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Impact of ventilation and filtration strategies on energy consumption and exposures in retail stores

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ABSTRACT

Different ventilation strategies can have an enormous impact on both exposures to contaminants of concern (COCs) and energy use in retail buildings. We applied a multi-contaminant model of an area-normalized retail store, and developed estimates for distributions of model inputs. We then used these distributions in a Monte Carlo simulation for six cities to compare the impacts of the ASHRAE 62.1–2013 ventilation rate procedure (VRP), demand controlled ventilation (DCV), and indoor air quality procedure (IAQP), with or without using a high particulate efficiency filter. Results showed that for cities where outdoor $PM_{2.5}$ concentration is low, adopting the IAQP with low efficiency $PM_{2.5}$ filter in grocery stores and the VRP with high $PM_{2.5}$ efficiency in non-grocery stores yielded the greatest exposure benefits. For cities with high outdoor $PM_{2.5}$ concentration, adopting the VRP with high $PM_{2.5}$ efficiency for all store types yielded the greatest exposure benefits. However, these exposure benefits also caused an increase in energy consumption, and the magnitude depends on the city's climate, outdoor $PM_{2.5}$ concentration and the retail store type. We propose a new pollutant exposure control ventilation (PECV) strategy, where ventilation rates are weighed against exposure to different COCs, and the ventilation rate that is most climatically advantageous is chosen.

1. Introduction and background

The indoor air quality (IAQ) of retail buildings is an important occupational exposure consideration: the retail sector employs 15 million workers, approximately 10% of the U.S. workforce [1], and the average American above the age of fifteen spends 0.48 h per day purchasing goods and groceries [2]. Inside these buildings, ventilation is mainly used to promote the comfort of occupants by diluting emissions of indoor-generated pollutants. The measurable benefits of increased ventilation rates are decreased sick building syndrome symptoms and improved perceived air quality, leading to economic benefits including better productivity and positive impact on retail sales [3–6]. However, in certain situations ventilation may have a negative impact on indoor air quality as it can transport ambient pollution indoors (e.g., [7]). Beside its impact on air quality, ventilation has a great impact on overall building energy consumption; just considering the retail sector, eliminating ventilation would decrease the total energy use index (i.e., building's energy use as a function of its size) by 8.4% on average, with the gas energy use index decreasing by 27.8% [8]. Balancing air quality concerns and energy usage in retail buildings is key to reducing energy consumption without increasing exposure of the occupants.

Over the past two decades, researchers and practitioners have expended considerable effort to find the minimum ventilation rates that will reduce energy consumption while maintaining an acceptable indoor air quality. Among the most commonly adopted ventilation rates are those specified by ASHRAE Standard 62.1–2013 [9]. This standard provides two alternative procedures for selecting the minimum ventilation rate for commercial buildings: 1) a prescriptive approach: the ventilation rate procedure (VRP); and 2) a performance-based approach: the indoor air quality procedure (IAQP).

1.1. Ventilation rate procedure (VRP)

The VRP is the more widely used procedure. The prescribed minimum ventilation rates are the sum of two quantities: the

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minimum rate of outdoor air supply per unit floor area, and the minimum rate of outdoor air supply per occupant. The VRP is assumed to maintain an acceptable indoor air quality as perceived by at least 80% of occupants. Bluyssen et al. [10] tested 44 buildings with mean ventilation rates of 25 L/s·person (far above the current ventilation rates specified by the VRP) and found that air quality in 64% of these buildings did not satisfy 80% of the occupants. In addition, a review of ventilation measurements in retail stores found that half of the stores tested met or exceeded the VRP; nonetheless, these ventilation rates were not sufficient to keep all pollutants below their most conservative limits [11]. Specifically, there is no documentation of the adequacy of VRP in maintaining an acceptable indoor air quality in retail buildings.

One variation to the VRP that further saves energy is the use of demand control ventilation (DCV), often based on CO_2 concentrations in buildings with variable occupancy. The impact of DCV on indoor air quality remains less investigated. To our knowledge, only eight literature studies investigated whether controlling ventilation by measuring occupancy (DCV-based CO_2) could keep pollutants (e.g., formaldehyde, TVOC, radon) below their reference or regulatory limits [12–20]. Five of these studies found that DCV was not sufficient to control the measured pollutants below their established limits. DCV-based CO_2 does not generally control outdoor-generated pollutants, nor does it account for pollutants generated indoors but independently of human activities. Thus, the ability of VRP or DCV to maintain an acceptable IAQ in buildings depends highly on the source strengths, pollutant sources, and infiltration rates, which are specific to building type and location.

1.2. Indoor air quality procedure (IAQP)

Another approach to control ventilation is to follow the performance-based approach, the IAQP, specified in ASHRAE Standard 62.1–2013 [9]. In the IAQP, contaminants of concern (COCs) are selected and the minimum ventilation rate is defined to be the larger rate resulting from an objective assessment based on COCs emission rates and concentration limits, and a subjective assessment of air quality. In the objective assessment, the IAQP requires designers to select the ventilation rate that will keep each individual COC below its established limit. This ignores the fact that some pollutants (e.g. ozone, and some particles) can be generated outdoors, and keeping the ventilation rate to a minimum may be more advantageous from both exposure and energy perspectives. Furthermore, there is often a lack of knowledge of source strengths (used in the IAQP to calculate the required ventilation rate) in different types of buildings and a poor understanding of how different sources of emissions should be added together.

The impacts of VRP, DCV-based CO_2, and IAQP on energy usage and exposure to contaminants of concern, whether generated indoors, outdoors or both, are not sufficiently investigated. This is especially the case for retail stores, which have very few studies on how ventilation rates affect energy, and health. The main objective of this paper is to determine an exposure-based, energy-efficient ventilation strategy for different retail types and locations.

Specifically this paper answers the following questions:

1. What are the effects of ventilation rates determined by VRP, DCV-based CO_2, and IAQP on COCs concentrations found in retail buildings?
2. What happens to COCs concentrations if we increase particle filter efficiency?
3. What is the optimal ventilation–filtration combination strategy that will lead to a balance between exposure to pollutants and energy consumption?

The results from this study could help building designers and other researchers in understanding the impact of different ventilation strategies recommended by energy standards on indoor air quality and HVAC energy use in retail buildings. Additionally, this paper proposes a new ventilation strategy suitable for different retail types and locations that reduces energy consumption without increasing indoor exposures.

2. Simulation methodology

2.1. Overview

The methodology comprises four steps: (1) identifying contaminants of concern; (2) assessing the impact of control strategies on COCs concentrations; (3) quantifying exposures; and (4) computing energy consumption. Each step is summarized below.

2.1.1. Contaminants of concern in retail buildings

Zaatari et al. [11] identified contaminants of concern in retail buildings by using data compilation from 28 literature studies (235 stores, > 70 pollutants), and found that $PM_{2.5}$ and acrolein are the main contaminants of concern for which control methods should be prioritized, with the caveat mentioned in the study that more acrolein concentration data is needed to confirm the finding about acrolein. In the present paper, we used these identified contaminants of concern as well as two additional pollutants, formaldehyde and acetaldehyde, because they were found above their reference exposure limit in few of the tested stores (e.g., Siegel et al., 2013). These two pollutants were used for further assurance that the selected control strategy will not increase concentrations of these pollutants above the level where they will be considered as contaminants of concern (COCs).

2.1.2. Impact of control strategies on COCs concentrations

We used a time-averaged mass balance multi-contaminant model to evaluate two alternative exposure control scenarios. The first control scenario calculates $PM_{2.5}$, acrolein, formaldehyde, and acetaldehyde concentrations based on different ventilation strategies. The second scenario complements the first scenario with increased $PM_{2.5}$ filtration.

