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Using multiobjective optimizations to discover dynamic building ventilation strategies that can improve indoor air quality and reduce energy use

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ABSTRACT

Ventilation plays a crucial role in promoting the comfort and health of building occupants. It is sometimes costly in terms of energy consumption, but can also be beneficial from an energy perspective when free cooling is available. This work is an exploratory analysis of the hypothesis that simultaneously optimizing energy and indoor air quality (IAQ) objectives can yield better results than existing ventilation control methods. A multiobjective optimization framework was set up to determine optimal time-resolved outdoor airflow and zone temperature setpoints. Test cases were implemented in a modeled office building by numerical, simulation-based optimization for a core and perimeter zone and for typical weather days in January, July, and October in Philadelphia. Results showed that conventional approaches were dominated by the optimized strategies in some cases. Most strikingly, in the core zone in January, mechanical system energy use was reduced by 20–30% with nearly unchanged or improved IAQ. The optimized strategies employed a low-temperature morning flush, a time-shift of some ventilation to the mid afternoon when outdoor air did not require as much heating, and a reduction in ventilation in the evening when it was not as effective at reducing exposure. Cases in July and October demonstrated another benefit: significant IAQ improvements at low energy cost. The results show that there is significant room for improvement in reducing the energy use associated with providing good IAQ.

1. Introduction

Ventilation introduces outdoor air (OA) into a building to dilute indoor-emitted contaminants and protect indoor air quality (IAQ). Most commercial buildings use mechanical ventilation, with rates set in advance according to a standard. For example, the ventilation rate procedure (VRP) of ASHRAE 62.1 specifies a minimum rate V_{bz} for a zone with floor area A_z (m^2) and P_z design occupants as:

$$V_{bz} = R_a A_z + R_p P_z \quad (1)$$

This additive approach includes a per-area component R_a (L/s m^2) intended to dilute non-occupant emissions and a per-occupant component R_p (L/s occ) to provide additional dilution of human bioeffluents [1].

This ventilation air must be conditioned to maintain appropriate ranges of indoor temperatures and relative humidity, which requires energy use by the heating, ventilation, and air conditioning (HVAC) system of the building. HVAC end uses are a major part of energy consumption in commercial buildings, which totaled 18 quadrillion Btu in 2011 alone, accounting for 19% of total US energy use [2]. Some existing strategies modify the rates described by Eq. (1) to achieve energy savings. These include demand controlled ventilation (DCV), which resets the rate based on the actual number of people present when there are fewer than the P_z design occupants, and air-side economizer control, which introduces more OA when it can provide free cooling. These two strategies are not mutually exclusive, and methods have been proposed to combine them more effectively, for example by better identifying and switching between the minimum OA and economizing operating regimes [3].

There is no guarantee, however, that the current standard framework can provide the best IAQ for the least amount of energy. It relies on two local controllers with uncoordinated objectives: one sets a minimum OA rate based entirely on a ventilation standard in conjunction with the design or current zone population, and another determines if a larger rate would be beneficial purely from an energy standpoint. Furthermore, what actually matters for occupant health and productivity is the *concentration* of contaminants

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indoors over the entire occupied period, not the *rate* at which OA is introduced at a given moment. An alternative approach is developed here: using indoor pollution concentration metrics over an entire day to assess IAQ and the optimization of a combined energy and IAQ objective to determine the best ventilation strategy. Herein, a *ventilation strategy* comprises a trajectory of coupled OA flow rates and zone temperature setpoints. This approach has the potential to identify more flexible control that can take advantage of building and weather dynamics. Although applicable to any building, the information gained from the optimizations is particularly useful for existing buildings, where other interventions like pollutant source control are often not cost-effective.

No one seems to have proposed a similar method for discovering a whole-day, optimized IAQ and energy operational strategy. In the realm of ventilation, the most similar work has focused on optimization in the design phase, including setting static flowrates based on some formulation of optimal tradeoffs between energy and IAQ (or a proxy), e.g., Ref. [4]. There has been less attention to optimal *control* of ventilation over a time horizon. Sherman and Walker have examined dynamic strategies for whole house ventilation in the residential sector, based on a generic contaminant exposure and information about the operation of local exhaust fans [5]. Their work is based on achieving equivalency to a standard, rather than optimization of an outcome, and, moreover, the features of commercial and residential ventilation are quite different.

