAE 62.1-2010, as well as impacts of a morning flush (so-called here to distinguish this IAQ-focused air movement strategy from the more common thermal purge), which has been proposed but not quantified.

2. Simulation methodology

2.1. Overview

The simulation consisted of an individual office IAQ model (Sections 2.2–2.3) that used inputs to produce time-resolved concentration values of relevant contaminants, coupled with a model of the US office sector (Sections 2.4–2.11) that generated the inputs to the IAQ model. The inputs (emission rates, filtration, etc.) were randomly selected from distributions that accurately characterize real US offices. This procedure was repeated in a Monte Carlo simulation 288,000 times. For each sample or iteration, the time-resolved output was used to compute IAQ metrics, such as peak and mean values of contaminants during the daytime.

2.2. Office space dimensions, locations, and schedules

To produce broadly applicable results, as few assumptions as possible were made regarding mechanical systems, zonal arrangements, and distribution networks, since these vary widely among office buildings. The space modeled is a single well-mixed zone, 92.5 m^2 (1000 ft^2) in floor area with a ceiling height of 2.4 m (8 ft). All input parameters were normalized to this floor area for easy scalability.

To study a variety of climatic and outdoor air scenarios, the space was modeled in metropolitan Houston, Los Angeles, Minneapolis, Philadelphia, Phoenix, and Seattle. In most cases, regional results are presented separately. In some cases where regional variations were not large, overall effects are reported with the six regions equally represented.

The office schedule is common in all modeled cases. The HVAC system operates continuously from 7 a.m. until 10 p.m. The exception is in cases where there is a morning flush, which always occurs between 6 a.m. and 7 a.m. The flush factor intensity, f_f, indicates the multiple of R_aA_z (28.3 l/s or 60 cfm) at which the system ventilates for that entire hour (e.g. $f_f = 2$ means that the ventilation rate is 56.6 l/s (120 cfm) between 6 a.m. and 7 a.m.). Occupancy is possible between 7 a.m. and 9 p.m. The period from 8 a.m. to 6 p.m. is labeled the daytime, while the margins in the morning and evening are labeled off-peak. Office schedule, occupancy, and system operational parameters are listed by time of day in Table 1. For IAQ processes, all reported summary results are for the daytime period.

2.3. IAQ processes

For any indoor contaminant the rate of change of concentration C (μg/m^3) is related to its sources, S (μg/m^3-h), and total loss rate, L (h^{-1}), by

$$\frac{dC}{dt} = S - LC \tag{2}$$

Contaminants and indoor air processes are divided into eight groups: (1) total volatile organic compounds (TVOC) directly emitted by building materials and furniture; (2) TVOC from outdoor sources; TVOC secondary emissions as a result of ozone surface reactions on (3) building materials and furniture and (4) occupant skin and clothing; particulate matter from outdoor sources with (5) diameter less than 2.5 μm ($PM_{2.5}$) and (6) diameter less than 10 μm (PM_{10}); (7) ozone (O_3) from outdoor and indoor sources; and (8) carbon dioxide (CO_2) generated by occupant respiration and from outdoor air exchange. Each group has its own sources and losses, which are summarized in Table 2. All air movements are expressed in air exchange rates, which are found from corresponding airflow rates $\dot{V}$ by

$$\lambda = \frac{\alpha \dot{V}}{V} \tag{3}$$

where the constant α is a conversion factor that depends on the units of $\dot{V}$ and V. Nearly all parameters in Table 2 vary by time of day and may be zero-valued during some periods (e.g. ventilation air exchange in the middle of the night). Transient and distribution-based parameters are discussed in the following sections.

2.4. Occupancy parameters

Occupant density is a critical parameter when evaluating ventilation strategies. The ventilation rate, according to Equation (1) and the equations in Table 1, depends on the zone population (actual or design), as do some emission and deposition rates in Table 2. To model the design zone population $P_{z,des}$, a lognormal distribution was derived from two sources. The first was the US EPA's 1994–1998 BASE study of 100 US office buildings [14]. As part of the study, the number of workstations was counted, and a lognormal distribution with geometric mean (GM) = 4.91 and geometric standard deviation (GSD) = 1.42 was fit as the number of workstations observed per 100 m^2. The other source was workstation density information for 31 office projects compiled by Carter and Zhang from floor plans they obtained from seven major office furniture manufacturers [15]. Maximum likelihood estimation of their reported values yielded a lognormal fit with GM = 5.52 and GSD = 2.01. The distribution parameters from the two analyses were averaged geometrically to yield a lognormal distribution for $P_{z,des}$ with GM = 5.21 occupants per 100 m^2 (4.84 occupants per 1000 ft^2) and GSD = 1.69.

Actual zone population at each hour was then modeled as a binomial distribution in which the number of trials was the design population. During the highest occupancy periods of the day (9 a.m.–12 p.m. and 1–4 p.m.) the likelihood of each occupant being present was 0.78, which was the mean value of fractional occupancy observed in BASE data (for which nearly all observations were taken in mid-morning or mid-afternoon) [14]. During the medium occupancy periods of the day (8–9 a.m., 12–1 p.m., and 4–7 p.m.) the likelihood of presence was 0.45, based on judgment and with reference to US DOE office schedules. During low occupancy periods (7–8 a.m. and 7–9 p.m.) the likelihood of presence was assumed as 0.10. There were no occupants between 9 p.m. and 7 a.m. The term $P_{z,ave}$ denotes the average value of actual zone population, and $P_{z,frac}$ is the ratio of $P_{z,ave}$ to $P_{z,des}$.

2.5. TVOC distributions

Composition and distribution information for TVOC primary emissions and outdoor concentrations were also derived from BASE study data, which include four time averaged samples (over approximately 9 h), taken at three indoor and one outdoor locations at each of 100 representative US office buildings [16]. The 43 compounds detected inside 75% or more of the BASE buildings were selected as the constituents of TVOC in this study.

For outdoor concentrations, the arithmetic mean and 5th, 25th, 50th, 75th, 95th, and 100th percentile values for each VOC were available. For the mean and each percentile, the values of individual VOCs were summed to yield a composite outdoor TVOC concentration. Each statistic must be regarded as a composite since there is no guarantee that the percentiles of the individual VOC concentrations were concomitant. A lognormal distribution with GM = 69.4 μg/m^3 and GSD = 2.35 was fit to these composite outdoor TVOC statistics. Fractional composition of individual VOCs in outdoor TVOC was regarded as constant across the distribution and determined by the makeup of the median composite outdoor TVOC.

A similar method was used with the BASE indoor values to generate summary statistics for composite indoor TVOC (median = 260.5 μg/m^3). Indoor concentrations were then assumed to be bimodal, the two sources being outdoor-to-indoor transport and primary whole-building emissions. A lognormal distribution was estimated for ventilation rates observed in BASE buildings [14]. A series of Monte Carlo trials (separate from sector-wide Monte Carlo analysis) was then used to find the lognormal distribution of

Table 1
Different periods of time considered in the simulation and their respective occupancy classes and airflow rates.

