Building and Environment 128 (2018) 320–335

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Interplay of ventilation and filtration: Differential analysis of cost function combining energy use and indoor exposure to $PM_{2.5}$ and ozone

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A R T I C L E I N F O

Keywords:
Ventilation
Filtration
Building energy simulation
Indoor air quality
$PM_{2.5}$
Ozone

A B S T R A C T

This study investigated the effects of ventilation and filtration on building energy consumption and exposure to $PM_{2.5}$ and ozone in U.S. offices. Energy use and indoor $PM_{2.5}$ and ozone concentrations were predicted in 15 locations for a typical office with either a constant air volume (CAV) or variable air volume (VAV) mechanical system. For each office and location, annual simulations were performed with combinations of fixed ventilation ranging 20–100 CFM/occ (9.4–47 L/s/occ) and filters ranging in efficiency corresponding to MERV 8–16 and HEPA. Energy use was monetized using historic costs, and $PM_{2.5}$ and ozone exposures were monetized using incidence valuations and concentration-response functions. These outcomes were combined into a singular cost function, which was characterized empirically as a function of ventilation and filtration. Various partial derivatives of the cost function were calculated to observe trends and interdependencies. Exposure cost was 5.5 times higher than energy cost for cases with common filters (MERV 8–11). Even with high filter efficiency, exposure cost was greater than energy cost on average. Filtration had a much stronger effect than ventilation on indoor contaminant levels and the total cost function. The differential analysis revealed that ventilation and filtration complement each other: Implementing a high efficiency filter can mitigate negative effects of ventilation, and higher ventilation rates can increase the efficacy of filtration (e.g. increasing ventilation from 20 to 60 CFM/occ increased filtration efficacy by 1.2–1.5 for VAV offices).

1. Introduction

Buildings have strong impacts on global energy consumption and greenhouse gas (GHG) emissions. For instance, the U.S. Department of Energy (DOE) [1] and Orme [2] state that buildings are responsible for about 40% of U.S. energy consumed. Furthermore, the U.S. Energy Information Agency (EIA) reported that buildings accounted for 38% of all GHG emissions in the U.S. in 2009, and the U.S. commercial building sector accounted for 20% of those GHG emissions [3]. Office buildings, which are the focus of this study, consume 19% of all energy consumed by commercial buildings, making them the largest contributor to building energy consumption in the commercial sector in the U.S. building stock [1].

The U.S. DOE adds that about one-half of the energy consumed by U.S. buildings is by heating, ventilation, and air conditioning (HVAC) systems [1]. The outdoor air flow rate is often described as the most influential parameter in building energy consumption sensitivity analyses [4–6], demonstrating ventilation's strong influence on building energy use. But beyond consuming energy, HVAC—particularly ventilation—can improve indoor environmental quality (IEQ) generally, which includes ensuring thermal comfort and good indoor air quality (IAQ), among other factors [7]. The importance of improving indoor environments is demonstrated by Jenkins et al. [8] and Klepeis et al. [9], both of which note that Americans spend roughly 90% of their time in buildings. They note the particular role ventilation plays on IEQ by discussing the consequences of the near-continuous exposure to pollutants while indoors.

Almost all green building certification schemes that exist worldwide, of which 55 were reviewed by Wei et al. [10], promote ventilation as a primary method to manage IAQ. While ventilation standards around the world, like ASHRAE Standard 62.1–2013, BS EN 15241:2007, and AS 1668.2–2012, provide minimum ventilation guidelines to maintain "acceptable" indoor air quality [11–13], higher ventilation rates may reduce some negative health and cognitive outcomes of occupants [14–19]. They can also help mitigate occupant exposure to indoor-generated pollutants like volatile organic compounds (VOCs) [20,21]. Though favorable in this light, higher ventilation can still engender a number of negative effects. As noted before, it is responsible for a substantial portion of energy consumption and GHG emissions [1–3,22]. Excessive ventilation may also degrade IAQ

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http://dx.doi.org/10.1016/j.buildenv.2017.10.025
Received 10 August 2017; Received in revised form 18 October 2017; Accepted 20 October 2017
Available online 22 October 2017

by introducing outdoor pollutants indoors, including particulate matter (PM), ozone (O_3), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and carbon monoxide (CO) [19,23,24]. However, only a small portion of green building certification schemes assessed in Wei et al. [10] discussed any of these pollutants and their contribution to IAQ degradation. Sundell et al. [19] argues that a lack of attention is given to these pollutants indoors despite the extensive documentation of the health effects caused by the exposure to them in outdoor environments [19,25–27].

Of the pollutants just discussed, exposure to PM likely has the most serious health impacts [25,28,29]. The most common method to reduce PM indoors is by use of air filtration (and other air-cleaning devices) [11,30–32]. ASHRAE classifies air filters by their Minimum Efficiency Reporting Value (MERV), which ranges from 1 to 20 [33]. ASHRAE Standard 62.1–2013 requires filters in commercial buildings to have a MERV of 8 or higher [11], while the usage of MERV 13 denotes "superior commercial buildings," and MERV 17 and higher are defined as "high-efficiency particulate arrestance (HEPA)" filters. To receive points for "enhanced IAQ" towards Leadership in Energy and Environmental Design (LEED) green building certification, one must use an air filter of MERV 13 or higher [34]. A MERV 13 filter is capable of reducing ~70% of $PM_{2.5}$ (total particle mass with aerodynamic diameter < 2.5 μm) in the airstream [35,36]. The use of HVAC air filters has shown to have significant benefits in multiple studies [37–41].