Estimates for distributions of inputs across the retail sector were modeled by Monte Carlo simulations for multiple combinations of cities, seasons, store types, and period of day. Six US cities were chosen to cover different climates as well as different outdoor air quality: Austin, Philadelphia, Minneapolis, Seattle, Los Angeles, Phoenix; two seasons: winter and summer; two store types: grocery and non-grocery (reflective of different ventilation requirements in ASHRAE 62.1–2013 [9]); and two periods of the day: store-open and store-closed. A summary of the weather information related to the cities is provided in the supporting information.

The time-average pollutant mass-balance model, provided by Riley et al. [21] is modified by adding an indoor source emission term:

$$C_{out} \times (Q_{OA} \times (1-\eta) + p \times Q_i) + E \times V - C_{in} \times (Q_R \times \eta + \beta \times V + Q_{EX}) = 0 \quad (1)$$

C_{out} and C_{in} are the outdoor and indoor concentrations [μg/m^3], Q_{OA} is the mechanical outdoor air airflow rate [m^3/h], p is the penetration factor of particles through leaks in building envelopes and major openings (dimensionless, ranging from 0 to 1), Q_i is the infiltration airflow rate [m^3/h], E is the indoor emission rate [μg/h], Q_R is the recirculation airflow rate [m^3/h], η is the filter efficiency (dimensionless, ranging from 0 to 1), β is the first-order indoor loss rate of the pollutant by deposition to surfaces and/or reactions [per hour], V is the volume of the store [m^3], and Q_{EX} is the exhaust airflow rate [m^3/h]. The emission sources of the pollutants considered in this analysis are not assumed to change instantaneously, which allows for time-averaged analysis.

We applied this model on a single zone, area-normalized store for easy scalability. An essential requirement to apply this model is to assume a well-mixed space. Several studies have used this assumption for retail stores (i.e., [22–24]). Also, this model assumes that formation and losses by homogenous and heterogeneous reactions are negligible when compared to removal by ventilation. The parameters shown in Eq. (1) are discussed in detail in Section 2.2.

2.1.3. Exposure assessment

The disability-adjusted life year (DALY) metric was chosen as the common metric of exposure to compare exposures to contaminants of concern for different control strategies, as an alternative to relying on the widely varying published health standards or guidelines. The main strength of the DALY metric is that it combines the fatal and non-fatal health outcomes into a single value (i.e. years of life lost due to death and disability) [25]. This metric is commonly used and is endorsed by the World Health Organization (WHO).

Pollutant concentrations calculated from step 2 (described in Section 2.1.2) were used in Monte Carlo simulations to quantify the number of DALYs lost central estimates by sampling from uncertainty distributions of DALY factors reported in epidemiological or extracted from animal toxicity data studies (based on Logue et al., 2012 [26]).

2.1.4. Energy usage assessment

To assess the energy consumption of different ventilation and filtration scenarios, we built an energy model for a typical big-box retail store (10,000 m^2) using the e-Quest building energy modeling software (DOE2 e-Quest, version 3.64, 2010 [27]). We used this model to compare the energy required to cool and distribute the air throughout the building, over the range of different ventilation scenarios, and the six US cities. The different ventilation scenarios were specified by a specific air exchange rate. For that reason, the fan-only mode (i.e. economizer mode), where air exchange rate can be increased (beyond what is defined in ASHRAE Standard 62.1–2013 [9]) when free cooling is provided by the low outdoor temperatures, was not included in this analysis.

The energy usage assessment also takes into consideration the difference of energy used by fans between the different scenarios. As mentioned earlier, the second exposure control scenario repeats the assessment of different ventilation rates but replaces the low $PM_{2.5}$ efficiency filter (ASHRAE Standard 52.2–2012 [27] Minimum Efficiency Reporting Value; MERV 8) with higher $PM_{2.5}$ efficiency filter (MERV 13). The energy used by fans when a low $PM_{2.5}$ efficiency filter is installed was adjusted to account for the additional fan energy used in a case with high $PM_{2.5}$ efficiency filter. Based on the field collected data and energy modeling, Zaatari et al. [28] found that replacing a MERV 8 filter with a MERV 13 filter in units with fan speed control (i.e. units that maintain a constant supply airflow rate) increase the fan power draw by 11%. The fan energy usage takes into account cooling only, but any energy impacts for heating are likely to be much smaller [28,29].

2.2. Simulation parameters

A description of the modeling parameters are divided into five sections: (1) Locations, schedules, retail types, occupancy, dimensions; (2) HVAC parameters; (3) Outdoor concentrations; (4) Emission rates; and (5) Filtration, deposition, and penetration. A detailed description of these parameters is discussed below. A summary of these inputs is provided in the supporting information.

2.2.1. Locations, schedules, retail types, occupancy, dimensions

Six cities, two seasons (summer and winter, by calendar), and two time periods that correspond to store open and store closed times were considered in this paper. Store open hours were assumed to be from 7:00 am till 10:00 am, while closed otherwise.

Retail stores were classified into two general types: grocery and non-grocery type stores, because the ventilation rate specified by the VRP is the same for all non-grocery retail types. For the initial analysis, four retail types were chosen: grocery, general merchandise, home improvement stores, and other (including electronics, offices, and furniture stores). This division to four types was made based on reported differences in indoor emission rates, and occupancy frequency. However, the initial analyses results showed that there is no much difference between the retail types other than grocery and thus all other retail types were collapsed into non-grocery.

The occupancy is an important parameter to determine the ventilation rate specified by DCV. Generally, there are a lack of studies that measured occupancy in any environment, and specifically in retail buildings. To determine occupancy ranges, the maximum number of occupants per floor area reported in 20 unique retail stores in two studies [30,31] were used in combination with the hourly occupancy profile provided by Ng et al. [32] for stand-alone reference retail buildings. The proposed hourly profile is similar to that observed by Siegel et al. [31]. In their report, Siegel et al. [31] observed that the trend of occupancy was repeatable on a daily basis for the measured stores; also, the occupancy did not vary by season when comparing values of different test weeks in the same store. Thus, we did not do any further adjustments of the hourly occupancy profile for different days or seasons. We added the number of employees to the number of customers following the average number reported by EIA ([33]; Table B-1): 0.8 workers/100 m^2 for non-grocery stores and 1.3 workers/100 m^2 for grocery stores.

It should be noted that some of the observed maximum occupancy numbers reported from literature for retail stores were higher than what is reported as maximum number in ASHRAE Standard 62.1–2013 [9]. For example, Chan et al. [30] reported the maximum number of people observed for a grocery store to be 10 people/100 m^2, which is higher than ASHRAE maximum number of 8 people/100 m^2. This will play a role in decreasing the difference between ventilation rates suggested by DCV and VRP.

For each retail type, the occupancy sample values included in the simulation were generated from uniform distributions with lower and higher range equal to the 10th and 90th percentile observed at the stores (10th percentile occupant frequency per 100 m^2 = 0.8 for non-grocery, and 2.3 for grocery; 90th percentile occupant frequency per 100 m^2 = 5.9 for non-grocery, and 12.5 for grocery). Using uniform occupancy distributions rather than a detailed occupant behavior model is unlikely to impact significantly the energy results because the energy consumption attributed to occupants is fairly small when compared to other sources (lighting, equipment, and cooling/heating of return air). However, it should be noted that this model will likely benefit when true occupancy profile data for different cities is used. The knowledge of the true occupancy profile will depend on the availability of real-time occupancy sensing data. Current available technologies are generally inaccurate (beam-breaks at doors/other locations, extrapolations from transaction counts or vehicles in parking lot, infrequent manual counting), labor-intensive (frequent manual counting), or expensive (digital analysis of security camera footage).

The building volume to floor area ratio was selected to be 6.1 m, based on stand-alone retail reference building provided by Ng et al. [32].

