An Optimal CO$_2$-Based Demand-Controlled Ventilation Strategy to Improve Ventilation Flexibility in Large Airport Terminals

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Abstract

Large ventilation demand is a major reason for the high energy usage of large airport terminals. This study proposed an optimal CO$_2$-based demand-controlled ventilation (DCV) strategy to improve the ventilation flexibility of airport terminals. The proposed DCV strategy dynamically modulates the outdoor airflow rate in the airport terminal based on flight schedules, thus reducing ventilation load while maintaining acceptable indoor air quality. The time-of-use tariff is considered in the proposed DCV strategy to enable demand response and minimize operating costs. Using an airport terminal in Beijing, China, as a testbed, simulation results indicated that the optimal strategy reduced the operating costs by 42.6% and the energy consumption by 41.4% compared with a baseline strategy with fixed outdoor airflow rate. Meanwhile, the energy consumed during the peak demand periods was reduced by 44.6%, offering considerable potential for energy flexibility.

Highlights

- DCV strategy was developed for ventilation flexibility
- Air infiltration was measured and considered
- A passenger dwell model was proposed to estimate occupancy based on flight schedules
- Superior performance of the proposed DCV strategy was validated

Introduction

Modern airport terminals are characterized by high ceilings, large interior spaces, and transparent or semi-transparent envelopes that provide better natural lighting, outdoor views, and a sense of spaciousness. However, these architectural features can also result in higher energy consumption to maintain a comfortable indoor environmental quality (IEQ). Previous studies have shown that the energy consumption intensity of large airport terminals can be two to three times higher than that of typical large-scale commercial buildings with similar systems and that heating, ventilation, and air conditioning (HVAC) systems are responsible for approximately 40–80% of the total energy consumption (Lin et al., 2020; Yildiz et al., 2022).

Airport terminals have considerable potential to provide energy flexibility to help manage the imbalance between energy supply and demand in the power grid. With the rapid growth of renewable energy—for example, wind and solar energy—its intermittent nature based on changing weather conditions poses enormous challenges to the balance and reliability of the grid (Wang et al., 2019). The solution to this problem from the supply side—that is, by adding back-up fossil-fuel generators—would entail a large investment, cause high carbon emission and could leave the grid operating at a lower efficiency most of the time (Wang et al., 2019). Consequently, changing the energy usage of buildings from their normal consumption patterns—also known as building-side demand response—has emerged as a cost-effective, feasible, and widely applicable approach to optimizing power usage and reducing the problems associated with balancing the grid (Satchwell et al., 2021). Large airport terminal spaces can provide a unique advantage for the flexible operation of ventilation systems compared with typical non-residential buildings such as offices. Large indoor spaces can be used as outdoor air storage pools to shift the ventilation loads from peak to off-peak periods. The basic idea is to increase the outdoor airflow rate during off-peak periods and maintain the indoor CO$_2$ at a relatively low level, thus allowing a lower outdoor airflow rate or shutting down the outdoor air supply during peak periods, as shown in Figure 1.

![Figure 1: Ventilation load shifting through pre-ventilation strategy.](image_url)
for consumers (Jordehi, 2019). Generally, DR programs are offered only to large end users, and most buildings must participate through third-party aggregators (Darwazeh et al., 2022). However, large airport terminals with their enormous building footprints and high energy consumption densities can bid directly into DR programs, earning higher rewards, and reducing intermediate costs. Another way to engage end users in building-side energy management is by introducing time-of-use (ToU) tariffs into the power market. A static ToU tariff typically divides a day into several segments and sets different tariffs on an hourly basis to incentivize DR. A ToU tariff would offer airport terminals great opportunities to reduce operating costs by shifting energy usage from peak to off-peak periods, taking advantage of the energy tariff spread between the off-peak and peak periods.

There has been a dearth of research on the potential for DR through DCV in large-space buildings. While many studies discussing DR strategies for HVAC systems have focused on adjusting the temperature setpoint, operating frequency, and number of chillers and pumps, less attention has been paid to adjusting the outdoor airflow rate (Chen et al., 2018; Cui et al., 2015; Yin et al., 2016). Rotger-Griful et al. assessed the DR potential of ventilation fans in a 12-storey residential building in Denmark (Rotger-Griful et al., 2016). Energy flexibility was quantified based on the simulation results, and the trade-offs between energy flexibility, resident comfort, and energy efficiency were discussed. Vand et al. simulated the energy efficiency and operational cost savings of a real-time pricing-based DR strategy applied to an educational office in the cold climate region (Vand et al., 2020). The design and maximum allowable CO2 concentrations were set to 800 and 1,200 ppm, respectively. In this case study, the benefits of DR in terms of energy and cost savings were found to increase with occupancy. Maask et al. examined the duration and cost savings of DR achieved by shutting down a ventilation system for different space sizes and occupant numbers (Maask et al., 2020). The results indicated a close relationship between the ventilation flexibility, space size, and occupant density. Additionally, the CO2 concentration was found to have the greatest impact on the duration of ventilation shutdown, compared with temperature and humidity.