Filtration, although beneficial, does have associated financial burdens. The filter itself and its installation cost money, and more efficient filters tend to be more expensive [37]. Air filters also have a finite lifetime of about a few months to a year, after which they need replacement [37,40]. In addition to explicit costs, air filters may cause an increase in fan energy consumption because air flowing through them experiences a pressure drop, causing variable speed fans to draw more power [37,38,42], and may even have some impact on constant speed fans [43,44]. Studies estimate the annual cost of filtration to be \$2.5~\$15 per occupant [37,40,42], depending on filter MERV and type. Despite this inherent financial burden, it has been shown that the favorable effects of filtration, particularly in the reduction $PM_{2.5}$ exposure and associated occupant mortality, are significantly larger than the cost of filtration and that high efficiency filtration is quite beneficial compared with its cost [37–41].

Ventilation and filtration are thus technologies used to improve IAQ and create healthy indoor environments. Because going beyond minimum ventilation standards may have positive wellbeing impacts—but implementation beyond minimums of both ventilation and filtration can have health and/or monetary costs, which were shown to be perceived by stakeholders as grounds for dismissal [45]—we investigated cost impacts of those technologies in U.S. office buildings. Offices were analyzed since those buildings are a dominant energy consumer wherein people spend a large amount of time. Specifically, this study simulated energy use and IAQ exposure outcomes for a representative office, outfitted with either a constant-air-volume (CAV) or variable-air-volume (VAV) mechanical system and within one of 15 cities spanning ASHRAE climate regions. A *cost function* was developed that considers the costs of both ventilation and filtration explicitly, along with the monetized negative impacts of ventilation due to exposure, which can be compared to any developed benefit functions. Empirical results from the modeling were used to assess the magnitude of *changes of this cost function with unit changes* of ventilation rates or of filtration efficiencies or pressure drops. The ability of using better filtration efficiency to have reductive impacts on the PM exposure cost, especially as the ventilation rate was increased (potentially to realize other benefits), was explicitly investigated.

2. Methodology

The overall goal of this work was to create a *predictive cost function* for the cost value associated with changes due to ventilation and filtration. This cost function accounts for HVAC energy consumption (electricity and natural gas were considered), as well as costs associated with IAQ exposure and its health endpoints. Only outdoor criteria pollutants with the strongest health-oriented concentration-responses (C-R) were considered; i.e., fine particles ($PM_{2.5}$) and ozone (O_3). These pollutants well capture the holistic negative IAQ effect associated with *increasing ventilation rates* (*VR*), since they are introduced indoors herein via outdoor-to-indoor transport with air exchange and have strong C-R functions. And of these, PM exposure has the strongest relative risk associated with it [25]. This last fact is relevant to this work, as one of its main foci was to explore whether *efficient PM filtration* can mitigate the adverse PM exposure effects due to increasing ventilation. If so, the use of efficient filtration should be in tandem with using higher VRs for their positive effects on office indoor environments (e.g. increased productivity, reduced sick building syndrome symptoms, reduced exposure to airborne illnesses, etc. [15]).

The per-occupant (occ) cost function, J (US\$/occ), was defined as follows:

$$J = J_E + J_{IAQ} + J_{filter} \tag{1}$$

where J_E, J_{IAQ}, and J_{filter} (US\$/occ) are the costs due to energy consumption, the costs associated with indoor exposure to $PM_{2.5}$ and ozone of outdoor origin, and the costs associated with regular filter purchase and replacement, respectively. To analyze the effect on J due to ventilation rate (VR) alone and assess the impact of incremental ventilation increases, the derivative of the cost function J can be taken with respect to the ventilation rate, VR (ft^3/min/occ = CFM/occ):

$$\frac{\partial J}{\partial VR} = \frac{\partial J_E}{\partial VR} + \frac{\partial J_{IAQ}}{\partial VR} \tag{2}$$

Similarly, to assess the impact of filtration on the operational cost of the building, the derivative of the cost function J with respect to filtration can also be taken:

$$\frac{\partial J}{\partial filter} = \frac{\partial J_E}{\partial filter} + \frac{\partial J_{IAQ}}{\partial filter} + \frac{\partial J_{filter}}{\partial filter} \tag{3}$$

where "filter" denotes any parameters associated with the filter that affect the cost function. To be able to take analytical partial derivatives of the cost function, empirical equations were fit to the simulated results as function of ventilation and filter parameters. While the cost due to filter purchase and replacement, J_{filter}, can make up a significant portion of the overall cost of filtration [37,40], it was excluded from the empirical definition of J due to variability between products available in the market as shown in Section 2.4. Despite the exclusion, the nominal and differential magnitudes of this parameter are detailed separately in this article and require a case-by-case analysis to properly incorporate them into the analysis presented herein.

The following subsections illustrate the methodology used to compile and derive the different components of J, the total cost function. For a brief summary, the various components of J were estimated using a collection of models. Energy consumption was estimated with simulations using EnergyPlus [46], a research grade energy simulation software, and those energy consumption outcomes were coupled with recent energy prices to compute cost. The use of EnergyPlus to assess the impacts of changing VR [47] and for other similar purposes [48–52] has been validated. Costs associated with IAQ were calculated by estimating indoor concentrations of various pollutants using a semi-transient predictive model and combining those concentrations with C-R functions and incidence costs, as has been recently done in multiple studies [28,37,38,40,53]. Filter cost was calculated using data from an air filter manufacturer and synthesized from other studies. These models, while inherently different, are certainly interdependent; for instance, filter data were utilized in both the energy and IAQ simulations, and airflow outputs from the energy simulations were used in the IAQ simulations to predict health outcomes.