Period	Subscript	Time	Occupancy	Ventilation rate	Recirculation	Infiltration
Flush	fl	6 a.m.–7 a.m.	No	$28.3 f_f$ l/s ($60 f_f$ cfm)	No	Night rate if $f_f = 0$ Day rate if $f_f \neq 0$
Off-peak	op	7 a.m.–8 a.m. & 6 p.m.–10 p.m.	Variable	$\dot{V}_v \triangleq R_aA_z + R_pP_z$	Constant	Day rate (constant)
Daytime	da	8 a.m.–6 p.m.	Variable	$\dot{V}_v \triangleq R_aA_z + R_pP_z$	Constant	Day rate (constant)
Nighttime	ni	10 p.m.–6 a.m.	No	0	No	Night rate (constant)

Table 2
Model contaminants and their specific source and loss terms.

	Contaminant	Sources (μg/m³-h)	Loss rate (h⁻¹)
1	TVOC primary emissions	$\frac{E_{TVOC}}{V}$	$\lambda_v + \lambda_i$
2	TVOC from outdoors	$(\lambda_v + \lambda_i)C_{TVOC,out}$	$\lambda_v + \lambda_i$
3	TVOC secondary emissions, building materials/furniture	$G_{bm}y_{bm}\beta_{O_3,bm}\frac{C_{O_3}}{G_{O_3}}$	$\lambda_v + \lambda_i$
4	TVOC secondary emissions, occupant skin and clothing	$G_{occ}y_{occ}\beta_{O_3,occ}P_z\frac{C_{O_3}}{G_{O_3}}$	$\lambda_v + \lambda_i$
5	$PM_{2.5}$	$((1-\eta_{v,PM_{2.5}})\lambda_v + p_{PM_{2.5}}\lambda_i)C_{PM_{2.5},out}$	$\lambda_v + \lambda_i + \eta_{r,PM_{2.5}}\lambda_r + \beta_{PM_{2.5}}$
6	$PM_{2.5-10}$ [a]	$((1-\eta_{v,PM_{2.5-10}})\lambda_v + p_{PM_{2.5-10}}\lambda_i)C_{PM_{2.5-10},out}$	$\lambda_v + \lambda_i + \eta_{r,PM_{2.5-10}}\lambda_r + \beta_{PM_{2.5-10}}$
7	Ozone [b,c]	$(\lambda_v + \lambda_i)C_{O_3,out} + \frac{E_{O_3}P_z}{V}$	$\lambda_v + \lambda_i + \beta_{O_3,bm} + \beta_{O_3,occ}P_z$
8	CO_2 [b]	$(\lambda_v + \lambda_i)C_{CO_2,out} + \frac{E_{CO_2}P_z}{V}$	$\lambda_v + \lambda_i$

[a] Using integrated filtration/deposition/penetration parameters over the two particle diameter ranges 0–2.5 μm and 2.5–10 μm gives the best representation of size-resolved behavior. See Section 2.9 for details.
[b] Ozone and CO_2 expressions are in terms of mass concentration, but results are reported in ppb and ppm respectively. The CO_2 emission rate was constant at 0.3087 l/min (0.0109 cfm) per occupant, a rate associated with a typical office activity level of 1.2 met. Outdoor CO_2 was constant at 450 ppm.
[c] Ozone emissions are from a photocopier, for which the rate of use is modeled as proportional to occupant density.

whole-building emissions, given the distributions of ventilation rates and TVOC outdoor and indoor concentrations. The result was a median emission rate of 613 μg/h/m² of floor area (57 μg/h/ft² of floor area), corresponding for ETVOC/V to a GM = 252 μg/m³ h and GSD = 1.62. Species fractions of TVOC from emissions were regarded as constant across the distribution. Compositional information on indoor and outdoor TVOC is available in the Supplementary Information (SI).

2.6. Ozone and particles

Outdoor PM and ozone concentrations were taken directly from EPA hour-resolved monitoring data [17]. All data from 2007 to 2010 at sampling sites located in counties in each city's Metropolitan Statistical Area (MSA) [18] were included. The dataset therefore includes both suburban and urban samples. EPA reference method data for $PM_{2.5}$ were used for all cities except Houston and Minneapolis, where none were available and non-reference method data were used. No PM_{10} simulation was performed for Houston since hourly resolved outdoor data were not available there. All PM was from outdoors in the simulation; however ozone was also generated indoors by photocopier use. The generation rate was 300 μg/h-occ, based on an assumption of 15 ug/copy and 20 copies per occupant per hour.

The data were processed so that each observation represented a full day with measured values at each hour. The observations were then sampled directly, with equal representation among the six cities and the four seasons (defined in the usual way, e.g. 21 March–21 June for spring). Values between hours were linearly interpolated. When reported as a single model input, in summaries, or the sensitivity analysis, the C_{out} values for $PM_{2.5}$, PM_{10}, and ozone are the daytime (8 a.m.–6 p.m.) mean outdoor concentration.

2.7. Indoor chemistry

Ozone gas-phase chemistry was not found to have a large impact on the concentration of any of the included contaminants, so only ozone surface reactions were included in the model. The relevant parameter for surface reactions is the deposition rate, β (h⁻¹). For building materials and furniture, a lognormal distribution with GM 2.5 h⁻¹ and GSD 1.5 was used for $\beta_{O_3,bm}$. The distribution was selected as representative based on the many field measurement values summarized in Weschler [19] and is the same as was used in a recent modeling study of residences [20]. For human skin and clothing, parameters were derived from Wisthaler and Weschler, who reported deposition velocities on the order of 0.4–0.5 cm s⁻¹ for a nominal human skin/clothing surface area of 1.7 m² per occupant [21]. Selecting the low limit of the deposition velocity range yielded $\beta_{O_3,occ} = 0.108$ h⁻¹ per occupant.

Products of these building material and human surface reactions were also included. For building materials and furniture, molar yields were derived primarily from the secondary emission rate (SER) work of Wang and Morrison [22]. Their field test results from a 14 year old house were combined (assuming an 80/20 ratio of carpet-like to kitchen counter-like surfaces), and then averaged with the yields derived from a chamber test of a carpet. Wang and Morrison had difficulty measuring acetaldehyde and also reported very high nonanal yields, so results for 1-, 2-, 3-, 5-, 6-, and 9-aldehydes were augmented, either by averaging or substitution based on engineering judgment with yields reported for SER chamber experiments [23]. The resulting total aldehyde molar yield was 0.31. For occupant skin and clothing reactions, molar yields were taken directly from those reported by Wisthaler and Weschler for their in vivo experiment [21]. The resulting total product molar yield was 0.40. Composition of secondary products is available in the SI.

2.8. Particulate filtration, deposition, and penetration

Particles of different sizes are affected in dramatically different ways by filtration, deposition, and envelope penetration. Following the general methodology of Riley et al. [24], representative size distributions were used to calculate integrated parameters according to $x = \sum x_j m_j / \sum m_j$, where x is the parameter of interest, x_j is its value in size bin j, and m_j is the mass of the particles in size bin j. The summation was conducted over two ranges of particle diameter, one from 0 to 2.5 μm ($PM_{2.5}$) and one from 2.5 to 10 μm ($PM_{2.5-10}$). Using $PM_{2.5-10}$ rather than PM_{10} yielded integrated particle parameters that represented actual size-resolved particle behavior much more accurately. Results are still reported in terms of PM_{10}. In addition, since the particle size distributions are different indoors and outdoors, integrated parameters were calculated for both ventilation and recirculation airflows.

Particle size-resolved inputs were derived from a number of sources, and generally followed the methods of Waring and Siegel

Table 3
Summary of ventilation strategies and their respective airflow rates.