2.2.2. HVAC parameters

2.2.2.1. Supply rate. The total supply air exchange rate was assumed to be equal to 1.94 store volumes per hour, as reported by Ng et al. [32]. This value is consistent with the values used in Apte et al. [22] for a general merchandise store (1.99 per hour) and within the uncertainty of the value reported by Siegel et al. [31] for 14 stores (1.67 ± 0.6 per hour).

2.2.2.2. Infiltration rate. The infiltration rate during the day was assumed to follow a lognormal distribution with a geometric mean of 0.35 h^{-1} and geometric standard deviation of 2.1 as developed by Chan [34]. In her study, Chan used a set of leakage measurements and a combination of the LBL and Shaw-Tamura infiltration models to predict infiltration in unpressurized buildings over the US commercial building stock using the monthly averaged climatic data. Chan's findings agree with findings from Lagus and Grot [35] and Cummings et al. [36]. These studies measured commercial buildings in Florida and in California, and found that the infiltration rate alone produced air-exchange rates that were 10–80% of those with the ventilation system on, with a mean ratio of about 40%. From Siegel et al. [31], the infiltration rates were calculated by subtracting the measured total supply rate from the mechanical ventilation rate. The median infiltration rate was found to be 0.32 per hour (albeit with large uncertainty), which is consistent with Chan's finding.

For retail stores, infiltration is mainly driven by large openings such as entrances, exits, and loading docks since most of the retail stores are depressurized [31]. In the model developed for this paper, all openings were assumed to be closed at night, and, since retail stores have very little to no windows, the infiltration rate was assumed to be much less at night, and divided by 4 based on engineering judgment.

2.2.2.3. Ventilation rate. Three main ventilation rate strategies were considered; these rates corresponded to those calculated from the VRP, DCV-based CO_2, and IAQP (as described in ASHRAE Standard 62.1–2013 [9]). Two additional strategies were investigated as alternatives to the VRP (VRP-C, VRP-NG); however, due to the paper length limitation, only some of these analyses are presented in this paper. VRP-C differs from the VRP by setting the ventilation rate zero at night, and VRP-NG differs from the VRP by reducing the ventilation rate specified for non-grocery stores to be equal to that specified for grocery stores. Strategies other than the IAQP scenario are described in Fig. 1.

For all scenarios, the recirculation rate (supply rate minus outdoor ventilation rate) during the store-closed period was set equal to zero.

The IAQP depends on an objective and subjective assessment of the indoor air quality in the space. In this work, the objective assessment was based solely on $PM_{2.5}$ concentrations. We applied Eq. (1) (time-averaged mass-balance equation) for $PM_{2.5}$ to find the ventilation rate that will result in the desired $PM_{2.5}$ concentration. The desired concentration is defined in ASHRAE Standard 62.1–2013 (Appendix B; [9]) and corresponds to the National Ambient Air Quality Standards (NAAQS) of 12 μg/m^3 over a one-year average. Acrolein (i.e., the other identified contaminant of concern) was not included in the objective assessment because indoor and outdoor acrolein concentrations were higher than the acrolein established limits at the stores included in this analysis (stores measured by Dutton et al., 2013 [24]), limiting the value of

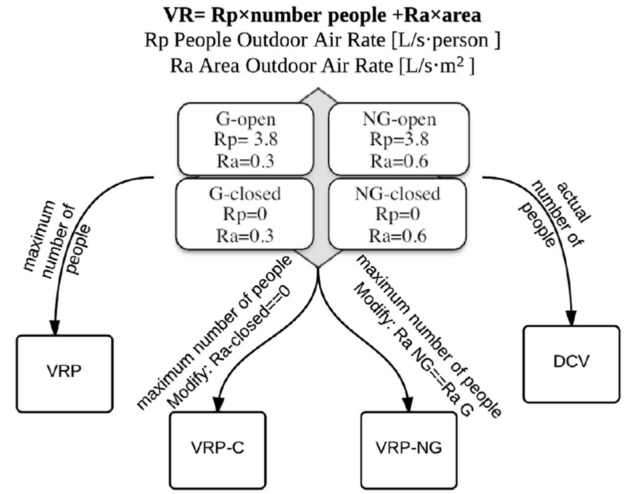

Fig. 1. Summary of ventilation scenarios for grocery stores (designated as G), and non-grocery stores (designated as NG).

ventilation to decrease its indoor concentration.

The subjective assessment was based on the value reported by Dutton et al. [24]. In their study, they concluded that an air exchange rate of 0.2 per hour could satisfy at least 80% of occupants in retail buildings. It is important to note that Dutton et al. [24] only evaluated one big box retail store and relied on simulated shoppers (i.e., not actual shoppers or store employees) to evaluate satisfaction with IAQ.

2.2.3. Outdoor concentrations

Outdoor $PM_{2.5}$ concentrations were taken from EPA-hour resolved monitoring data for 2012 year [37], which was the same year in which indoor pollutant emission rates used for this study are measured [40]. The samples included are all urban samples except for Austin and Minneapolis, where suburban samples were used because urban data were not available. EPA reference method data were used for all cities except for Austin and Philadelphia, where none were available and non-reference method data were used. The sample values included in the simulation were generated from lognormal distributions that represent each of the six cities, two seasons, and two periods. Distribution parameters of $PM_{2.5}$ outdoor concentrations are provided in the Supporting Information.

For the remaining pollutants, outdoor concentrations were taken from the median concentration measured in State of California [38]: outdoor formaldehyde concentration equaled to 2.5 μg/m^3, outdoor acetaldehyde concentration equaled to 1.9 μg/m^3, outdoor acrolein concentration equaled to 0.8 μg/m^3. The outdoor California reference concentrations of formaldehyde and acetaldehyde were consistent with measurements done in Pennsylvania, reported in Siegel et al. [31]. However, these values are lower (by factor of 2 or more) than those provided by RIOPA study [39] for Los Angeles data conducted between May 1999 and February 2001. It should be noted that the reported outdoor concentration of state of California (ARB) data prior to 2001 were higher than the recent years and consistent with values reported in the RIOPA study [39]. For acrolein, we are not aware of available reliable data from sources other than the ARB.

2.2.4. Emission rates

For $PM_{2.5}$, two studies reported indoor emission rates for retail stores: Dutton et al. [24], and Zaatari et al. [40]. Dutton et al. [24] reported $PM_{2.5}$ emission rates for 4 retail stores (n = 3 grocery stores, and n = 1 non-grocery store). Zaatari et al. [40] reported $PM_{2.5}$ emission rates for 14 different stores, 24 site visits (n = 5 grocery stores, n = 19 non-grocery stores). In the present paper, we used the relevant store parameters reported in Zaatari at al [40]. and we repeated the parametric analysis to generate $PM_{2.5}$ emission rates during day and night.

Combining emission rates from Dutton et al. [24] and the calculated emission rates based on Zaatari et al. [40] dataset, median emission rates for grocery stores ranged from 2.3 to 48.2 μg/m^2•h during the day and 0.3–15.4 μg/m^2•h during the night. Median emission rates for non-grocery stores ranged from 0.01 to 13.8 μg/m^2•h during the day and 0.01–3.3 μg/m^2•h during the night.

For other pollutants (formaldehyde, acetaldehyde, and acrolein), only emission rates during the day period were available from literature studies. Median emission rates for formaldehyde reported by Grimsrud et al ([41], n = 3), Bennett et al ([42], n = 7), Dutton et al ([24], n = 8), and Nirlo et al ([43], n = 18). for non-grocery stores ranged from 64 to 110 μg/m^2•h; with median emission rate across all studies equal to 80.1 μg/m^2•h. Median emission rates for formaldehyde reported by Dutton et al ([24], n = 3), and Nirlo et al. ([43], n = 5). for grocery stores ranged from 26.3 to 53 μg/m^2•h; with median emission rate across these two studies equal to 39.7 μg/m^2•h.