The main objective of this research is to develop an optimal strategy for CO2-based DCV in large airport terminals to achieve the optimal energy efficiency, energy flexibility, and operating-cost savings while satisfying the IAQ requirements. By considering the effects of air infiltration and the varying occupancy patterns of the airport terminal, the proposed DCV strategy could accurately modulate the outdoor airflow rate to maintain an acceptable IAQ and improve the ventilation efficiency of the HVAC system. Moreover, DR could be achieved by taking advantage of the large interior space of the airport terminal to shift the ventilation load from peak to off-peak periods based on the current ToU tariff.

Method

In this study, we proposed an optimal CO2-based demand-controlled ventilation (DCV) strategy to improve the ventilation flexibility of airport terminals for better energy efficiency and to provide appropriate demand response services. The novelties of the proposed DCV strategy include: (i) Effect of air infiltration on ventilation demand is considered through on-site CO2 measurement; (ii) A passenger dwell model is integrated to estimate the occupancy of airport terminal based on flight schedules for dynamic control; (iii) Time-of-use tariff are considered to provide ancillary services and minimize operating costs.

Case study

In this study, the departure lounge of a large airport terminal in Beijing, China, was selected as the case study. The floor plan of the terminal lounge is as shown in Figure 2, the function of each area in the lounge being highlighted in different colors. Due to the COVID-19 pandemic, the international departure lounge was closed at the time of the study. The total area of the terminal lounge—excluding the international departure lounge, office, and baggage claim area—is approximately 120,000 m². The floor height is between 8.5 m to 15 m, with an average of 10.5 m. A VAV system is used in an airport terminal lounge to regulate the indoor thermal environment and IAQ. Twenty-two air-handling units (AHUs) are installed to supply outdoor air to the enclosed offices and business areas, while the operation of these units is not optimized in this study. Airport flight schedules in 2021 were collected to estimate the number of passengers occupying the terminal.

The infiltration rate of the airport terminal was measured using the tracer gas method using the decay period technique based on the mass-balance equation. Using artificial sources to achieve high differences in the concentrations of the tracer gas between indoor and outdoor environments in large airport-terminal spaces can

![Figure 2: Floor plan of the airport terminal lounge.](https://doi.org/10.26868/25222708.2023.1716)
be very expensive and time-consuming, so the CO₂ exhaled by occupants in the airport terminal was used as the tracer gas in this study (Liu et al., 2018). The use of occupant-generated CO₂ also allowed us to calculate the infiltration rates over a longer period to obtain more representative results. Fifteen CO₂ instruments were deployed uniformly in the departure and arrival lounges to monitor the indoor CO₂ concentration, as shown in Figure 2. The range of the CO₂ monitoring instruments was 0–5,000 ppm, the accuracy being ± (30 ppm + 3% of the reading). The CO₂ concentration was measured at 5-min intervals and all instruments were calibrated before any measurements were taken.

The CO₂ concentration was measured from July 1 to August 31, 2021. The period between 0:00 and 4:00 each day was chosen as the decay period to calculate the infiltration rate as almost no passengers occupied the terminal lounge during this period. The infiltration rate \( A_I \) can be determined by fitting the following equation to the measurements (Tang et al., 2021):

\[
\ln \left( \frac{C_{in,t} - C_{out}}{C_{in,0} - C_{out}} \right) = -A_I t
\]

where \( C_{in,0} \) denotes the initial indoor CO₂ concentration; \( C_{in,t} \) denotes the CO₂ concentration at time \( t \); \( C_{out} \) denotes the outdoor CO₂ concentration, assumed to be constant at 400 ppm.

