Optimal Supply Air Temperature Control for Dedicated Outdoor Air System Under Varying Climate Zones

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Abstract
The importance of dedicated outdoor air systems (DOAS) is widely acknowledged as properly designed and operated DOAS can ensure adequate indoor air quality (IAQ) in an energy-efficient way. Nonetheless, there is limited guidance in determining control sequences of operating the DOAS. In this regard, this paper aims to present an optimal supply air temperature (SAT) control strategy for DOAS. For this purpose, EnergyPlus-based primary school building models were developed under six different climate zones. Then, Genetic Algorithm (GA) was adopted to determine the optimal DOAS SAT control sequence that would minimize the energy cost of the heating, ventilation, and air conditioning (HVAC) system operation. Results show that approximately 1.3 % to 63.3 % of energy cost savings could be achieved, compared to conventional rule-based control (i.e., outdoor air temperature-based reset control). This study highlights that the optimal control allows energy-efficient DOAS operations while guaranteeing sufficient ventilation and dehumidification.

Highlights
- EnergyPlus-based building energy models were developed to simulate the DOAS-level and zone-level air thermal behavior.
- GA was adopted to determine the DOAS SAT control sequence to reduce the energy cost of operating the HVAC system.
- DOAS SAT control strategies for increased energy efficiency while maintaining the IAQ, in terms of ventilation and dehumidification, were proposed.

Introduction
Air conditioning (AC) systems in buildings serve two main purposes: (1) preserving the indoor thermal environment by heating, cooling, and dehumidifying spaces and (2) distributing fresh outdoor air inside to enhance IAQ (Khattar and Brandemuehl 2002). However, as the aforementioned demands (i.e., thermal load and ventilation requirements) do not always correspond, having a single AC system to handle thermal load and dehumidification could overestimate the outdoor air intake resulting in system oversize and energy waste (Lu et al. 2022; Saber et al. 2014; Lu et al. 2020; Deng, Lau, and Jeong 2014). DOAS has been acknowledged to be a promising solution to address the issue by decoupling the thermal conditioning and ventilation operations of an AC system. DOAS is a type of HVAC system adopted specifically to condition outdoor air brought into buildings and distribute it to occupied spaces for ventilation (ASHRAE 2017). Properly designed and operated DOAS is acknowledged to have the following advantages.

(1) **Sufficient ventilation and dehumidification:** DOAS is designed to provide 100% outdoor air (i.e., no returning air mixed) to occupied spaces by conforming to ASHRAE Standard 62.1-2019 (ASHRAE 2019a) to ensure sufficient ventilation for IAQ. Additionally, a cooling coil placed inside a DOAS unit serves to cool down outdoor air so that indoor latent load can be removed for dehumidification purposes (Mumma 2001).

(2) **Improved energy efficiency:** Compared to other typical AC systems (e.g., typical constant air volume (CAV) and variable air volume (VAV) systems) systems, DOAS requires a less volumetric outdoor airflow rate. The DOAS provides the minimum outdoor airflow required for ventilation purposes, while separate AC systems (e.g., fan-coil units, active chilled beams, etc.) handle zone heating and cooling by recirculating indoor air (Kim et al. 2019). Aside from that, DOAS is often equipped with energy recovery systems (e.g., total energy recovery wheel) (ASHRAE 2017). These characteristics of the DOAS not only enable the reduction of HVAC equipment size (such as fans, chillers, and boilers) but also lower the operational energy use for AC systems (Jae-Weon, Mumma, and Bahnfleth 2003).