Median emission rates for acetaldehyde reported by Bennett et al ([42], n = 6), Dutton et al ([24], n = 7), and Siegel et al. ([31], n = 12). for non-grocery stores ranged from 13 to 57.9 μg/m^2•h; with median emission rate across all studies equal to 14.8 μg/m^2•h. Median emission rates for acetaldehyde reported by Dutton et al ([9], n = 3), and Siegel et al. ([31], n = 7). for grocery stores ranged from 130 to 266 μg/m^2•h; with median emission rate across all studies equal to 198 μg/m^2•h.

Emission rates for acrolein were reported only by one study (Dutton et al. [24], n = 6: 3 grocery stores and 3 non-grocery stores): the median and mean emission rate for grocery stores was 23 μg/m^2•h 30.4 μg/m^2•h, respectively and was 9 μg/m^2•h and 14.49 μg/m^2•h for non-grocery stores.

For each retail type and for each pollutant, the emission rates included in the simulation were generated from uniform distributions with lower and higher range equal to 10th and 90th percentiles observed at the considered stores.

2.2.5. Filtration, deposition, and penetration

Particulate filtration efficiency, deposition rate, and penetration factor are not well known for commercial buildings. Methods for estimating these parameters are explained in details is in Zaatari et al. [40]. In summary, the 10th, and 90th percentile of $PM_{2.5}$ filter efficiency corresponds to 17% and 32% respectively; and the 10th, and 90th percentile of $PM_{2.5}$ deposition rate corresponds to 0.17 per hour and 0.36 per hour respectively. Particle penetration factor was estimated to be equal to unity because of the preponderance of large openings in retail stores. For gas phase contaminants (acrolein, formaldehyde, and acetaldehyde), the deposition, filtration and penetration losses are assumed to be negligible.

3. Results and discussion

The results section is divided into four sub-sections. The first section explores the effects of different ventilation scenarios on the identified contaminants of concern (i.e., $PM_{2.5}$ and acrolein); formaldehyde and acetaldehyde were also analyzed to ensure that the selected control strategy did not increase the concentration of these pollutants beyond a level where they would be considered as COCs. The second section repeats the work of the first section but replaces the low $PM_{2.5}$ efficiency filter with a high $PM_{2.5}$ efficiency filter. The third section presents the number of DALYs lost and the energy results for the different considered scenarios and the fourth section determines the optimal ventilation–filtration combination strategy that led to a balance between the number of DALYs lost and energy consumption.

3.1. Effect of ventilation scenarios on pollutants concentrations: the case of low $PM_{2.5}$ efficiency filter

Fig. 2 displays modeled $PM_{2.5}$ indoor concentrations averaged across all cities in both seasons, and are differentiated for store-open and store-closed periods, grocery and non-grocery retail types, and four different ventilation strategies.

$PM_{2.5}$ concentrations in grocery stores were higher than those reported for non-grocery stores for any ventilation scenario, mainly due to higher indoor emission sources. These results are consistent with field and modeling data reported in Dutton et al. [24] and Zaatari et al. [40]. Across all cities, median $PM_{2.5}$ indoor concentrations were comparable when applying the VRP or the DCV strategy. The VRP-C yielded higher concentrations when compared to the VRP for store-closed period because of lower ventilation rates (VRP-C assumes zero ventilation rate when the store is closed). Comparing IAQP with the other strategies revealed that IAQP resulted in lower median $PM_{2.5}$ concentration for grocery stores and higher median value for non-grocery stores. For all ventilation strategies, stores located in at least one city had indoor $PM_{2.5}$ concentrations higher than 12 μg/m^3 ($PM_{2.5}$ concentration of interest defined in ASHRAE Standard 62.1–2013 [9]). This is not expected when following the IAQP because the ventilation rates were calculated by setting $PM_{2.5}$ concentration equal to 12 μg/m^3. To explore this issue, Fig. 3 shows $PM_{2.5}$ indoor concentrations and air exchange rate for two cities (Austin and Los Angeles) during the summer season, differentiated by store type, period, and different ventilation parameters. Results in Fig. 3 show that in Austin, it was favorable to increase the air exchange rate in grocery stores to dilute indoor-generated $PM_{2.5}$ because the $PM_{2.5}$ indoor-to-outdoor ratios in these stores were larger than unity. Considering the IAQP, $PM_{2.5}$ concentration in grocery stores in Austin was maintained at 12 μg/m^3 with a median air exchange rate of 2.8 per hour during store-open period and 0.4 per hour during store-closed period. This large increase in air exchange rate relative to the VRP during store open period is caused by the high indoor concentration (higher than the desired concentration, 12 μg/m^3) and the median outdoor concentration close to the desired concentration of 12 μg/m^3. The

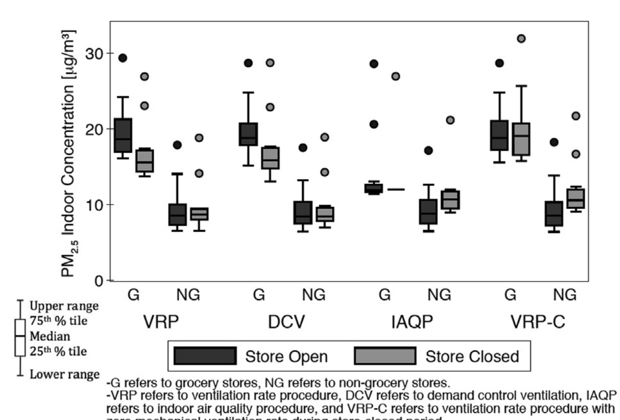

Fig. 2. Modeled $PM_{2.5}$ indoor concentrations using a typical particle filter averaged for all cities and both seasons, differentiated by store schedule (store open and closed), retail type (G: grocery, and NG: non-grocery), and different ventilation strategies (VRP, DCV, IAQP, and VRP-C).

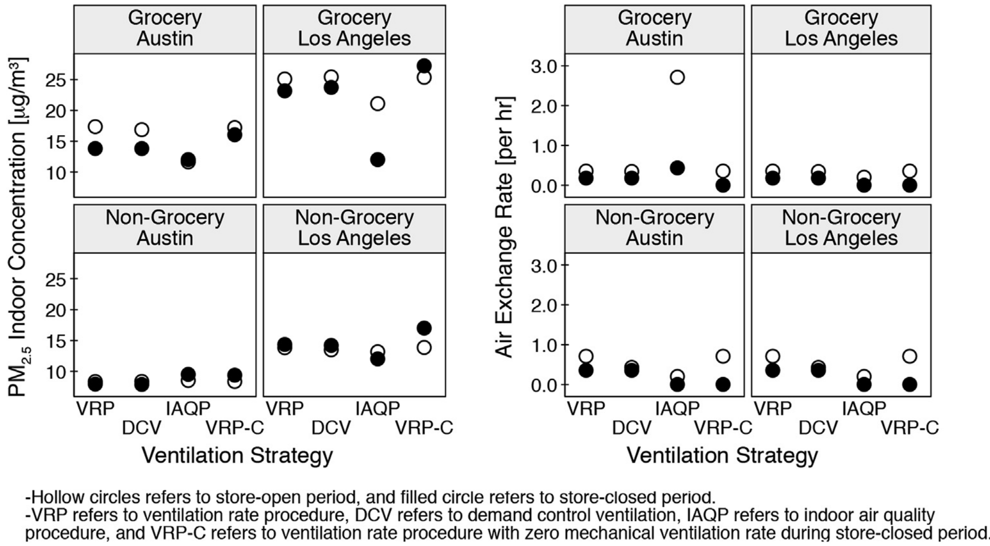

Fig. 3. $PM_{2.5}$ indoor concentrations (left graph) and air exchange rate (right graph) during the summer season for store-open and closed periods for two cities (Austin and Los Angeles), differentiated by store type (Grocery and non-grocery), and different ventilation strategies (VRP, DCV, IAQP, and VRP-C). Hollow circles represent store-open period and filled circles represent store-closed period.

same trend was observed for other cities with comparable outdoor concentrations such as Phoenix and Minneapolis.