	Strategy	Standard	R_a, l/s (cfm)	R_p, l/s (cfm)	DCV	f_f
1	Fixed	62.1-2010	28.3 (60)	2.4 (5)	No	0
2	DCV	62.1-2010	28.3 (60)	2.4 (5)	Yes	0
3	DCV + 1fl	62.1-2010	28.3 (60)	2.4 (5)	Yes	1
4	DCV + 2fl	62.1-2010	28.3 (60)	2.4 (5)	Yes	2
5	DCV + 3fl	62.1-2010	28.3 (60)	2.4 (5)	Yes	3
6	2001 VRP	62-2001	0 (0)	9.4 (20)	No	0

[25]. The base outdoor mass distribution was the urban one reported by Jaenicke [26]. Filter efficiency data were obtained from ASHRAE Standard 52.2 tests for Minimum Efficiency Reporting Value (MERV) <5, 6, 11, and 15 filters [27], and extended beyond the testing range of 0.3–10 μm with the method of Riley et al. [24] according to the fibrous filtration theory outlined in Hinds [28]. Deposition values were those modeled by the Riley et al. least squares fit for experimental data, and values for envelope penetration followed their application of the idealized crack theory of Liu and Nazaroff [29]. For the indoor distribution, nominal median ventilation, recirculation, and infiltration air exchange rates (0.64 h^{-1}, 4.16 h^{-1}, and 0.25 h^{-1}, respectively) were used to determine the steady state mass distribution for each MERV filter. For simplicity, it was assumed that the same MERV filter acts on ventilation and recirculated air.

Integrated particle penetration, which was modeled as dependent on the outdoor size distribution, was constant at 0.975 for $PM_{2.5}$ and 0.288 for $PM_{2.5-10}$. For filtration, a distribution of filter use across the office sector was required. BASE data on test space filter ratings ($N = 182$) indicated that the cumulative percentage of office HVAC systems using MERV6 or below was 20.9%, MERV11 or below was 76.9%, and MERV15 or below was 95.0%. These distribution data were used along with the integrated filtration removal efficiencies of each filter to develop lognormal distributions for particle removal over the office building stock for ventilation and recirculation in the two integrated size ranges. Samples were redrawn if they exceeded the set maximum values (listed in Table 4). Note that for Monte Carlo simulations, since the same filter acts on both $PM_{2.5}$ and $PM_{2.5-10}$ and on ventilation and recirculated air, only the efficiency for $PM_{2.5}$ ventilation air was sampled directly from its distribution; distribution parameters were then used to compute the appropriate values for the other three PM composition classes.

Values for the integrated deposition rate β for $PM_{2.5}$ and $PM_{2.5-10}$ under MERV6, MERV11, and MERV15 filtration were plotted against the filtration efficiency for $PM_{2.5}$ ventilation air and good fits were

Table 4
Summary of distribution-based input parameters.

Input	Location	Lognormal parameters		Percentiles					
		GM	GSD	10%	25%	50%	75%	90%	Max
$P_{z,des}$ (occ/100 m^2)	All cities	5.21	1.69	2.69	3.77	5.11	7.53	10.22	47.34
$P_{z,ave,da}$ (occ/100 m^2)	All cities	3.37	1.72	1.69	2.37	3.36	4.84	6.67	31.09
$P_{z,frac,da}$ (−)	All cities	–	–	0.56	0.60	0.65	0.70	0.73	1.00
E_{TVOC}/V (μg/m^3-h)	All cities	251.7	1.62	134.8	182.2	252.0	348.5	465.6	2193.6
$C_{TVOC,out}$ (μg/m^3)	All cities	69.1	2.34	23.2	39.2	69.0	123.1	206.3	1929.9
$C_{O_3,out}$ (ppb)	Average	–	–	18.5	25.6	34.8	45.1	54.8	105.18
	Houston	–	–	17.1	22.9	31.4	41.7	51.9	91.62
	Los Angeles	–	–	22.1	30.4	39.2	48.9	59.9	105.18
	Minneapolis	–	–	18.8	25.1	32.2	40.9	48.9	76.10
	Philadelphia	–	–	17.7	24.7	34.1	46.8	57.7	99.62
	Phoenix	–	–	27.6	35.5	44.1	53.0	59.4	76.41
	Seattle	–	–	14.3	21.0	27.9	35.3	41.7	76.42
$C_{PM_{2.5},out}$ (μg/m^3)	Average	–	–	4.4	6.0	8.4	15.6	22.8	78.06
	Houston	–	–	6.2	7.0	9.1	12.4	19.5	28.63
	Los Angeles	–	–	5.5	8.1	15.4	21.5	30.8	43.51
	Minneapolis	–	–	4.7	6.7	9.6	16.3	21.3	40.64
	Philadelphia	–	–	5.3	8.4	13.7	21.5	29.7	78.06
	Phoenix	–	–	4.8	5.5	7.0	8.8	12.0	22.72
	Seattle	–	–	2.9	3.4	4.7	7.0	9.5	26.54
$C_{PM_{2.5-10},out}$ (μg/m^3)	Average	–	–	11.58	16.04	23.75	34.86	49.35	124.65
	Houston	–	–	–	–	–	–	–	–
	Los Angeles	–	–	15.03	22.89	32.85	45.35	62.17	118.17
	Minneapolis	–	–	11.94	15.96	22.12	31.12	42.28	110.37
	Philadelphia	–	–	11.75	16.31	22.73	32.31	46.31	102.54
	Phoenix	–	–	15.06	19.84	27.83	38.89	52.70	124.65
	Seattle	–	–	8.93	12.16	15.96	23.34	32.36	75.91
$\beta_{O_3,bm}$ (h^{-1})	All cities	2.5	1.50	1.5	1.9	2.5	3.3	4.2	13.01
$\beta_{PM_{2.5}}$ (h^{-1})	All cities	–	–	0.07	0.07	0.08	0.09	0.09	0.12
$\beta_{PM_{2.5-10}}$ (h^{-1})	All cities	–	–	2.07	2.39	2.74	3.09	3.41	4.86
$\eta_{v,PM_{2.5}}$ (−)	All cities	0.12	3.72	0.02	0.05	0.12	0.29	0.64	0.95
$\eta_{r,PM_{2.5}}$ (−)	All cities	0.08	3.40	0.02	0.04	0.08	0.18	0.38	0.95
$\eta_{v,PM_{2.5-10}}$ (−)	All cities	0.56	1.64	0.30	0.40	0.56	0.78	1.00	1.00
$\eta_{r,PM_{2.5-10}}$ (−)	All cities	0.51	1.76	0.25	0.35	0.51	0.74	1.00	1.00
$\lambda_{i,ni}$ (h^{-1})	Average	–	–	0.10	0.18	0.34	0.63	1.07	11.08
	Houston	0.44	2.42	0.14	0.24	0.46	0.81	1.34	8.48
	Los Angeles	0.44	2.36	0.14	0.24	0.44	0.80	1.30	11.08
	Minneapolis	0.20	2.41	0.06	0.11	0.20	0.37	0.62	4.11
	Philadelphia	0.28	2.43	0.09	0.15	0.28	0.51	0.83	5.32
	Phoenix	0.44	2.40	0.14	0.24	0.45	0.81	1.34	8.72
	Seattle	0.28	2.38	0.09	0.15	0.29	0.51	0.82	4.15
$\lambda_{i,da}$ (h^{-1})	Average	–	–	0.02	0.04	0.10	0.22	0.42	7.16
$\lambda_p = \lambda_v + \lambda_r$ (h^{-1})	All cities	4.80	1.56	2.69	3.54	4.78	6.43	8.39	14.98

found, with $\beta_{PM_{2.5}} = 0.171\eta^2_{v,PM_{2.5}} - 0.1378\eta_{v,PM_{2.5}} + 0.0918$ ($R^2 = 0.983$) and $\beta_{PM_{2.5-10}} = -0.392\ln(\eta_{v,PM_{2.5}}) + 1.9018$ ($R^2 = 0.989$). (These formulas yield $\beta_{PM_{2.5}} = 0.08\ h^{-1}$ and $\beta_{PM_{2.5-10}} = 2.73\ h^{-1}$ at the median value of $PM_{2.5}$ ventilation filtration efficiency.)