Despite the DOAS's potential advantages, there is limited guidelines regarding its control sequence. Even though the operational strategy of DOAS significantly impacts its energy efficiency, DOAS control, in practice, highly relies on simple rule-based control strategies (e.g., outdoor air dry-bulb temperature (OADT)-based reset control) (ASHRAE 2017; Feng and Cheng 2018). A few important issues have been raised regarding this DOAS control phase, including insufficient ventilation, dehumidification, and neutralizing SAT out of concern for over-cooling (Murphy 2018). Particularly, poor ventilation and dehumidification by AC units are likely to cause a significant risk to occupants’ comfort and health concerns (Winkler, Munk, and Woods 2019; Hao et al. 2007). Moreover, trying to neutralize the SAT
might require redundant reheating to result in excessive energy consumption (Murphy 2018).

The concerns listed above are closely related to and consequently have an effect on determining the DOAS supply air control sequence. In this regard, a simulation-based study using EnergyPlus (DOE 2019) was conducted to investigate the optimal SAT strategy of DOAS and identify its energy-saving potentials.

**Building energy modeling**

**Model geometry**

The target building of this study is the commercial prototype primary school model developed by the US Department of Energy (DOE) (Deru et al. 2011). The 3D rendering of the building is presented in Figure 1. This selected building is a one-story building a gross area of 6,871 m². The building has three pods (i.e., Pod 1/2/3) and a pod consists of four classrooms (i.e., 2 multi classrooms and 2 corner classrooms). For this study, the classrooms in Pod 1 were selected as the target zone (Figure 2). Each multi classroom and corner classroom in Pod 1 accounts for 477 m² and 99 m², respectively.

![3D rendering view of DOE prototype primary school building.](image)

**Occupancy schedule**

Occupancy schedule is one of the most important factors to take into account when performing building energy simulation as the occupants are the principal agent to control building systems including HVAC, lighting, and equipment (Pang, Lu, and O’Neill 2022). However, it is acknowledged that, in terms of time and space, occupancy profiles are stochastic (Hong et al. 2017). In this regard, dynamic occupancy schedules are considered to reflect their stochasticity. For this study, occupancy schedules based on an existing primary school calendar in Colorado, U.S. was adopted. The schedules account for students’ movement between classes, lunchtimes, and breaks, and so on. Please note that the schedules were created and adopted as part of a previous published study (Ye et al. 2021). Figure 3 represents a sample one-day schedules for the classrooms in Pod 1.

![Sample one-day occupancy profile for the target building.](image)

**HVAC system**

The target classrooms are connected to a single air loop equipped with a DOAS for ventilation purposes. Figure 4 depicts the DOAS considered for this study. It is a typical DOAS suggested in ASHRAE Design Guide for Dedicated Outdoor Air System, which contains a total-energy (enthalpy) wheel, a cooling coil, and a reheating coil (ASHRAE 2017). In Figure 4, the upper path illustrates the process of incoming outdoor air (OA) conditioning, while the lower path represents the exhaust air (EA) from the target zones. The OA first recovers energy from the EA by going through the total-energy wheel (OA’). Then, the air is further conditioned by the cooling and heating coil, in order. It is notable that the air supplied to the zones (CA) is entirely the fresh outdoor air as there is no return air being mixed with the incoming OA.

![DOAS unit with exhaust air recovery.](image)

For the DOAS supply fan, a VAV fan is adopted to simulate demand-controlled ventilation (DCV). In this regard, the DOAS supply fan can be sized based on the design outdoor airflow rate, according to ASHRAE Standard 62.1-2019 (i.e., Ventilation for Acceptable Indoor Air Quality) (ASHRAE 2019a). To determine the required amount of outdoor airflow for ventilation ($V_{oz}$), it is suggested to first calculate the breathing zone outdoor airflow ($V_{hz}$) and divided it by the distribution effectiveness ($E_z$). It can be computed by Equations (1) and (2).

$$V_{hz} = R_p P_x + R_o A_x$$  \hspace{1cm} (1)

$$V_{oz} = V_{hz} / E_z$$  \hspace{1cm} (2)
Where $P_z$ is zone population, $A_z$ is zone floor area, $R_F$ is OA rate required per person, $R_{ac}$ is OA rate required per unit area, and $E_z$ is the zone air distribution effectiveness. For classrooms, $R_F$ and $R_{ac}$ can be assumed to be 5 L/s and 0.6 L/s-m², respectively (ASHRAE 2019a).