In Los Angeles, the outdoor concentration was higher than the indoor concentration ($PM_{2.5}$ IO ratios lower than unity); this required the air exchange rate to be reduced to the minimum allowed to minimize infiltration of ambient $PM_{2.5}$. According to ASHRAE standard 62.1–2013 [9], the minimum air exchange rate in an occupied zone can not be zero during store open period; rather, it should be equal to the air exchange rate identified by a subjective assessment of IAQ identified based on occupants' survey responses collected for a similar type of building. The minimum air exchange rate that matches the satisfaction of 80% of occupants in retail buildings corresponds to 0.2 per hour (Dutton et al., [24]). This minimum air exchange rate was not sufficient to keep $PM_{2.5}$ indoor concentration in grocery stores below 12 $\mu g/m^3$; the likely cause for this was the combination of high infiltration rate along with high $PM_{2.5}$ outdoor concentrations for these stores.

For non-grocery stores, following the IAQP, both cities (Austin and Los Angeles) were assigned the minimum air exchange of 0.2 per hour during store-open period. In Austin, $PM_{2.5}$ indoor and outdoor concentrations were low (lower than 12 $\mu g/m^3$) and no extra dilution was needed. In Los Angeles, again, $PM_{2.5}$ indoor concentrations were greater than the desired concentration because of the elevated outdoor concentration and the high infiltration rate.

To explore the effects of these ventilation rates on acrolein, formaldehyde, and acetaldehyde concentrations, Monte Carlo simulations were repeated to calculate the concentrations of these pollutants, given the different ventilation strategies. Fig. 4 shows the median indoor concentrations of formaldehyde, acetaldehyde, and acrolein during store-open period averaged for the six cities, for grocery and non-grocery retail types and for different ventilation strategies.

As shown in Fig. 4, the IAQP applied to grocery stores with $PM_{2.5}$ indoor-to-outdoor ratios less than unity yielded the highest pollutant concentrations because the recommendation for these stores is to keep the air exchange rate to a minimum. Since formaldehyde, acetaldehyde, and acrolein are pollutants mainly generated indoors, lowering the air exchange increased these pollutants (formaldehyde and acrolein concentrations were 22% and acetaldehyde was 27% higher that those reported using the VRP). By analogy, ventilating grocery stores based on IAQP in cases where $PM_{2.5}$ indoor-to-outdoor ratios was larger than unity (i.e., increasing air exchange rate above that required by the VRP or the DCV) yielded the lowest formaldehyde, acetaldehyde, and acrolein concentrations (formaldehyde and acrolein concentrations were 31% and acetaldehyde was 38% lower that those reported for the VRP). For non-grocery stores, indoor concentrations were low; thus, air exchange rates were kept to a minimum, causing an increase of the concentrations of pollutants other than $PM_{2.5}$.

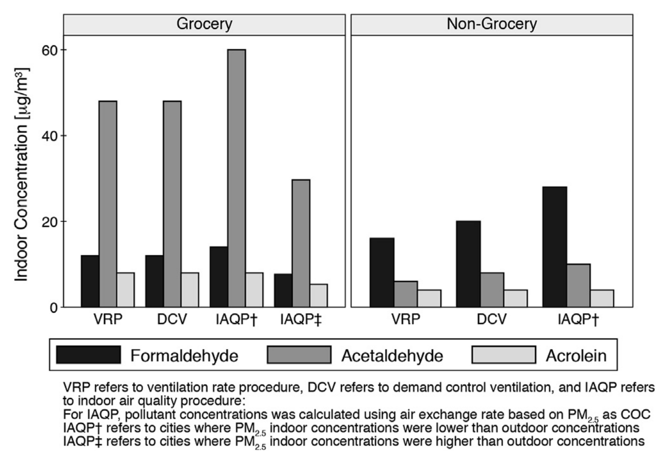

Fig. 4. Median formaldehyde, acetaldehyde, and acrolein indoor concentrations during store-open period averaged across all cities and in both seasons, differentiated by retail type (Grocery and non-grocery), and different ventilation strategies (VRP, DCV, IAQP, and VRP-C). Pollutant concentrations following the IAQP were calculated using $PM_{2.5}$ as a COC and a typical efficiency particle filter.

In addition to dilution, using filtration is an important PM control strategy that may be less energy intensive. The next section explores the change in pollutants concentrations when using a high $PM_{2.5}$ efficiency filter.

3.2. Effect of ventilation scenarios on pollutants concentrations: the case of high $PM_{2.5}$ efficiency filter

This section investigates the impact of using a high $PM_{2.5}$ filter

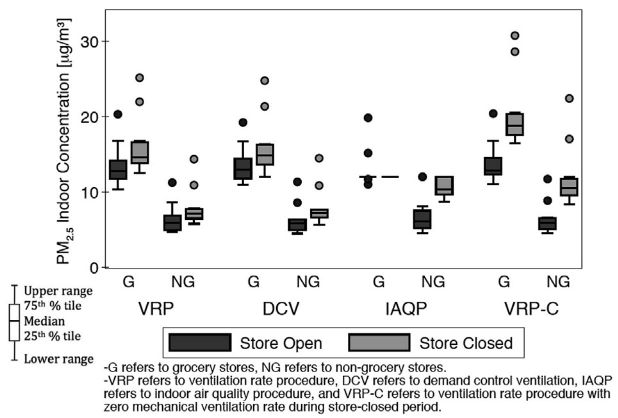

Fig. 5. Modeled $PM_{2.5}$ indoor concentrations using a high particle efficiency filter averaged for all six cities and both seasons, differentiated by store schedule (store open and close), retail type (G: grocery, and NG: non-grocery), and different ventilation strategies (VRP, DCV, IAQP, and VRP-C).

efficiency on pollutant concentrations: in the calculation, low $PM_{2.5}$ efficiency filter (ASHRAE Standard 52.2–2012 Minimum Efficiency Reporting Value; MERV 8 [27]) switched to high $PM_{2.5}$ efficiency filter (MERV 13). Fig. 5 is a repeat of Fig. 2 but with a high efficiency filter. Note that the ventilation rate determined by the IAQP-based $PM_{2.5}$ is the ventilation rate calculated to reduce $PM_{2.5}$ below 12 μg/m^3 with a high efficiency filter in place.

As expected, using a high $PM_{2.5}$ efficiency filter (efficiency = 80%) decreased $PM_{2.5}$ indoor concentrations for all ventilation strategies; nonetheless, $PM_{2.5}$ indoor concentrations were higher than 12 μg/m^3 in at least one city for any of the ventilation strategies. For IAQP, the calculated air exchange rate was 0.2 per hour (minimum allowed) for all cities and for both retail types. This air exchange rate was sufficient to reduce elevated $PM_{2.5}$ concentrations in stores with $PM_{2.5}$ IO ratios larger than unity. For the stores in locations with high outdoor concentrations, the high infiltration rates and emission rates present at these stores diminished the effect of high filtration efficiency, resulting in $PM_{2.5}$ concentrations higher than 12 μg/m^3.