Additionally, air infiltration could occur when passengers passed through entrances and gates during the daytime. The volume of air infiltrating through the doors (\( G_{door} \)) is dependent on the volume of airport passengers, which can be estimated as follows:

\[
G_{door} = nV_{door}\rho
\]

where \( n \) denotes the number of people passing through; \( V_{door} \) denotes the volume of air infiltrated through the door for passing one person—that is, 4–4.75 m³ for a general door, 3.25–3.5 m³ for a door with a foyer, and 0.3–1 m³ for a revolving door, depending on the number of people passing per hour; and \( \rho \) denotes the outdoor air density.

**Occupancy estimation**

The dynamics related to the number of passengers in the departure lounge are critical parameters for determining the outdoor airflow rate to maintain an acceptable IAQ. Based on the flight schedule, a method was proposed to estimate the number of passengers in the departure lounge in advance. First, the aircraft types, capacities, and occupancy rates were collected, information which could be easily obtained in advance from airports and airlines, to calculate the number of passengers carried on each flight, as follows:

\[
n = C_A \times O_r
\]

where \( C_A \) denotes the capacity of the aircraft and \( O_r \) denotes the occupancy rate.

Subsequently, a passenger dwell model was proposed to characterize the variation in the number of passengers occupying the departure lounge before the scheduled departure time for each flight, as shown in Figure 3.

**Ventilation model**

The proposed DCV control strategy used CO₂ concentration as an indicator of IAQ. A recognized first-order mass-balance equation was then adopted to calculate the change in indoor CO₂ concentration under different ventilation strategies and occupancy profiles, expressed as follows:

\[
\frac{dC_{in}}{dt} = -AC_{in} + AC_{out} + \frac{E}{V}
\]

where \( C_{in} \) denotes the indoor CO₂ concentration, \( t \) denotes the time, \( A \) denotes the total air change rate, \( C_{out} \) denotes the outdoor CO₂ concentration (constant at 400 ppm), \( E \) denotes the indoor CO₂ emission rate, and \( V \) denotes the indoor space volume.

The total air change rate \( A \) considers the air change rate resulting from infiltration \( A_I \) and the outdoor airflow rate \( Q \) supplied by mechanical ventilation, expressed as follows:
\[ A = A_t + \frac{Q}{V} \quad (5) \]

The indoor CO₂ emission rate \((E)\) can then be calculated by multiplying the number of occupants \((n)\) by the CO₂ generation rate per person \(\left( G_{\text{person}} \right)\), as follows:

\[ E = n \times G_{\text{person}} \quad (6) \]

The CO₂ generation rate of a person is determined by their physical activity and physical characteristics, which can be calculated as follows \((\text{Lu et al., } 2022)\):

\[ G_{\text{person}} = \frac{0.00276 \times A_D 	imes M 	imes R_Q}{0.23 R_Q + 0.77} \quad (7) \]

where \(A_D\) denotes the DuBois surface area, \(1.8 \text{ m}^2\) for an average size; \(M\) denotes the physical activity level in METs; and \(R_Q\) denotes the respiratory quotient, 0.83 for an average condition \((\text{Ventilation for Acceptable Indoor Air Quality, } 2016)\).

During the cooling period, the total energy consumption \((E)\) of the outdoor air supply includes the energy consumed for cooling the outdoor air \((E_{\text{cool}})\) and the energy consumed for the outdoor air distribution \((E_{\text{fan}})\), which can be calculated using Eqs. \((8)-(10)\). It should be noted that Eq. \((10)\) considers the fan efficiency and damper openings and therefore sets the exponent to two instead of three \((\text{the theoretical value that ignores the damper adjustment})\).

\[ E = E_{\text{cool}} + E_{\text{fan}} \quad (8) \]

\[ E_{\text{cool}} = \frac{Q \rho (h_{\text{out}} - h_{\text{in}})}{COP_{\text{System}}} \quad (9) \]

\[ E_{\text{fan}} = E_r \left( \frac{Q}{Q_d} \right)^2 \quad (10) \]

where \(h_{\text{out}}\) and \(h_{\text{in}}\) denote the outdoor and indoor air enthalpy, respectively; \(\rho\) denotes the air density; \(COP_{\text{System}}\) denotes the coefficient of performance of the HVAC system, which is set at 3 in this case study; \(E_r\) denotes the rated power of the fan; and \(Q_d\) denotes the designed airflow rate.

Thus, the operating cost can be calculated by multiplying the hourly energy consumption with the hourly tariffs specified in the current ToU tariff, as shown in Figure 4. The ToU tariff includes four electricity rates specified hourly—that is, the valley, flat, ordinary-peak, and critical-peak rates.

Figure 4: The ToU tariffs on an hourly basis.