Meanwhile, since the DOAS terminal unit typically discharges the air that is cooler than the air in the zone space, $E_z = 1$. As a result, for this study, the DOAS supply fan is designed to handle approximately 2.17 m³/s of outdoor air.

For DOAS cooling coil, a ‘dynamic reset’ humidity control is adopted. The cooling coil operates dynamically, instead of maintaining a static dewpoint temperature, according to the zonal humidity level. To elaborate, the cooling coil outlet (SP in Figure 5) humidity ratio is controlled to maintain the zonal relative humidity levels (i.e., $H_1$ to $H_6$ in Figure 5) at the designated dehumidifying setpoint (i.e., 60% RH in this study).

![Figure 5: Schematic of dynamic reset cooling coil operation.](image)

Since DOAS unit primarily serves the ventilation and dehumidification needs, separate zonal HVAC systems are required for space air heating and cooling. For this study, fan-coil units (FCUs) are installed to cover the sensible load in each zone. The zone heating and cooling setpoint temperatures are 21°C and 24°C, respectively.

For the plant loop, a cooling tower, water-cooled chiller, and a gas-fired condensing boiler are modeled to supply cooling, chilled and hot water, respectively, for the DOAS and FCUs (Figure 6).

![Figure 6: DOAS + FCU configuration.](image)

### Climate zones

A total of six locations in six different climate zones in the U.S. are considered (Table 1). The ASHRAE climate zones 2A, 3B, 4A, 4C, 6A, and 6B are selected to represent varying outdoor air temperature (i.e., hot, warm, mild, and cold) and humidity (i.e., humid, dry, marine) levels, as described in Table 1.

**Table 1: Selected climate zones**

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Location</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>Tampa, FL</td>
<td>Hot – humid</td>
</tr>
<tr>
<td>3B</td>
<td>El Paso, TX</td>
<td>Warm – dry</td>
</tr>
<tr>
<td>4A</td>
<td>New York City</td>
<td>Mild – humid</td>
</tr>
<tr>
<td>4C</td>
<td>Seattle, WA</td>
<td>Mild – marine</td>
</tr>
<tr>
<td>6A</td>
<td>Rochester, MN</td>
<td>Cold – humid</td>
</tr>
<tr>
<td>6B</td>
<td>Great Falls, MT</td>
<td>Cold – dry</td>
</tr>
</tbody>
</table>

Building construction-relevant parameters (e.g., envelope configuration) are modified according to the climate zone, referring to the commercial prototype primary school models developed by the DOE (Deru et al. 2011).

### Optimal control

**Genetic Algorithm-based optimization**

In order to search for the optimal control sequence of DOAS SAT, Genetic Algorithm (GA) is selected as an optimization solver. GA is a well-acknowledged metaheuristic algorithm that has been widely adopted for developing HVAC system controls (Kim, Jeon, and Kim 2016; Congradac and Kulic 2009). GA mimics the mechanism of the ‘survival of the fittest’. First, multiple solution (i.e., DOAS SAT in this case) candidates, known as populations, are generated at random. Then, each population is evaluated based on its fitness score (i.e., objective function). Populations with high fitness scores survive and are selected as parents. The parents go through mating to generate children for the next generation. Beyond the capability of the parents, the children varyate themselves by crossover and mutation procedures, to further enhance the search space and increase the possibility of discovering superior solutions. After all, the entire procedure is repeated over a number of generations until the best solution (or a reasonably good solution) with the highest fitness score is found. Figure 7 represents the conceptual flowchart of the GA. For this study, PyGAD, a popular GA library in Python, is adopted (Gad 2021).

![Figure 7: Flowchart of the GA [Modified from (Gad 2021)].](image)
and mutation) rate. The hyperparameters are selected empirically as shown in Table 2.