Fig. 6 show results from the analysis similar to the one presented in Fig. 4 but with using a high efficiency filters. The only

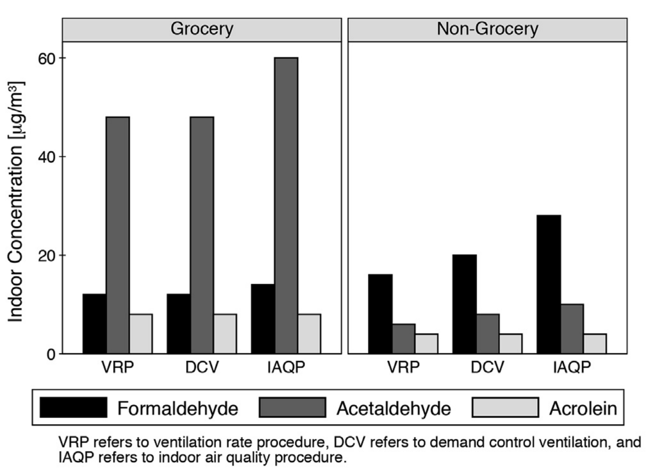

Fig. 6. Formaldehyde, acetaldehyde, and acrolein indoor concentrations during store-open period averaged across all six cities in both seasons, differentiated by retail type (grocery and non-grocery), and different ventilation strategies (VRP, DCV, IAQP, and VRP-C). Pollutant concentrations following the IAQP were calculated using $PM_{2.5}$ as a COC and a high efficiency particle filter.

difference between these two figures is that the IAQP increases formaldehyde, acetaldehyde, and acrolein concentrations for both stores with $PM_{2.5}$ IO ratios higher and lower than unity, showing the drawback when ventilation is focused on a single pollutant. As mentioned above, the calculated air exchange rate from the IAQP for all stores was 0.2 per hour, resulting in a decrease in dilution of these pollutants (i.e., higher formaldehyde, acetaldehyde, and acrolein concentrations).

The next section puts these results in context of exposure and energy consumption.

3.3. Exposure and energy consequences of different ventilation and filtration scenarios

This section evaluates the control options of indoor exposures to pollutants by presenting the burden of disease (i.e., DALYs lost) attributable to each pollutant and the corresponding energy consumption.

Fig. 7 shows the DALYs lost from exposure to acetaldehyde, acrolein, formaldehyde, and $PM_{2.5}$ for different ventilation scenarios and filter efficiencies (top figure), and a more detailed display of number of DALYs lost attributed to exposure to $PM_{2.5}$ and acrolein (bottom figure). Note that the y-axis on the top graph is a log-scale and in the bottom graph is a linear-scale. Also, the impact of an additional ventilation scenario was introduced in this figure

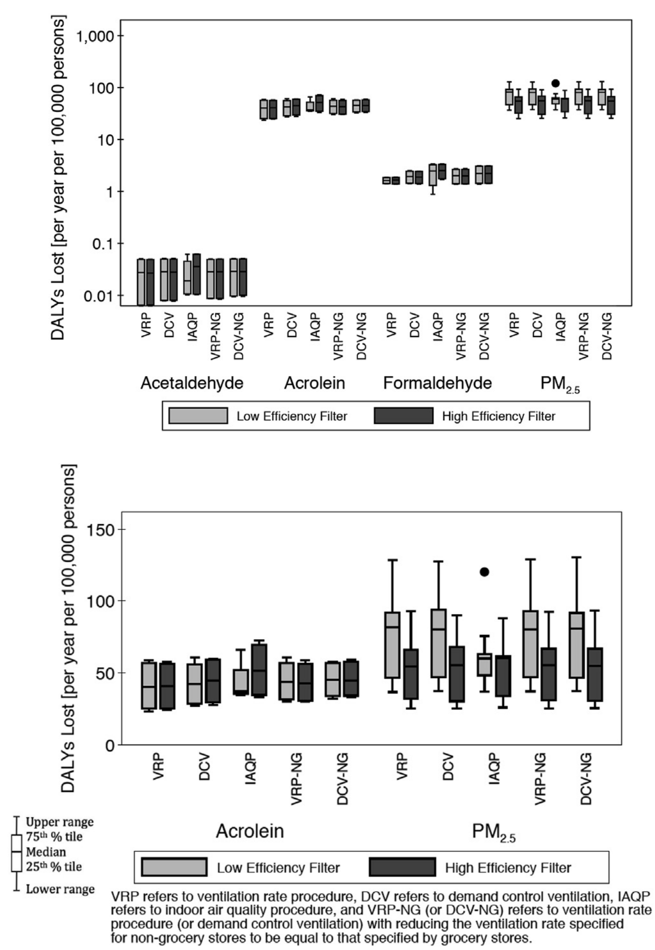

Fig. 7. Modeled DALYs lost from exposure to acetaldehyde, acrolein, formaldehyde, and $PM_{2.5}$ for different ventilation scenarios and filter efficiencies (top figure). The y-axis is a log-scale. A detailed display of the number of DALYs lost attributed to exposure to $PM_{2.5}$ and acrolein is presented in the bottom figure.

(VRP-NG). This ventilation scenario reduced the ventilation rate required for non-grocery store to that required by the grocery store (as explained earlier in Fig. 1).

The top figure in Fig. 7 shows that the DALYs attributed to formaldehyde and acetaldehyde for all ventilation scenarios were small when compared to those attributed to acrolein and $PM_{2.5}$, and the bottom figure shows that the DALYs attributed to $PM_{2.5}$ were 60% higher than those attributed to acrolein (e.g., median DALYs per 100,000 persons across all scenarios attributed to formaldehyde = 1.79; acetaldehyde = 0.019; acrolein = 37.4; $PM_{2.5}$ = 60 DALYs).

Table 1 summarizes the total DALYs lost calculated by summing the DALYs from exposure to all pollutants. It is important to remember that the total DALYs were essentially the sum of DALYs from exposure to acrolein and $PM_{2.5}$. This table also shows the percentage change of different ventilation and filtration scenarios relative to the VRP/low $PM_{2.5}$ filter efficiency scenario. Table 1 shows that the DALYs lost resulting from the IAQP with high efficiency filter were higher than those reported for IAQP with low efficiency filter for grocery stores. This finding is counter-intuitive. The reason is that using a high efficiency filter decreased $PM_{2.5}$ indoor concentration substantially so that the ventilation rate required was the minimum ventilation rate (i.e. 0.2 per hour). Setting the ventilation rate in grocery stores to a minimum level increased the concentrations of other pollutants generated indoors; of particular interest is acrolein because it contributed significantly to the DALYs lost.

Table 2 summarizes the electrical consumption by store HVAC systems for different locations and ventilation and filtration scenarios. Before identifying the optimal control strategy, it is important to mention that (1) lowering the air exchange in Los Angeles and Seattle increased electrical consumption because outdoor air conditions often helped in cooling the store. As mentioned previously, the economizer mode was not considered in this analysis, if implemented, this mode will capture additional savings. Another observation from Table 2 is that on average DCV offered no advantage over VRP in grocery stores from either energy or air quality perspectives; the air exchange specified for DCV is approximately equal to that specified for VRP.

The data displayed in Tables 1 and 2 and shows that for grocery stores located in cities where outdoor $PM_{2.5}$ concentration is less than 12 $\mu g/m^3$ (all except Los Angeles), adopting the IAQP with low efficiency $PM_{2.5}$ filter led to the highest health benefits. On average, IAQP leads to 26% decrease in the number of DALYs compared to the VRP. This gain in health benefits translated into 113% average increase in air exchange rate: 72%, on average, increase in electrical consumption of ventilation alone, $8800 average increase in annual cost, with the annual increase in Austin being the highest at $25,000 for the considered 10,000 m^2 model building. For grocery stores located in Los Angeles, adopting the VRP with high $PM_{2.5}$ filter efficiency led to the highest health benefits, with electrical consumption equal to $1100 (additional energy cost of higher efficiency filtration) more than that realized by the VRP with low efficiency filters. It should be noted that the analysis only considers energy use and not capital costs for filters.