2.9. Infiltration

For building infiltration at night, when the HVAC system is off and the building is unpressurized, the starting point was the lognormal fit (GM 0.34 h^{-1} and GSD 2.0) developed by Chan, who used a set of leakage measurements, Commercial Buildings Energy Consumption Survey (CBECS) information, and a combination of the LBL and Shaw–Tamura infiltration models to predict infiltration in unpressurized buildings over the US commercial building stock [30,31].

Each sampled value was then multiplied by a regional coefficient. These coefficients were derived from the overall and four regional lognormal distributions of the Murray and Burmaster fit to 2844 values for residential infiltration [32]. Regional fractions were defined as the ratio of the regional GM to the overall GM, under the operational assumption that the relation of median infiltration between regions in commercial buildings is similar to the relation of median air exchange between regions in residences. This procedure yielded fractions of 0.59 for Minneapolis, 0.81 for Philadelphia, 0.83 for Seattle, and 1.30 for Houston, Los Angeles, and Phoenix.

To account for building height differences, results from the CBECS 2003 [33] were used to probabilistically assign each Monte Carlo sample to one of five size bins, and then based on size to assign it a number of stories. Distributions were estimated for leakage rates at 75 kPa reported for blower door tests in a leakage dataset [34] and 24 additional measurements from New York state [35]. These were used to develop treatment effects for building height, again using ratios of GMs. The resulting factors were 1.20 for one story, 0.85 for two stories, 0.86 for three stories, and 0.56 for greater than three stories.

To adjust for pressure effects during the day, some energy modelers have multiplied the night infiltration rate by 0.25 [36], while others have suggested less reduction for tall buildings where stack and wind effects reduce the influence of mechanical pressurization. In this study, slightly larger fractions were used with some provision for different effects in taller buildings. The fraction was generated by a beta distribution with $q = 1.4$ and $r = 2.5$ (central tendency 0.35) for buildings with five or fewer stories and a beta distribution with $q = 2.5$ and $r = 2.5$ (central tendency 0.50) for buildings with more than five stories.

2.10. Monte Carlo sampling and ventilation strategies

In the Monte Carlo simulation, 2000 full-day samples were drawn for each of the 24 city/season combinations, for a total of 8000 samples per city and 48,000 samples overall. For each of these 48,000, six ventilation strategies were tested, for a total of $N = 288{,}000$ runs. The strategies are given in Table 3. The values of R_p in Table 3 are multiplied by P_z, as per Equation (1). For fixed cases (1 and 6), the value of P_z is the design zone population. For DCV cases, the value of P_z is the actual zone population, and the ventilation rate follows population changes exactly. Such ideal or tracking DCV is increasingly practical in spaces with people counters, radio frequency enabled employee ID tags, and/or other occupancy sensors; where these sensors are not available, simple control methods exist to use CO_2 to estimate zone population and closely approximate tracking DCV [3,8]. Ventilation strategy 1, fixed ventilation with current Standard 62.1-2010 rates, is the base case for comparisons. All IAQ modeling represents days in which the outdoor air supply is limited to the ventilation rate, i.e., no economizer use.

2.11. Summary of office sector parameters

The IAQ-related parameters described in Sections 2.4–2.10 that are distribution-based are summarized in Table 4. When lognormal distribution parameters are listed, they usually characterize the distribution used to generate samples; the exceptions are $P_{z,\text{ave,da}}$ and $\lambda_{i,\text{ni}}$, which were generated by other methods but observed to be sufficiently lognormal to provide reasonable fits. For filtration, sample values were generated from lognormal distributions but rejected if they exceeded the value in the maximum column; similarly, for primary supply air exchange rate, $\lambda_p = \lambda_v + \lambda_r$, the values were generated from a lognormal distribution but increased to the ventilation air exchange rate if at any time λ_v exceeded the sampled value of primary air supply.

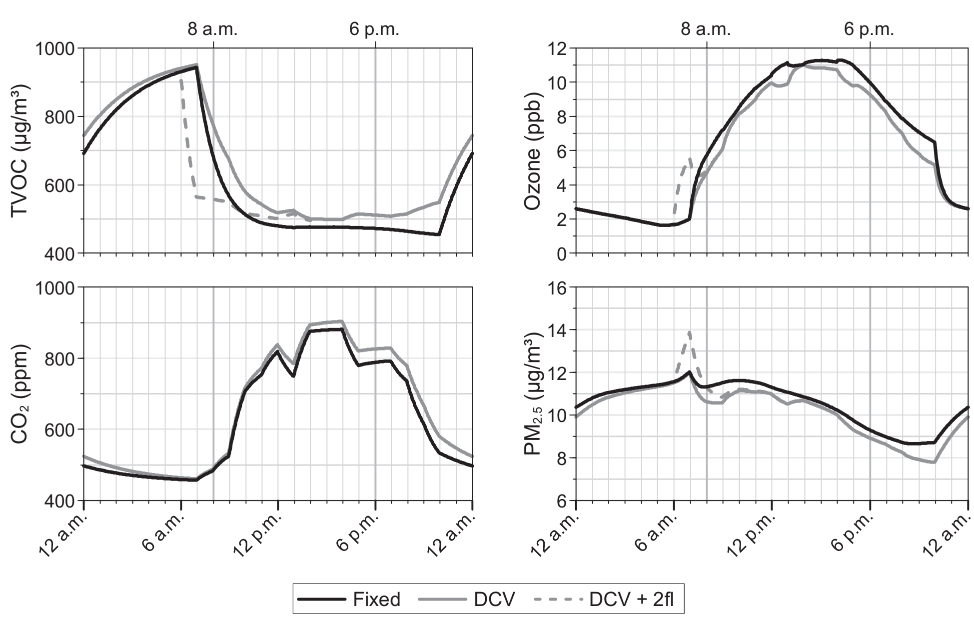

Fig. 1. 24 h concentrations for TVOC, ozone, CO_2, and $PM_{2.5}$ for the illustrative scenario in Philadelphia.

3. Results and discussion

3.1. Illustrative transient case

A sample case illustrates many of the observed trends, shown in Fig. 1. It was generated with median office sector inputs and average hourly outdoor concentrations in Philadelphia in the summer. Design occupant density was 5.11 occupants per 100 m^2 (4.75 occupants per 1000 ft^2), and P_z at each hour was generated by sampling the binomial distribution, as described in Section 2.4.