Optimization problem and algorithm

The optimization problem was defined as determining the hourly outdoor air flow rate of the terminal departure lounge from 6:00 to 22:00, which minimizes operating costs, maintains an acceptable IAQ, and provides ancillary services to the grid. A constraint was set such that the indoor CO₂ concentration was maintained below 1,100 ppm (700 ppm higher than that of the outdoor air), which was the upper limit of the acceptable IAQ, as specified in the ASHRAE standard \((\text{Ventilation for Acceptable Indoor Air Quality, } 2016)\).

An advanced evolutionary algorithm called the unified non-dominated sorting genetic algorithm (U-NSGA-III) was adopted to solve defined mono- and multi-objective optimization problems. The U-NSGA-III algorithm is an improved algorithm based on the well-known NSGA-II and the recently proposed NSGA-III algorithms, and has been shown to have better performance on both mono- and multi-objective optimization problems \((\text{Seada & Deb, } 2015)\). Unlike the NSGA-II algorithm, the U-NSGA-III algorithm predefines a set of reference points to enhance the diversity of the obtained solutions, performing non-dominated sorting in a manner similar to the NSGA-II algorithm, but first filling in the underrepresented reference directions when selecting solutions. Thus, the obtained solutions are likely to be widely distributed on or near the Pareto-optimal front. By introducing a niching-based tournament selection operator in the selection process, the U-NSGA-III algorithm has demonstrated better convergence performance than the NSGA-III algorithm for mono- and bi-objective optimizations.

Results and discussion

Infiltration rate measurement

The infiltration rate of the airport terminal was measured from June 1 to August 31, 2021, using the tracer gas method with the decay period technique based on the mass-balance equation. Additionally, the infiltration air resulting from the entry and exit of passengers through the entrance and gates of the airport terminal was calculated resulting from the entry and exit of passengers through the airp ort terminal was calculated by the CO₂ generation rate of a person, which was the upper limit of the acceptable IAQ, as specified in the ASHRAE standard \((\text{Ventilation for Acceptable Indoor Air Quality, } 2016)\).

Passenger estimates

Figure 5 shows the daily passenger traffic of the investigated airport during July and August, 2021, based on the flight schedule and proposed passenger dwell
model. Owing to the impact of COVID-19, the number of passengers has fluctuated considerably, with daily passengers traffic well below the design value. In particular, the number of passengers falls to almost one-eighth of the design value in August, 2021.

Although the daily number of passengers is highly variable, the normalized daily passenger curve is highly consistent throughout the two months, as shown in Figure 6. Each day, the number of passengers begins to increase around 5:00, going through several waves, and finally dropping to almost zero by 24:00. The average normalized daily passenger volume, represented by the red curve, shows four passenger peaks at approximately 7:00, 11:00, 14:00 and 18:00, respectively. Notably, the passenger peak at approximately 18:00 is much lower and more unstable than the other three peaks. Three valleys are evident at approximately 9:00, 13:00 and 17:00.

The low passenger traffic caused by COVID-19 greatly reduced the ventilation demand of the airport terminal investigated. For a few days in August, 2021, mechanical ventilation was not required because the demand for outdoor air could be satisfied solely by infiltration. However, because travel restrictions have been relaxed considerably in response to the reduced virulence of the virus and high vaccination rates worldwide, a discussion of routine circumstances is more pertinent. Consequently, the estimated passenger volume was scaled up in this study such that its daily peak reached the design value of 20,000 to offset the impact of the COVID-19 pandemic. For example, Figure 7 shows the estimated and adjusted passenger volume on July 6. The adjusted passenger volume was used in the following scenario analysis and DCV optimization.

**Model validation**

To validate the established ventilation simulation model, the estimated number of passengers based on passenger dwell model was used as an input to calculate the CO₂ concentration in the departure lounge based on the ventilation mathematical model, the results being compared with the measurements. Figure 8(a)–(d) shows the calculated and measured CO₂ concentrations in the departure lounge on four typical days in July and August, 2021. The ventilation system was operated at a fixed rate on the test days, resulting in relatively low CO₂ concentrations. The CO₂ concentration measured at 5:00 am was used as the initial indoor CO₂ concentration in the ventilation calculations, helping to offset the systematic error of the measuring device and thus, more accurately assess the impact of variations in passenger volume. The comparison results show that the calculated CO₂ concentration exhibit good consistency with the measurements, with an average mean absolute percentage error (MAPE) of 0.015. Consistent waveforms are evident between the calculated CO₂ concentrations and the measurements, indicating a high degree of agreement between the passenger volume estimates and the actual situation. Meanwhile, this comparison validates the adopted ventilation mathematical model under varying occupancy profiles and air infiltration rates.
Optimization of ventilation system