For non-grocery stores, it is most beneficial from a health perspective to adopt the VRP with high $PM_{2.5}$ efficiency filter. This leads to a decrease of 20% of the number of DALYs lost when compared to the VRP with low $PM_{2.5}$ efficiency filter, with electrical consumption equal to $1200 (additional energy cost of higher efficiency filtration). Adopting the reduced VRP (half the air exchange rate) with high $PM_{2.5}$ efficiency filter, instead of the VRP with high $PM_{2.5}$ efficiency filter, led to sacrificing 8% of health benefits and $1700 decrease in annual cost for the considered 10,000 m^2 model building.

A comparison between the ventilation rates prescribed by the VRP (ASHRAE Standard 62.1–2013 [9]) for grocery and non-grocery stores revealed that non-grocery stores have higher recommended ventilation rates than grocery stores (approximately double). As for the IAQP (ASHRAE Standard 62.1–2013 [9]), results are reversed when compared to the VRP results. This is because grocery stores have higher emissions and higher indoor concentrations, and thus they should be recommended higher ventilation rates (with the caveat that this assumes outdoor air concentration are low). A potential revision of ASHRAE Standard 62.1 is warranted given the new information available about retail stores; ventilation rates in grocery stores should be higher.

Fig. 8 synthesizes the information in Tables 1 and 2 and presents exposure and energy issues together for most of the scenarios considered here. In Fig. 8, points in the upper right quadrant are those where both exposure and energy outcomes would get worse switching from a baseline of the VRP with low-efficiency filters. Similarly, the lower left quadrant suggests an improvement in both dimensions. Fig. 8 excludes all of the Seattle non-grocery store data

Table 1
Summary of DALYs lost for different control scenarios and percentage change in DALYs lost relative to the VRP/low $PM_{2.5}$ filter efficiency scenario.

City[a]	DALYs lost per year per 100,000 persons [% change switching from VRP low PM η[b]]									
	VRP low PM η[b]	DCV low PM η[b]	IAQP low PM η[b]	VRP-NG low PM η[b]	DCV-NG low PM η[b]	VRP high PM η[c]	IAQP high PM η[c]	DCV high PM η[c]	VRP-NG high PM η[c]	DCV-NG high PM η[c]
Grocery										
Aus	147 (0%)	152 (3%)	100 (−32%)			124 (−15%)	132 (−10%)	127 (−14%)		
PA	152 (0%)	150 (−1%)	118 (−23%)			125 (−18%)	130 (−14%)	129 (−15%)		
LA	186 (0%)	185 (0.5%)	187 (0.4%)			151 (−19%)	160 (−14%)	151 (−19%)		
Mn	143 (0%)	140 (−2%)	104 (−27%)			115 (−20%)	132 (−8%)	121 (−16%)		
Ph	146 (0%)	154 (6%)	113 (−23%)			121 (−17%)	136 (−6%)	124 (−15%)		
Stl	160 (0%)	160 (−0.2%)	132 (−17%)			127 (−21%)	133 (−17%)	132 (−18%)		
Non-Grocery										
Aus	75 (0%)	78 (4%)	87 (16%)	83 (11%)	84 (13%)	60 (−19%)	74 (−2%)	65 (−14%)	67 (−11%)	71 (−5%)
PA	74 (0%)	81 (9%)	88 (20%)	82 (11%)	86 (16%)	59 (−20%)	71 (−3%)	64 (−14%)	65 (−12%)	68 (−8%)
LA	106 (0%)	108 (2%)	114 (8%)	111 (5%)	115 (9%)	80 (−25%)	100 (−5%)	82 (−22%)	87 (−18%)	88 (−16%)
Mn	65 (0%)	69 (6%)	77 (18%)	72 (10%)	75 (15%)	52 (−20%)	63 (−4%)	58 (−12%)	59 (−10%)	64 (−2%)
Ph	67 (0%)	71 (5%)	83 (23%)	74 (10%)	77 (15%)	56 (−17%)	70 (3%)	61 (−9%)	63 (−7%)	65 (−3%)
Stl	74 (0%)	79 (6%)	88 (18%)	82 (10%)	85 (14%)	59 (−21%)	74 (−1%)	64 (−15%)	64 (−14%)	67 (−11%)

[a] Aus stands for Austin, PA stands for Pennsylvania, LA stands for Los Angeles, Mn stands for Minneapolis, Ph stands for Phoenix, and Stl stands for Seattle.
[b] Low PM efficiency filter corresponds to a MERV 8 filter.
[c] High PM efficiency filter corresponds to a MERV 13 filter.

Table 2
Summary of electricity consumption for different control scenarios and percentage change in electricity consumption relative to the VRP/low $PM_{2.5}$ filter efficiency scenario.

City[b]	Electricity consumption-cooling MWh[a] [% change switching from VRP low PM η[c]]									
	VRP low PM η[c]	DCV low PM η[c]	IAQP low PM η[c]	VRP-NG low PM η[c]	DCV-NG low PM η[c]	VRP high PM η[d]	IAQP high PM η[d]	DCV high PM η[d]	VRP-NG high PM η[d]	DCV-NG high PM η[d]
Grocery										
Aus	175	173	399			186	156	184		
	(0%)	(−1%)	(128%)			(7%)	(−11%)	(6%)		
PA	95	95	98			106	103	106		
	(0%)	(0%)	(3%)			(11%)	(8%)	(11%)		
LA	53	54	66			62	75	63		
	(0%)	(1%)	(23%)			(17%)	(40%)	(18%)		
Mn	89	89	97			99	98	99		
	(0%)	(0%)	(8%)			(11%)	(11%)	(11%)		
Ph	179	178	238			193	171	192		
	(0%)	(−1%)	(33%)			(8%)	(−4%)	(7%)		
Stl	28	29	46			37	55	38		
	(0%)	(3%)	(63%)			(32%)	(96%)	(35%)		
Non-Grocery										
Aus	245	191	145	175	155	256	156	202	186	167
	(0%)	(−22%)	(−41%)	(−29%)	(−37%)	(5%)	(−36%)	(−17%)	(−24%)	(−32%)
PA	109	98	92	95	93	119	103	109	106	103
	(0%)	(−10%)	(−15%)	(−12%)	(−14%)	(10%)	(−5%)	(0%)	(−2%)	(−5%)
LA	24	47	66	53	62	33	75	56	62	71
	(0%)	(94%)	(173%)	(122%)	(155%)	(37%)	(210%)	(131%)	(159%)	(193%)
Mn	94	90	89	89	89	104	98	100	99	98
	(0%)	(−5%)	(−6%)	(−6%)	(−6%)	(11%)	(4%)	(6%)	(5%)	(4%)
Ph	238	191	157	179	165	252	171	205	193	178
	(0%)	(−20%)	(−34%)	(−25%)	(−31%)	(6%)	(−28%)	(−14%)	(−19%)	(−25%)
Stl	5	22	46	28	39	14	55	31	37	48
	(0%)	(366%)	(881%)	(500%)	(726%)	(193%)	(1074%)	(559%)	(693%)	(919%)

[a] Electricity consumption for a typical 10,000 m^2 store.
[b] Aus stands for Austin, PA stands for Pennsylvania, LA stands for Los Angeles, Mn stands for Minneapolis, Ph stands for Phoenix, and Stl stands for Seattle.
[c] Low PM efficiency filter corresponds to a MERV 8 filter.
[d] High PM efficiency filter corresponds to a MERV 13 filter.