In Fig. 1 and hereafter, TVOC refers to the sum of TVOC from all sources (primary emissions, secondary emissions, and indoor/outdoor transport). Using ASHRAE 62.1-2010 rates with fixed ventilation, TVOC reaches a near steady state around 11 a.m. The concentration tails off very slightly in the late afternoon, as ozone and occupancy levels—and therefore secondary products—begin to decrease, but ventilation remains constant. At 10 p.m. the system is shut off and the only removal is due to nighttime infiltration, and the concentration approximately doubles during the night. At 7 a.m. the system begins ventilating again and the concentration decreases, but slowly, since at this air exchange rate the time to 95% of steady state is just over 5 h. The high nighttime concentration, combined with the slow morning decrease, together have the effect of elevating the daytime mean. Furthermore, the daytime peak TVOC occurs at 8 a.m., a pattern typical of many, though not all, cases.

The overall TVOC concentration pattern is similar when using ASHRAE 62.1-2010 rates with DCV. Qualitatively, the effects are a slight increase throughout the day, a slower decline in the morning, and a rise in the early evening. The slower morning decline accounts for most of the greater mean and peak values observed with DCV. By the afternoon, when the zone population is near design and the nighttime effects have decayed, TVOC concentration with DCV only slightly exceeds the fixed ventilation baseline. DCV impacts on secondary emissions play only a minor role. When the ventilation rate is reduced (e.g. at lunchtime and in the early evening), the dominant effect is that less TVOC is removed and concentration rises; this effect overwhelms any TVOC reductions due to reduced supply of ozone and skin surfaces for reactions. Adding a flush with $f_f = 2$ (i.e., 56.6 l/s or 120 cfm), reduces both peak and mean TVOC by reducing the concentration at the beginning of the workday. Between about noon and 6 a.m. the next morning, this strategy is basically identical to DCV without a flush.

For ozone, three effects dominate the transient profile. The first is the diurnal outdoor ozone concentration, which is at its minimum (16 ppb) at 5 a.m. and its maximum (54 ppb) at 3 p.m. The second is that, because most ozone comes from outdoors, greater outdoor-to-indoor air exchange increases the indoor concentration. The third is the high loss rates of ozone due to scavenging by building materials and occupant skin and clothing. Together these account for the shape of the ozone/time curve, which follows outdoor trends at a fraction of outdoor values when ventilation is on, and quickly drops to very low concentrations when the only source of ozone is infiltration. Indoor sources from photocopier emissions play an extremely minor role, but they might be more important during periods of high volume photocopying, which were not simulated. Under these circumstances, changing ventilation strategies within the range considered has very little effect. Implementing DCV yields very slight reductions in concentration throughout the day. The flush produces a small spike, but this effect quickly decays.

Like ozone, $PM_{2.5}$ is driven by outdoor concentration but suppressed by high non-ventilation removal, due in this case to filtration. The outdoor peak (20.8 $\mu g/m^3$ at 9 a.m.) is reflected only in a very mild local maximum indoors. The concentration decreases during the day because outdoor levels decrease during the day and

Table 5
Summary of daytime mean and peak values under fixed ventilation and DCV, as well as the percent change, which is defined as DCV concentration minus the baseline concentration, divided by the baseline concentration × 100.

City	Fixed VRP			DCV			% change		
	10th	50th	90th	10th	50th	90th	10th	50th	90th
Mean total TVOC ($\mu g/m^3$)									
Hou	246	448	824	263	486	903	3	7	15
LA	258	455	829	276	492	902	3	7	15
Min	295	518	927	324	577	1029	4	10	19
Phl	278	494	903	301	543	996	4	9	18
Phx	257	459	828	274	495	901	3	7	15
Sea	271	487	885	295	536	979	4	9	18
Peak total TVOC ($\mu g/m^3$)									
Hou	268	551	1206	291	622	1394	4	11	25
LA	280	552	1202	306	619	1383	4	11	24
Min	373	785	1631	424	914	1928	6	14	31
Phl	324	681	1498	361	784	1770	5	13	28
Phx	278	556	1190	302	624	1386	4	10	24
Sea	321	682	1465	359	785	1726	5	13	28
Mean $PM_{2.5}$ ($\mu g/m^3$)									
Hou	1.3	5.3	11.8	1.3	5.1	11.5	−6	−3	−1
LA	1.8	7.5	19.6	1.7	7.3	19.1	−6	−3	−1
Min	1.1	5.0	13.5	1.0	4.8	13.1	−7	−3	−1
Phl	1.5	6.7	18.3	1.4	6.4	17.8	−7	−3	−1
Phx	1.1	4.1	7.5	1.0	4.0	7.4	−6	−2	−1
Sea	0.6	2.5	6.0	0.6	2.4	5.9	−7	−3	−1
Peak $PM_{2.5}$ ($\mu g/m^3$)									
Hou	2.2	7.7	17.6	2.0	7.4	17.0	−9	−3	−1
LA	3.0	12.5	27.1	2.9	11.9	26.3	−8	−3	−1
Min	1.8	7.6	19.3	1.7	7.3	18.6	−10	−4	−1
Phl	2.4	10.0	27.5	2.2	9.6	26.7	−9	−3	−1
Phx	1.8	5.8	13.0	1.7	5.6	12.6	−8	−3	0
Sea	1.0	3.7	9.0	1.0	3.5	8.6	−10	−4	−1
Mean PM_{10} ($\mu g/m^3$)									
Hou	–	–	–	–	–	–	–	–	–
LA	2.1	9.0	20.9	2.0	8.6	20.3	−7	−3	−1
Min	1.2	5.9	14.5	1.2	5.6	14.0	−8	−4	−1
Phl	1.6	7.4	18.8	1.5	7.1	18.2	−7	−3	−1
Phx	1.3	5.6	10.1	1.2	5.3	9.7	−8	−4	−1
Sea	0.8	3.4	7.2	0.7	3.2	6.9	−8	−4	−2
Peak PM_{10} ($\mu g/m^3$)									
Hou	–	–	–	–	–	–	–	–	–
LA	3.4	13.8	28.9	3.2	13.2	27.9	−9	−3	−1
Min	2.0	8.5	20.1	1.9	8.1	19.2	−10	−4	−1
Phl	2.6	10.6	27.8	2.4	10.2	26.8	−9	−4	−1
Phx	2.2	8.2	17.1	2.0	7.7	15.9	−13	−5	−1
Sea	1.2	4.8	10.5	1.1	4.5	9.9	−12	−5	−1
Mean ozone (ppb)									
Hou	3.7	7.5	13.9	3.5	7.0	13.2	−10	−6	−2
LA	4.7	9.2	16.4	4.4	8.6	15.5	−10	−6	−3
Min	3.8	7.1	12.1	3.5	6.6	11.2	−10	−7	−3
Phl	3.7	7.7	14.3	3.5	7.2	13.3	−10	−6	−3
Phx	5.6	10.1	16.8	5.2	9.5	15.9	−10	−6	−3
Sea	3.1	6.3	10.9	2.9	5.9	10.2	−10	−6	−3
Peak ozone (ppb)									
Hou	4.7	9.2	17.4	4.5	8.8	16.4	−9	−4	−1
LA	6.2	11.6	20.9	6.0	11.0	19.7	−10	−4	−1
Min	4.6	8.3	14.3	4.5	7.9	13.3	−10	−4	−1
Phl	4.7	9.2	17.5	4.6	8.8	16.3	−10	−4	−1
Phx	7.0	12.2	20.4	6.7	11.5	19.1	−10	−5	−1
Sea	4.2	7.7	13.2	4.0	7.4	12.2	−10	−4	−1
Mean CO_2 (ppm)									
Ave.	605	752	963	611	772	1024	1	3	7
Peak CO_2 (ppm)									
Ave.	685	880	1157	688	892	1194	0	1	4

because recirculation-driven filtration continues to remove particles. The concentration rises overnight because recirculation (and therefore filtration) is turned off, so that by envelope penetration the indoor concentration slowly approaches outdoor the outdoor level. As with ozone, the impacts of the ventilation strategy are minimal. The concentration of PM_{10} is almost the same as $PM_{2.5}$. Because filtration is significantly better at removing large particles, and because large particles deposit from the air more quickly, relatively few indoor particles of outdoor origin have diameters greater than 2.5 μm.