In this section, the optimized ventilation strategy for airport terminal is presented and compared with the baseline strategy of setting a fixed outdoor airflow rate. The operating cost, indoor CO₂ concentrations, outdoor airflow volume, and DR ability are illustrated and compared for three typical cooling days with different occupancy profiles and outdoor weather conditions—that is, July 6, August 22, and August 30, 2021). Information regarding the three selected days is summarized in Table 1. The indoor thermal environment was set at 25°C and 50% relative humidity in accordance with the relevant Chinese standard. The total operating costs and energy consumption were compared over a two-month cooling period (July 1 to August 31, 2021).

Table 1: Information of the three typical cooling days.

<table>
<thead>
<tr>
<th>Typical cooling day</th>
<th>Day one, July 6</th>
<th>Day two, August 22</th>
<th>Day three, August 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekday</td>
<td>Tuesday</td>
<td>Sunday</td>
<td>Monday</td>
</tr>
<tr>
<td>Average occupant number</td>
<td>10,094</td>
<td>7,882</td>
<td>9,474</td>
</tr>
<tr>
<td>Outdoor temperature</td>
<td>25.1 ± 3.0 ° C</td>
<td>27.0 ± 2.9 ° C</td>
<td>23.9 ± 2.9 ° C</td>
</tr>
<tr>
<td>Outdoor humidity</td>
<td>81.0 ± 11.3%</td>
<td>77.7 ± 10.1%</td>
<td>79.2 ± 12.0%</td>
</tr>
</tbody>
</table>

The CO₂ concentration and outdoor airflow rate under the baseline and optimal strategies on the three typical days were as shown in Figure 9. The four ToU tariff rates—namely, the valley, flat, ordinary-peak, and critical-peak rates—are represented by the different background colors. The results show that the optimal ventilation strategy is more efficient than the baseline strategy. On three typical days, the optimal strategy saves 40%, 57%, and 43% of the operating costs over the baseline strategy while meeting the same IAQ constraints. Moreover, the potential for operating cost savings is greater on lower occupancy days owing to the presence of infiltrated air. In terms of the total ventilation volume, there are reductions of 31%, 39%, and 36% for the optimal strategy. The reason for the higher percentage reduction in operating costs than in the ventilation volume is that the optimization strategy uses the ToU tariff structure. For example, on July 6, the optimal strategy allows the ventilation system to operate at lower rates during peak and critical-peak hours by setting higher ventilation rates during flat hours (8:00–11:00, 15:00–16:00, and 17:00–18:00). The same type of control behavior is evident on the other two days when the optimal strategy is used. By shifting the ventilation demand from high-to low-tariff periods, considerable operating cost savings can be realized.
Throughout the two-month cooling period, the total operating cost and energy consumption were 311,006 CNY and 299,473 kWh for the baseline strategy and 178,433 CNY and 175,348 kWh for the optimal strategy, as shown in Figure 10. By reducing the ventilation rate and taking advantage of the ToU tariff, the optimal strategy reduces the operating costs by 42.6% and the energy consumption by 41.4% compared with the baseline strategy, the savings in operating costs and daily energy consumption ranging from 30–63.5% and 25.8–67.3%, respectively. Meanwhile, the energy consumed during the peak and critical-peak periods is reduced by 44.6% under the optimal strategy, offering considerable potential for energy flexibility to the grid.
Conclusion
In this study, we proposed a novel DCV control strategy for airport terminals to improve ventilation efficiency by considering the effects of air infiltration and occupancy dynamics on ventilation demand. Moreover, the proposed strategy enabled a DR by taking advantage of the terminal’s large interior space to shift the ventilation load from peak to off-peak periods based on the ToU tariff. Using a large airport terminal in Beijing, China, as a case study, the energy efficiency, demand flexibility, and economic performance of the proposed strategy were verified and compared with a baseline strategy using a fixed outdoor air supply rate. By reducing the outdoor airflow rate and taking advantage of the ToU tariffs, the optimal strategy could reduce operating costs by 42.6% and energy consumption by 41.4% compared with the baseline strategy. Moreover, the energy consumed during ordinary and critical-peak hours was reduced by 44.6% under the optimal strategy, offering considerable demand flexibility to the grid.

References