**Table 2: Hyperparameters for GA**

<table>
<thead>
<tr>
<th>Hyperparameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of generations</td>
<td>30</td>
</tr>
<tr>
<td>Population</td>
<td>49</td>
</tr>
<tr>
<td>Crossover/mutation rates</td>
<td>0.9/0.2</td>
</tr>
</tbody>
</table>

**Optimal control of DOAS SAT using GA**

The objective of the optimization is to minimize the HVAC system operation cost. In this regard, the GA sends a number of DOAS SAT to EnergyPlus models. Then, the operational energy costs for the models will be computed and sent back to the GA for it to find the optimal DOAS SAT (Figure 8).

![Figure 8: Schematic of DOAS optimal control.](image)

For this study, a total of 12 week-optimization (i.e., 4 heating weeks, 4 cooling weeks, 4 shoulder weeks) was implemented to search for the optimal SATs for each model under varying outdoor air conditions (Table 3).

**Table 3: Optimization periods for this study.**

<table>
<thead>
<tr>
<th>Category</th>
<th>Optimization period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating season</td>
<td>01-30 – 02-24</td>
</tr>
<tr>
<td>Cooling season</td>
<td>07-31 – 08-25</td>
</tr>
<tr>
<td>Shoulder season</td>
<td>10-09 – 11-03</td>
</tr>
</tbody>
</table>

The objective function is formulated to minimize the overall HVAC system operational cost for each timestep (i.e., hourly), as elaborated in Equation (3). The lower and upper boundaries of the supply air dry-bulb temperatures are set to be 9 °C and 24 °C, respectively (Equation (4)).

\[
\text{Find } \min f(x) = \alpha \cdot E_{\text{gas}} + \beta E_{\text{elec}}
\]

\[
\text{Subject to } x \in [9 \degree C, 24 \degree C]
\]

Where \( \alpha \) and \( \beta \) are rates for natural gas and electricity, and \( E_{\text{gas}} \) and \( E_{\text{elec}} \) represent hourly natural gas and electricity use, respectively.

The lower bound (i.e., 9 °C) was determined to guarantee the SAT to be higher than the cooling coil outlet temperature. The upper bound (i.e., 24 °C) was set to correspond with the upper limit of the zone air temperature (i.e., zone cooling setpoint temperature).

The utility price rates (i.e., \( \alpha \) and \( \beta \)) differ by climates, and the values from EIA 2021 are detailed below (Table 4) (EIA 2021).

**Table 4: Electricity and gas rates for commercial buildings in different climate zones (EIA 2021).**

<table>
<thead>
<tr>
<th>Category</th>
<th>Natural Gas Rate [dollar/ft²] (( \alpha ))</th>
<th>Electricity Rate [cents/kWh] (( \beta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>12.09</td>
<td>10.67</td>
</tr>
<tr>
<td>3B</td>
<td>8.49</td>
<td>9.14</td>
</tr>
<tr>
<td>4A</td>
<td>7.91</td>
<td>16.11</td>
</tr>
<tr>
<td>4C</td>
<td>9.42</td>
<td>8.75</td>
</tr>
<tr>
<td>6A</td>
<td>7.79</td>
<td>11.08</td>
</tr>
<tr>
<td>6B</td>
<td>8.70</td>
<td>9.50</td>
</tr>
</tbody>
</table>