Carbon dioxide levels begin the workday close to the outdoor concentration of 450 ppm, and increase as occupants arrive. Because the total air exchange with outdoors is relatively low, the approach to the new steady state after a change in zone population is slow and as a rule not achieved before the next change. With DCV, there is only a very slight rise in CO_2 concentration. With an area-minimum ventilation rate, DCV acts very much like fixed ventilation, since a decrease in occupant density has a much greater proportional impact on the total CO_2 generation rate than it does on the total ventilation rate. (For example, if one of four occupants in a 100 m^2 zone leaves, CO_2 generation is reduced by 25%, but the ventilation rate is only reduced by 6%.) One important implication is that, although CO_2 concentration may be a useful proxy for ventilation rate, it is not a sufficient indicator of IAQ in this implementation.

3.2. Monte Carlo analysis of DCV

Table 5 presents a summary of Monte Carlo results for daytime mean and peak of TVOC, $PM_{2.5}$, PM_{10}, and ozone (all by metropolitan area) and of CO_2 (as the average of the six cities since results were nearly identical). Three output distributions are summarized by their 10th, 50th, and 90th percentile values. The first two distributions are simulated concentrations under fixed ventilation and under DCV. The third is the distribution of percent changes. For each Monte Carlo sample, the percent change is first the DCV concentration minus the baseline concentration then divided by the baseline concentration × 100.

For TVOC, the differences among cities are far smaller than the variability observed within cities, as indicated by the spread of the percentiles. This fact is because the TVOC concentration results are most influenced by the primary emissions. The median concentrations by source (overall cities and ventilation strategies) are: 355 μg/m^3 due to emissions, 69 μg/m^3 introduced from outdoors, 24 μg/m^3 due to ozone surface reactions on building materials and furniture, and 5 μg/m^3 due to ozone surface reactions on occupant skin and clothing. Nonetheless, there are clear regional effects, due to two factors. The predominant one is that the infiltration rate is lower in colder climates, which increases mean and especially peak levels. This factor accounts for most of the differences between TVOC values observed in Minneapolis and Houston/Los Angeles/Phoenix. The secondary factor is outdoor ozone levels, which account for variability of about 10 μg/m^3 in daytime mean values and none of the variability in daytime peak values.

Implementing DCV increases the daytime means and peaks of TVOC in all cities, again with a slightly greater effect in colder cities with less infiltration. The differences observed in moving from fixed ventilation to DCV, like the differences among cities, are far smaller than the underlying process variability, which is due primarily to emission rate variability. For example, the 10th percentile office under DCV has much lower TVOC concentration than the median office under fixed ventilation. In terms of percent changes from DCV implementation, only 10% of buildings should experience increases in mean TVOC greater than about 15–20% or increases in peak TVOC greater than about 25–30%.

Assessing the impact of DCV (or other input parameters) on absolute TVOC concentration levels is more difficult, since neither ASHRAE nor other US regulatory bodies give direct guidelines for acceptable TVOC levels. In 2007, the German Federal Environment Agency proposed a tiered series of recommendations. Their Level 2 ranges from 300 to 1000 μg/m^3 and indicates no "relevant health-related concerns", while Level 3 ranges from 1000 to 3000 μg/m^3 and indicates "some objections and distinct health issues" [37]. With fixed ventilation, 6% of buildings have means and 22% have peaks that exceed 1000 μg/m^3; with DCV these percentages rise to 8% and 30%, respectively.

For particles, regional outdoor concentration differences lead to much greater inter-city variation (although still less than inter-percentile differences). For $PM_{2.5,}$ the ratio of the highest to lowest concentration cities (Los Angeles to Seattle) is about three, consistent across percentiles, for mean and peak, and for fixed ventilation and DCV. The $PM_{2.5}$ levels are not low, especially at the 90th percentile level in Houston, Los Angeles, Minneapolis, and Philadelphia. These are likely the result of high outdoor particle days, and therefore not representative of an annual average, but they nonetheless indicate that in some regions higher filtration

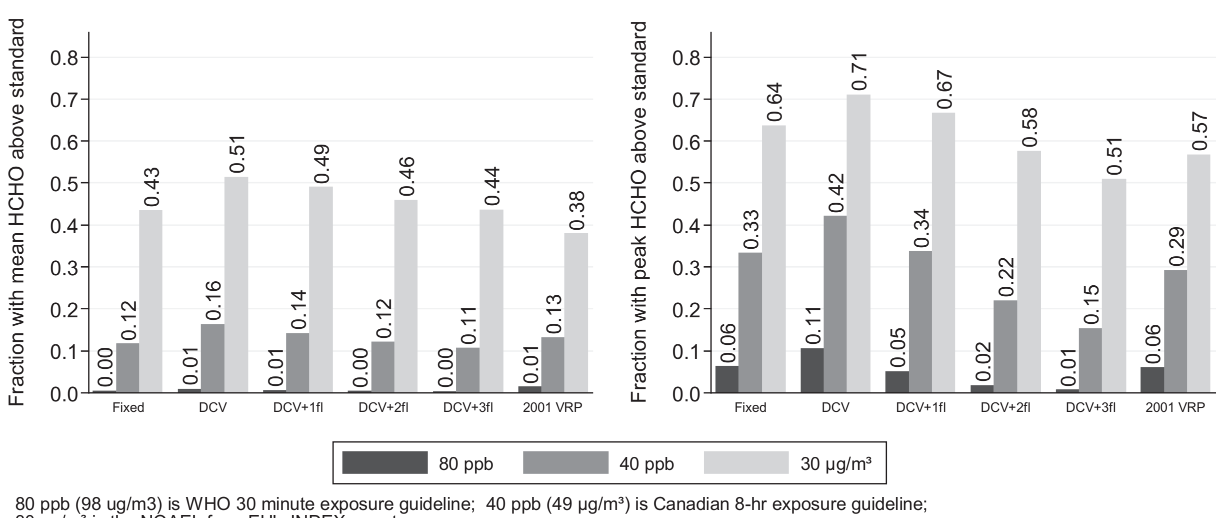

Fig. 2. Fraction of buildings that exceed given formaldehyde (HCHO) guideline levels under the six ventilation strategies.

efficiency may be needed to promote good particulate matter IAQ. Because of the high filtration and deposition removal of larger particles, indoor PM_{10} is composed mostly of $PM_{2.5}$ (about 70–100%, depending on region), and PM_{10} patterns closely follow those of $PM_{2.5}$.

Implementing DCV uniformly decreases $PM_{2.5}$ and PM_{10} daytime means and peaks, with median decreases in all categories of about 3–4%, and only 10% of buildings seeing decreases greater than about 7%. Overall, this change is quite small—nowhere near the magnitude of the differences due to filtration or outdoor concentration—and should probably be regarded as a fortunate side-effect of DCV implementation rather than a direct and measurable benefit.

