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Optimal decision making in ventilation control

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ABSTRACT

In this paper, a two-mode ventilation control of a single facility is formulated as a scheduling model over multiple time horizons. Using the CO_2 concentration as the major indoor air quality index and expected room occupancy schedule, optimal solutions leading to reduced CO_2 concentration and energy costs are obtained by solving the multi-objective optimization model formulated in the paper. A modified evolutionary strategy algorithm is used to solve the model at different time horizons. The optimized ventilation schedules result in energy savings and maintain an acceptable level of indoor CO_2 concentration.

1. Introduction

Maintaining air quality and providing thermal comfort is important for facilities supported by heating, ventilating and air-conditioning (HVAC) systems. According to published statistics, HVAC systems account for almost 31% of the electricity consumed by U.S. households [1]. Therefore, appropriate consumption of energy while maintaining the desired air quality has an impact on energy cost and indoor comfort.

The traditional approach to ventilation is to provide a fixed minimum ventilation rate per person based on the maximum occupancy of a facility. To provide air quality guidelines, ASHRAE Standard 90.1 [2] specifies the minimum ventilation rate of 2.5 l/s per person, while ASHRAE Standard 62-2004 [3] has been revised to the minimum ventilation rate of 10 l/s per person [4]. The number of occupants in any facility varies over time, and it is rare that the facility is fully occupied. This provides a good opportunity to save energy by ventilating facilities on demand [5]. Thus, the demand-control ventilation (DCV) is a commonly used strategy in HVAC systems based on signals from the indoor sensors, e.g., a CO_2 sensor. Both simulations and field tests of the CO_2-based DCV have demonstrated the potential to save energy [6], especially in facilities with a high occupancy density. A major difficulty with this approach is that CO_2 can only be used as a surrogate of human generated pollutants, whereas a CO_2 sensor cannot respond to pollutants such as emissions from furniture or painted materials. The location and stability of CO_2 sensors are also problematic. Therefore, different control strategies [7,8] have been developed to deal with these issues. Other sensors like the VOC (volatile organic compound) sensor, occupancy sensor, humidity sensor, particle sensor, and so on, are used to modulate the ventilation rate over time under various conditions. In addition, devices such as air-side economizers are also used in ventilation systems to reduce energy consumption [9]. The quantity of fresh air supply is determined on the basis of the outside air dry-bulb temperature, enthalpy or other thermal properties. These approaches are usually cost-effective in areas where the heating or cooling cost is high.

Various optimization models [10–12] and algorithms [13,14] have been discussed in the HVAC literature. In this paper, the on-off ventilation control is formulated as an optimization model. The model involves three objectives, namely the fan-on time period, the average CO_2 above threshold, and the time period corresponding to the CO_2 above a threshold. The model is solved by an evolutionary algorithm.

By optimizing fan on-and-off schedules on the basis of the trade-off among the three objectives, energy savings can be achieved, while proper air quality can be ensured by maintaining the CO_2 concentration in an acceptable range without installing any analog indoor sensors.

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Nomenclature

C	indoor CO_2 concentration, ppm
G	CO_2 generation rate of occupants, l/s
λ_v	air exchange rate, m^3/hr
C_{out}	outside air CO_2 concentration, ppm
A	area of surfaces on which indoor pollutants are removed by deposition, m^2
v_d	deposition velocity for the pollutant
Q_{ac}	air flow rate through an air cleaner, m^3/hr
ϵ_{ac}	efficiency of an air cleaner
Q	overall air ventilation rate, m^3/hr
V	volume of the facility, m^3
C_{last}	relative indoor CO_2 concentration at the start of a time step, ppm
C_{next}	relative indoor CO_2 concentration at the end of a time step, ppm
ΔT	sampling time interval, *s*
$t_0, t_1,\ldots, t_{N-1}, t_N$	time stamps of evenly divided intervals, *s*
Δt	time interval length, *s*
S_i	random variable denoting the number of occupants in time interval, (t_{i-1},t_i)
$f_i(\bullet)$	probability density function of S_i
x_i, Δx_i	fan start time and running time period in time interval, (t_{i-1}, t_i)
IQ	status of ventilation fan
Q_{mech}	mechanical ventilation rate, m^3/hr
Q_{nat}	natural ventilation, m^3/hr
C_{lim}	CO_2 limit, ppm
C_{ti}	relative CO_2 concentration at time stamp t_i, ppm
N_p	the expected number of occupants
P_0	initial population
$P_{external}$	external population
$P_{offspring}$	offspring population
P_{parent}	parent population
$N_{current}$	current population size cluster limit
N_{parent}	parent population size
M_i	the number of individuals in $P_{current}$ that solution *i* dominates
F_i	fitness of *i*th elite individual in the external population $P_{external}$
F_j	fitness of *j*th individual in the current population $P_{current}$
A	elite set including all elite solutions that dominate a certain solution in the current population $P_{current}$
r_i	*i*th solution variable before mutation
Δr_i	Gaussian noise imposed on *i*th solution variable
r_i'	*i*thsolution variable after mutation
σ	Standard deviation of Gaussian noise
Obj	objective value
w_i	*i*th weight
N	the number of intervals in the generalized model (see Fig. 2)
n	the number of sampling points of the CO_2 concentration above the threshold (see Fig. 4).