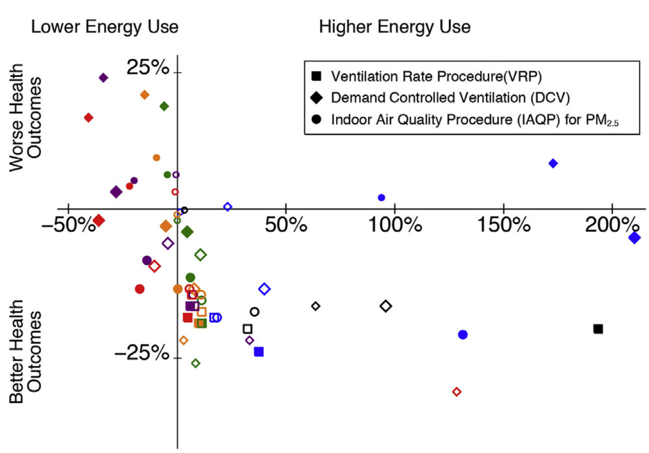

Fig. 8. Changes in energy use (x-axis) vs. changes in DALYs lost (y-axis) for simulated stores. In the figure, color indicates city (red = Austin, blue = Los Angeles, green = Minneapolis, orange = Philadelphia, purple = Phoenix, black = Seattle), hollow symbols are grocery stores, filled symbols are non-grocery stores, and symbol size indicates filter efficiency (small = MERV 8, large = MERV 13). Seattle non-grocery stores are excluded from figure because of the lack of an economizer model in this work. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

points because the presented analysis is unrealistic for conditions in Seattle that favor economizer use (low ambient temperatures and low outdoor $PM_{2.5}$ concentrations), as discussed above. Some of the Los Angeles results are similarly problematic, but for this location economizer use is often less beneficial for exposure reduction because of higher ambient particle concentrations. Fig. 8 suggests that choice of ventilation and filtration approach are specific to cities and that reasonable trade-offs between exposure and energy use are possible.

3.4. Pollutant control ventilation strategy

For all cities and for all retail types, adopting a suitable ventilation/filtration strategy (specific to retail type and location) led to substantial decrease in DALYs lost. A suitable control strategy should take into consideration all contaminants of concern: a single pollutant-approach to determine ventilation rates may overlook significant exposures from other pollutants generated from a different source (i.e. indoor vs. outdoor pollutants). Although the indoor air quality procedure (IAQP) specified in ASHRAE Standard 62.1–2013 requires the determination of the minimum ventilation rate to keep each contaminant of concern below its established limits, this method converges to the single pollutant-approach as it requires from an engineer to choose the larger ventilation rate determined by the different COCs. Thereby ignoring the fact that some pollutants (e.g. $PM_{2.5}$) can be generated outdoors and keeping the ventilation rate to a minimum might be more advantageous from both exposure and energy perspectives. Further, the established limits for each pollutant vary widely, and it might not be feasible to calculate the ventilation rate that will drive the pollutant below its limit. For example, acrolein levels indoors and outdoors were higher than the REL and depending on ventilation alone will not drive acrolein below its REL. As demonstrated in results shown Fig. 8, following the VRP or DCV specified in ASHRAE Standard 62.1–2013 [9] might not be the optimal solution from both energy and exposure perspectives.

Instead of relying on a single pollutant (IAQP-ASHRAE Standard 62.1–2013 [9]) or a prescribed number (VRP-ASHRAE Standard 62.1–2013 [9]), a proposed approach is the pollutant exposure control ventilation (PECV) strategy. The PECV finds an optimal ventilation rate based on weighing the exposures of different contaminants of concern, following the same DALY approach for the contaminants of concern identified in this work. However, ventilation rates are not limited only to those recommended by the standards. An example of applying PECV on a grocery store located in Los Angeles is shown in Fig. 9.

Fig. 9 shows that the total DALYs lost for air exchange rate between 0.2 and 1 per hour are comparable. The low air exchange rate (i.e., 0.2 per hour) increased DALYs lost from acrolein and decreased those for $PM_{2.5}$; the opposite happened when applying the higher air exchange rate (i.e., 1 per hour). Thus, the proposed strategy offers the flexibility to choose the air exchange rate that will lead to lower energy consumption. As mentioned previously, in Los Angeles, increasing the air exchange rate is often beneficial to decrease the energy consumption. This is due to the conditions of the outdoor air that are more favorable for free cooling (by use of economizer) in this city. Note that an additional decrease in DALYs lost can be obtained if a high efficiency filter is used, but this translates into additional energy costs as mentioned previously.

The suggested ventilation strategy depends mainly on the uncertainties associated with the estimated exposures (i.e. number of DALYs lost). The uncertainty bounds on exposure to some of the pollutants were higher than one order of magnitude. The major limitations in calculating the number of DALYs lost are associated with (1) quantifying $PM_{2.5}$ concentration-response (C-R) relationships are based solely on ambient epidemiological studies; (2) quantifying pollutants other than $PM_{2.5}$ is based on animal toxicity literature rather than on epidemiological concentration-response (C-R) relationships. Animal toxicity data requires interspecies extrapolations that generally involve larger uncertainties than the epidemiologically based C-R functions; (3) relying on non-threshold models (i.e., there is no concentration below which adverse health consequences do not happen, linear relationship between exposure and health effects). While this is likely true for $PM_{2.5}$ (Schwartz et al. [44]), it is not true for some VOCs (e.g., Salthammer and Bahadir [45]); and (4) taking into account only health impacts for which sufficient evidence exists in a quantitative format. This means that the total DALYs lost do not include burden of disease for which as yet incomplete or only qualitative evidence exists (i.e., might be excluding effects from important pollutants such as ultrafine particles and SVOCs). However, as those available health factors and the most recent scientific knowledge are used in estimating DALYs lost, the order of magnitude of the results should be sufficiently reliable for prioritizing pollutant control strategies.

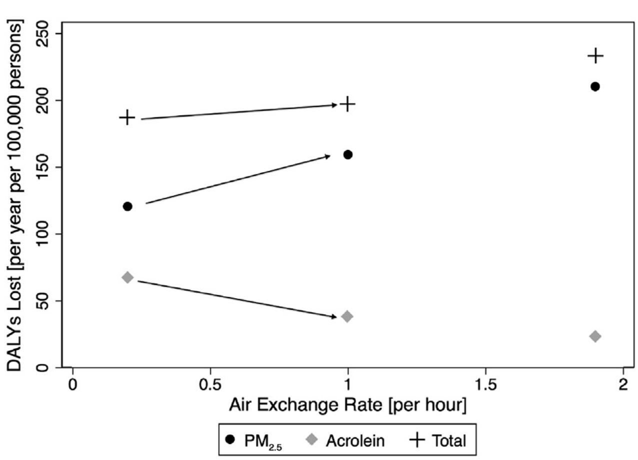

Fig. 9. Scatter plot of modeled DALYs lost from exposure to acrolein, and $PM_{2.5}$ as function of air exchange rate for a grocery store in Los Angeles.

4. Conclusion

This study modeled the impact of: (1) adjusting ventilation only, (2) adjusting filtration of supply air only, and (3) adjusting ventilation and filtration together on exposure and energy consumption in retail buildings. All approaches were able to provide substantial reductions in the exposure risks (19–26% decrease in DALYs lost); the magnitude of the reductions depended on the ventilation/filtration scenario, the retail store type, and the city climate and outdoor pollution level. For a typical 10,000 m^2 store, the magnitude of energy cost to achieve the maximum exposure benefits depended on the city and the retail type, ranging from $1000 in annual cost for filtration energy in a grocery store in Los Angeles to $24,000 as the annual cost of ventilation in a grocery store in Austin. A proposed strategy as alternative to the ventilation strategies recommended by the standards is the pollutant exposure control ventilation (PECV) strategy. This strategy is based on: (1) weighing the exposures of different contaminants of concern found in retail buildings, (2) identifying the range of ventilation rates that lead to low DALYs lost, and (3) choosing the optimal ventilation rate that leads to energy usage savings in the climate considered.

Acknowledgments

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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.2016.01.026.

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