Indoor ozone concentration also varies among cities, with relationships that are relatively stable across percentile levels, for fixed ventilation and DCV, and for peak and mean. However, the range of differences is small and no more than 5 ppb at the median level for either peak or mean. The regional variation is significantly less than that observed for outdoor ozone, since high reaction rates consume ozone quickly and flatten the differences. Overall, ozone values indoors are low, with at least 90% of buildings having daytime means less than 17 ppb in even the worst city (Phoenix). DCV implementation decreases means and peaks at all percentile levels, but never by more than 1.5 ppb. These changes are so small that, like the PM impacts, ozone decreases should probably be regarded as a fortunate side-effect of DCV implementation.

Carbon dioxide levels display very little regional variation under either fixed ventilation or DCV. Mean concentrations are generally low for both ventilation methods, remaining below 1150 ppm (or 700 ppm above ambient) at all percentiles. Peak concentrations slightly exceed this level at the 90th percentile. The percent change in mean CO_2 levels observed when moving from fixed ventilation to DCV is 7% or less in 90% of modeled buildings, and the proportional impacts on peak levels are even smaller.

3.3. Flushing and protecting worst-case scenario office spaces

According to the Monte Carlo results, the greatest IAQ impact of DCV is on TVOC levels. From the transient illustration, it is clear that much of this impact is because DCV allows the nighttime buildup of contaminants to persist longer into the day, increasing both mean and peak levels. One way to limit the impact is to augment DCV with a morning flush, which is defined here as ventilating at some multiple of the area minimum for the hour prior to the normal HVAC system startup time. As an example of the impact of the flush strategy, Fig. 2 indicates the fraction of buildings in which the mean or peak concentration of one TVOC constituent, formaldehyde, exceeds three levels. (These thresholds are identified in guidelines, but are not applied here according to their specific definitions or time intervals). All six ventilation strategies are shown, including fixed, DCV, DCV with flushes of three multiples of the area minimum (i.e., $f_f = 1$, 2, or 3), and fixed ventilation with the ASHRAE 62-2001 VRP rates.

With fixed ventilation, about 12% of buildings have mean values that exceed the 40 ppb level. Implementing DCV increases this value to 16%. Using DCV and adding a flush with $f_f = 2$ reduces the percentage back to 12%. The results are even more dramatic for daytime peak levels. For example, six percent of buildings using fixed ventilation exceed the less stringent 80 ppb level at some point during the day. The figure nearly doubles to 11% for buildings using DCV. Adding a flush with $f_f = 1$, which merely amounts to starting the ventilation an hour early at the area-minimum rate, reduces the figure to 5%, less than under the baseline strategy. Increasing to $f_f = 2$ decreases the amount further to 2%. Moreover, ozone and PM levels are not meaningfully increased by a morning

Table 6
Actual and standardized regression coefficients (SRC) for the different ventilation strategies and model inputs.

		R^2		Const.	Ventilation strategies DCV	DCV + 1fl	DCV + 2fl	DCV + 3fl	2001 VRP	Model inputs λ_p	$\lambda_{i,ni}$	$\lambda_{i,da}$	$P_{z,des}$	$P_{z,ave,da}$	C_{out} [a]	E_{TVOC}/V	β_{O_3}	$\eta_{lr,PM_{2.5}}$
TVOC	Mean	0.854	Coef.	199.6	48.2	30.9	11.5	−1.6	−27.4	0.03	−48.55	−278.26	−10.19	−9.88	1.00	1.38	1.48	–
			SRC	–	*0.073*	*0.047*	*0.017*	*−0.002*	*−0.041*	*0.000*	*−0.100*	*−0.259*	*−0.129*	*−0.082*	*0.393*	*0.766*	*0.007*	–
	Peak	0.678	Coef.	357.3	99.2	1.8	−109.8	−169.7	−52.1	0.12	−221.58	−325.13	−12.11	−3.56	1.01	1.86	1.60	–
			SRC	.	*0.092*	*0.002*	*−0.103*	*−0.159*	*−0.048*	*0.001*	*−0.277*	*−0.184*	*−0.094*	*−0.018*	*0.256*	*0.642*	*0.005*	–
$PM_{2.5}$	Mean	0.815	Coef.	3.5	−0.2	−0.2	−0.1	−0.1	0.2	−0.30	0.16	1.82	0.05	0.05	0.50	–	–	−10.20
			SRC	.	*−0.013*	*−0.012*	*−0.010*	*−0.009*	*0.012*	*−0.138*	*0.017*	*0.089*	*0.031*	*0.021*	*0.758*	–	–	*−0.503*
	Peak	0.742	Coef.	5.3	−0.3	−0.3	−0.2	−0.1	0.3	−0.41	0.37	2.90	0.05	0.13	0.68	–	–	−14.24
			SRC	.	*−0.017*	*−0.015*	*−0.010*	*−0.006*	*0.015*	*−0.128*	*0.026*	*0.096*	*0.022*	*0.035*	*0.719*	–	–	*−0.475*
Ozone	Mean	0.872	Coef.	3.5	−0.5	−0.5	−0.5	−0.5	0.7	0.00	0.10	5.51	0.17	0.08	0.21	–	−1.77	–
			SRC	.	*-0.049*	*−0.049*	*−0.049*	*−0.048*	*0.067*	*0.001*	*0.013*	*0.316*	*0.136*	*0.042*	*0.721*	–	*−0.494*	–
	Peak	0.834	Coef.	4.7	−0.6	−0.6	−0.6	−0.5	0.9	0.00	0.22	6.73	0.26	0.03	0.24	–	−2.15	–
			SRC	.	*−0.042*	*−0.042*	*−0.042*	*−0.042*	*0.070*	*0.002*	*0.023*	*0.318*	*0.166*	*0.012*	*0.689*	–	*−0.491*	–
CO_2	Mean	0.833	Coef.	589.8	27.6	27.2	26.9	26.7	−54.3	0.01	−6.15	−223.45	–	61.97	–	–	–	–
			SRC	.	*0.074*	*0.073*	*0.072*	*0.071*	*−0.146*	*0.000*	*−0.022*	*−0.351*	–	*0.832*	–	–	–	–
	Peak	0.818	Coef.	686.0	16.1	16.1	16.0	16.0	−70.9	0.04	−6.28	−296.60	–	75.67	–	–	–	–
			SRC	.	*0.035*	*0.035*	*0.035*	*0.034*	*−0.154*	*0.001*	*−0.018*	*−0.372*	–	*0.823*	–	–	–	–

[a] C_{out} refers to the daytime mean outdoor concentration of the relevant contaminant.

flush, since the small spike in their levels during the flush dissipates very quickly, as is illustrated in Fig. 1.

3.4. Monte Carlo sensitivity analysis

In order to assess the six ventilation strategies and compare their effect to the impact of other input parameters, a global sensitivity analysis was conducted. Inputs were divided into two classes. The first includes ventilation strategy treatment effects, which are mutually exclusive categorical variables that indicate which ventilation strategy is used. The baseline corresponds to no treatment effect. The second class includes all quantitative variables that are sampled randomly from distributions or datasets in the Monte Carlo simulation. A simple linear model was found to represent a large amount of the total variability observed in the dataset, with R^2 values in the range of 0.68–0.87. However, since residuals were not normal and IAQ processes are nonlinear with complex input interactions, it is important to regard the linear model as an account of average effects over the entire office sector. Table 6 reports both actual regression coefficients and standardized regression coefficients (SRCs). The SRC, sometimes called a beta coefficient, is the actual coefficient normalized by the ratio of the sample standard deviations of the dependent to independent variables and is useful for assessing the relative importance of the inputs. Data from all cities were included in the regression.