There has been substantial work on other problems in the optimal control of commercial buildings and their HVAC systems. Two recent reviews provide good summaries [6–8]. Related application areas include single-timestep controller-coordination problems [9], precooling and nighttime ventilation control [10], and active and passive thermal storage [11]. Like this work, most previous studies were conducted in simulated environments. Most were also based on optimizing an objective that was a weighted combination of individual objectives like energy use and comfort [12]; at least one included an instantaneous IAQ constraint or objective [13]. Many optimization routines have been tried and investigated, including standard nonlinear methods like sequential quadratic programming [12] and quasi-Newton algorithms [11], various direct search methods, dynamic programming [14], reinforcement learning [15], and stochastic techniques like genetic algorithm [13,16] and particle swarm optimization (PSO) [17]. For many applications, initial work involving these computationally demanding optimizations eventually led to the development of near-optimal control strategies or simplified rules that could be implemented [18–20]. We hope that solutions to the optimal ventilation strategy problem will follow a similar course.

The present work represents a first step, which is to assess the possible benefits of optimized HVAC control strategies that take into account both energy and IAQ goals. To this end, we formed an IAQ objective whose role is simply to scale concentration metrics so they are comparable to energy costs. We then applied the multi-objective optimization approach to a simulated case study: a small office building in Philadelphia. Two zones were considered independently, on representative days in January, July, and October. We analyzed the transient optimized strategies to identify useful trends in different seasons and spaces. We also used the most efficient tradeoff curves between IAQ and energy use to assess the outcomes of conventional ventilation strategies.

2. Methods

2.1. Optimization problem

The formulation of the finite horizon optimal control problem is well known. There are four classes of variables: system states (x), control variables (u), exogenous variables or disturbances (w), and observed outputs (y). The problem has three fundamental elements: a model that describes the propagation of the states over time and how they are observed, constraints that are imposed by physics or users, and an objective or cost function. (The term “cost” is always used in the context of optimization; it does not refer to monetary value.) In the discrete time formulation, the objective is a function of the outputs, states, control, and exogenous variables at all timesteps 0, . . ., N in the planning horizon:

$$\begin{aligned}&J(y_0,\ldots,y_N,\ \ x_0,\ldots,x_N,\ \ u_0,\ldots,u_{N-1},\ \ w_0,\ldots,w_{N-1})\\&\quad=J(Y_N,X_N,U_N,W_N)=J(U_N,W_N,x_0)\end{aligned} \tag{2}$$

The optimization problem is to find the control trajectory $U_N=\{u_0,u_1,\ldots,u_{N-1}\}$ that minimizes Eq. (2) (in deterministic problems) or its expected value (in stochastic problems), subject to the dynamics imposed by the model and to any additional constraints. The second equality in Eq. (2) is true because the trajectories X_N and Y_N are fully specified by the initial state x_0 and the state model of the dynamics and observations.

To optimize with respect to two goals, the objective can be formed as a linear combination:

$$J(U_N,W_N,x_0)=J_1(U_N,W_N,x_0)+cJ_2(U_N,W_N,x_0) \tag{3}$$

If c is fixed, both objectives can be mapped to a one-dimensional cost space and there is a unique solution. Such an ideal problem would result if one had reliable information about all costs and benefits of ventilation, including health and productivity outcomes of IAQ. However, when costs cannot be established with certainty, as is the case currently with IAQ-related objectives, c parameterizes the family of optimal values known as the Pareto frontier or curve.

2.2. Energy and IAQ cost functions

In this study, the first term in Eq. (3) was selected to be a measure of the HVAC site energy cost:

$$\begin{aligned}J_1(U_N,W_N,x_0)&=365\frac{\sum_{k=1}^{N}E_{k,\text{fan}}}{A}+365\frac{\sum_{k=1}^{N}E_{k,\text{cool}}}{A}\\&\quad+365\frac{\sum_{k=1}^{N}E_{k,\text{heat}}}{A}\end{aligned} \tag{4}$$

where the three numerators are, respectively, the total energy consumed on site during the modeled day by the fan, the cooling coil, and the heating coil. The denominator is the floor area served by the system. The objective was formulated with the standard annual energy use intensity (EUI) metric in mind to make it interpretable. The sum can be thought of as the extrapolated energy use intensity (EEUI): the amount of energy per floor area that would be used if every day of the year were exactly the same as the one in the optimization problem.

For this work, we developed a simple IAQ cost function to demonstrate the approach. It should be stressed that more work needs to be done to determine the best form of this objective based on current information about health, productivity, or comfort endpoints. Herein, the IAQ cost is best regarded as a computational tool utilized in the optimization. It was based on concentration metrics for two contaminants: carbon dioxide (CO_2) and total volatile organic compounds (TVOC), which is the sum of individual volatile organics. As a very general rule, CO_2 is an indicator of air quality related to contaminants emitted by occupants, and TVOC is an indicator of air quality related to contaminants emitted by building materials and furnishings. Using contaminants in these two categories is consistent with the current Standard 62.1-2010 VRP philosophy, wherein the per-person ventilation component R_p is required to address occupant-generated contaminants like CO_2