2. Problem formulation

Carbon dioxide concentration in indoor air is commonly used as an indicator of the outside air ventilation rate [15]. CO_2 is a practical and widely used metric for measuring air quality. Though it does not reflect all air containments, a high level of CO_2 concentration points to insufficient ventilation of indoor space. In facilities, such as classrooms with relatively stable occupancy rates during certain time periods, a high concentration of CO_2 can degrade the productivity of students [16,17]. In this paper, CO_2 is used as the index to optimize ventilation control.

2.1. CO_2 predictive model

The equilibrium CO_2 concentration in a single facility can be derived based on the number of occupants, the CO_2 generation rate of the occupants, and the supply quantity of the outside air. A diagram of a single facility ventilation system is shown in Fig. 1.

Define the air exchange rate $\lambda_v = Q/V$, where Q is the overall outside air ventilation rate and V is the volume of the facility. The steady-state of indoor CO_2 concentration is obtained from the mass balance in equation (1) [16].

$$\frac{dC}{dt} = \frac{G}{V} + \lambda_v C_{out} - \lambda_v C - v_d \frac{A}{V} C - \frac{Q_{ac}}{V} C \epsilon_{ac} \tag{1}$$

where: C: the indoor CO_2 concentration; G: the CO_2 generation rate of occupants; λ_v: the air exchange rate (defined above); C_{out}: the outside air CO_2 concentration; A: the surface area on which indoor pollutants are deposited; v_d: the deposition velocity of the pollutant; Q_{ac}: the air flow rate in an air cleaner; ϵ_{ac}: the efficiency of an air cleaner.

Equation (1) is based on the assumption that the indoor air CO_2 is completely mixed and the air flow rate in and out of the facility, including mechanical ventilation, infiltration, exfiltration, and so on, is balanced.

Note that the unit of C and C_{out} is a fractional concentration (v/v). A conversion factor between the fractional concentration and ppm is 10^6. All concentration-related variables used in this paper have

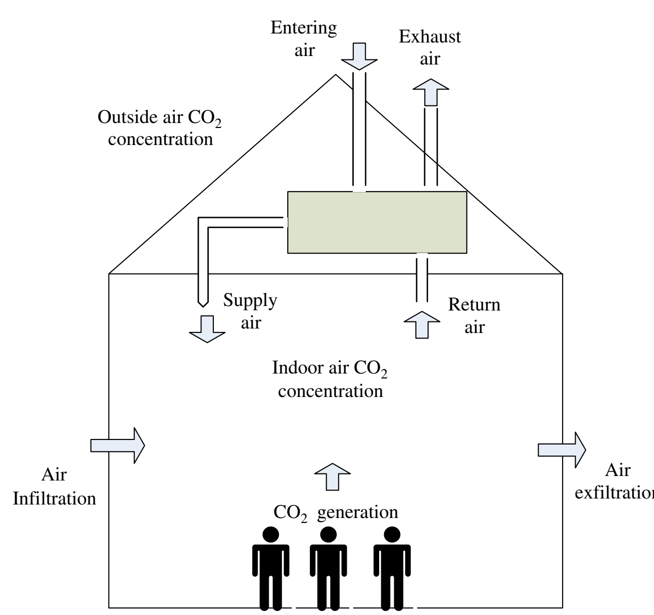

Fig. 1. Single facility ventilation system.