For the ventilation strategy treatment effects, the untransformed coefficients in Table 6 can be regarded as *average* impacts of switching from the baseline to the given strategy. For example, for daytime mean TVOC, on average, using DCV adds 48.2 μg/m^3 to the baseline value, using DCV with $f_f = 1$ adds 30.9 μg/m^3, using DCV with $f_f = 2$ adds 11.5 μg/m^3, and so forth. The roughly 50 μg/m^3 increase in mean and 100 μg/m^3 increase in peak TVOC concentration when moving from fixed ventilation to DCV are fully consistent with the 50th percentile results summarized in Table 5. The regression coefficients also confirm that a flush with $f_f = 1$ is on average sufficient to cancel out the increase in peak TVOC due to DCV implementation, as was shown for formaldehyde in the previous section. Flushes of greater intensity continue to decrease the peak values significantly.

At a glance, it is clear that on average the ventilation strategy does not impact strongly $PM_{2.5}$, ozone, or CO_2. The $PM_{2.5}$ impacts are all 0.3 μg/m^3 or less, the ozone impacts are all 1 ppb or less, and the CO_2 impacts are all (excepting the old VRP strategy) 30 ppm or less. These impacts are on the order of perhaps 1–3% of the range of concern of these contaminants indoors.

With respect to the continuous, non-ventilation strategy parameters, the untransformed coefficients can be used with the input parameter summaries (Table 4) to assess impacts quantitatively. Relative impacts can also be inferred quickly by comparing the SRCs. In general, the sum of the squares of SRCs equals (or nearly equals) the coefficient of determination R^2, so squaring the SRC and dividing by R^2 indicates the fraction of explained variability accounted for by the given input. For an R^2 of 0.8, for example, an SRC of less than 0.2 means that variable accounts for less than 5% of the total explained variability. However, the SRCs for ventilation effects cannot be analyzed in this manner, since as categorical variables they do not indicate the true variance in the underlying ventilation parameters.

For daytime mean TVOC, only the daytime infiltration rate, outdoor concentration, and normalized primary emission rate account for meaningful portions of the observed variation. The ozone deposition rate SRC is small, indicating that, on average, primary emissions and indoor/outdoor transport overwhelm the effect of secondary emissions. The implication is that reducing emissions is by far the single most effective method for reducing daytime mean TVOC concentration. Reducing ETVOC/V from the population median to the 25th percentile level would, on average and independent of other factors, reduce daytime mean TVOC by about 97 μg/m^3, which is a difference that is greater than that resulting from any of the ventilation strategy changes. The results for TVOC peak are similar, but with the addition that nighttime infiltration also plays a significant role, since the peak often occurs first thing in the morning.

For $PM_{2.5}$, the important factors are outdoor concentration, filtration, and primary airflow. Outdoor levels and filtration govern the introduction of particles, and filtration and recirculation flow account for the rate of removal. Increasing $\eta_{v,PM_{2.5}}$ from its population median to the 75th percentile level would, on average and independent of other factors, reduce daytime mean $PM_{2.5}$ by about 1.7 μg/m^3, which is again greater than any of the ventilation effects. For ozone, the important factors are outdoor concentration, daytime infiltration, and deposition rate. To a lesser extent, $P_{z,des}$ also impacts ozone concentration; this is an artifact of the design occupancy's effect on ventilation rate that is not fully accounted for by the ventilation categorical variables. Based on the information included in the model, ozone reactions on building materials/furnishings and occupant clothing/skin do not play a noticeable role in determining TVOC concentration, but they do play an important role in reducing ozone concentration. For CO_2, average occupancy is by far the most important factor, and daytime infiltration is the only other factor with a meaningful effect.

4. Conclusions

This study modeled the impact on IAQ in offices due to changes in ventilation from fixed rates to DCV (with morning flushes considered as well), using a Monte Carlo simulation over the US office sector in six cities, following the VRP rates of ASHRAE Standard 62.1-2010. Results indicate that:

- DCV implementation does not have large impacts on particles or ozone. The decrease in ventilation rate does slightly limit the introduction of these contaminants, which are primarily of outdoor origin, but the concentration difference is small because they already have large non-ventilation loss mechanisms. Carbon dioxide is also little changed by implementing DCV.
- The greatest impact of DCV is on VOCs, on average increasing mean TVOC about 50 μg/m^3 and raising the percent of buildings with means above 1000 μg/m^3 from 6% to 8%. DCV impacts on peak TVOC are greater, on average increasing TVOC by about 100 μg/m^3 and raising the percent of buildings with peaks above 1000 μg/m^3 from 22% to 30%. The principal mechanism is that DCV allows contaminants built up during the night to persist longer into the workday.
- Most of the variation in DCV impacts on TVOC concentration is due to lower average infiltration rates in colder climates. In colder areas, or in buildings known to be tightly sealed, DCV impacts are likely to be slightly greater.
- Adding a flush strategy to DCV mitigates these impacts, especially on peak levels. Even a very mild flush, corresponding to ventilating at the area-minimum rate for an hour, fully counteracts the impact of DCV on peak levels. Stronger flushes — on average, about twice the area-minimum rate — are needed to counteract the DCV impact on mean TVOC, and have the added benefit of reducing peak TVOC below the baseline. These results strongly indicate the potential benefits of a strategy that combines a morning flush and DCV in order to limit IAQ impacts, and even improve IAQ by some measures.

Overall, inter-percentile differences are much greater than ventilation strategy differences. The large per-area and small per-occupant components of the current ASHRAE VRP mean that even under DCV the daytime variance in ventilation air exchange will be relatively small in a typical office, which has fairly low occupant density. One result is that, excepting peak VOC concentrations in the worst-case buildings, offices that move from fixed ventilation to DCV are not likely to experience large IAQ changes. Furthermore, many buildings that make use of free cooling will see no DCV impact on TVOC during many portions of the year, when outdoor air intake is not limited to the minimum ventilation rate.

The Monte Carlo simulation also helps quantify other office IAQ effects, showing that:

- Ozone secondary reactions are responsible for removing significant amounts of ozone from the air, but their TVOC products have concentrations that are one to two orders of magnitude less than TVOC from primary emissions. However, it must be stressed that these products may still be important if they have health or irritation impacts at concentrations in the range of 5–50 $\mu g/m^3$.
- Indoor $PM_{2.5}$ levels in Houston, Los Angeles, Philadelphia, and Phoenix are relatively high in some cases, perhaps indicating a need for better filtration, at least at sometimes of the year.

The results for each city are broadly applicable to locations with similar climates and pollution regimes, and the six cities included in the simulation are typical of many urban and suburban locations in the US. This model only applies to offices, which are the best characterized of commercial buildings in terms of IAQ parameters, but similar distribution-based models could be developed for other occupancy classes. The present office model—and ultimately, perhaps, extensions to other building types—will be useful at the screening level for evaluating sector-wide IAQ sensitivity to many changes in building and HVAC parameters and operation, and for informing ventilation recommendations and other guidelines to promote good IAQ in commercial buildings.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2012.10.013.

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