**Optimal control (OC) vs. Rule-based control (RBC)**

To demonstrate the efficacy of optimal control (OC), it was compared with a typical rule-based control (RBC) with respect to energy cost. For the RBC, an OADT-based reset logic was considered. When dehumidification is required, the SAT is typically set at or below 12.8 °C. As a result, 12.8 °C is chosen as the baseline SAT of the RBC. Moreover, according to ASHRAE Standard 90.1: Energy Standard for Building Except Low-Rise Residential Buildings, HVAC systems connected to multiple zones need to allow resetting the SAT in response to representative building loads or outside air temperature (ASHRAE 2019b). For the reset, at least 25% of the difference of the design zone air temperature and the design SAT should be taken into account. In this study, as the design indoor air temperature and the baseline SAT are 24 °C and 12.8 °C, respectively, a minimum reset of 2.7 °C, raising the SAT to or above 15.5 °C, should be considered. In this regard, the lower and upper bounds of the RBC (i.e., reset control) are determined to be 12.8 °C and 15.5 °C, respectively. Figure 10 depicts the RBC logic adopted for this study. As shown in Figure 10, the The DOAS SAT setpoint is
set to 12.8 °C when the OADT is higher than 21 °C and the DOAS supply air temperature setpoint shall be 15.5 °C when the OADT is lower than 15.5 °C. Two OADT values (i.e., 15.5 °C and 21 °C) are selected based on an existing supply air reset control strategy, used in practice (Trane 2010).

Figure 10: Typical rule-based control logic for DOAS SAT (Trane 2010).

Figure 11 shows a sample result of DOAS SATs controlled by the RBC and OC. The gray backgrounds in the figure represent the unoccupied hours. It is noteworthy that, the DOAS SAT from the OC fluctuates dynamically over the entire heating, cooling, and shoulder seasons. As a result, OC has a larger variance than RBC when considering all DOAS SATs throughout all testing periods (i.e., the heating, cooling, and shoulder seasons) as shown in the probability density plots of SAT (Figure 12).

(a) Heating season

(b) Cooling season

Figure 11: Sample results for DOAS SAT RBC vs. OC in New York City (i.e., climate zone 4A).

Figure 12: Distribution plot of DOAS SAT under varying climate zones (RBC vs. OC).

Table 5 compares the energy cost to operate the HVAC system when each control strategy (i.e., RBC and OC) is applied. As can be seen, monthly energy cost saving potential varies from 1.3 % to 63.3 % depending on the climate zone and the season. The saving potential in the heating season is likely to be dominant with approximate saving rate range of [7.8 %, 63.3 %], followed by the shoulder season and the cooling season with the ranges of [2.3 %, 38.5 %] and [1.3 %, 5.6 %], respectively. Considering total savings across all seasons, the largest amount of savings, approximately $ 265, can be anticipated in climate zone 4A, which is characterized as mild and humid. Conversely, in climate zone 2A, which is classified as hot and humid, only $ 59 in savings is expected. The results indicate that when there are high demands for sensible and latent cooling (e.g., in cooling
season or at hotter locations), it may not be feasible to achieve significant energy savings.

Table 5: Energy cost comparison by climate zone and season (RBC vs. OC).

<table>
<thead>
<tr>
<th>Category</th>
<th>RBC [$]</th>
<th>OC [$]</th>
<th>Saving Rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A</td>
<td>Heating</td>
<td>435</td>
<td>401</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>568</td>
<td>556</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>576</td>
<td>563</td>
</tr>
<tr>
<td>3B</td>
<td>Heating</td>
<td>167</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>303</td>
<td>299</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>245</td>
<td>232</td>
</tr>
<tr>
<td>4A</td>
<td>Heating</td>
<td>368</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>677</td>
<td>644</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>491</td>
<td>472</td>
</tr>
<tr>
<td>4C</td>
<td>Heating</td>
<td>174</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>221</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>160</td>
<td>127</td>
</tr>
<tr>
<td>6A</td>
<td>Heating</td>
<td>300</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>398</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>296</td>
<td>182</td>
</tr>
<tr>
<td>6B</td>
<td>Heating</td>
<td>188</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>216</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>Shoulder</td>
<td>168</td>
<td>131</td>
</tr>
</tbody>
</table>

Figure 13 depicts daily energy cost savings as functions of OADT and outdoor air humidity ratio (OAHR). It can be seen that energy cost savings are negligible when daily average OADT is lower than -10 °C or higher than 20 °C (Figure 13 (a)). In addition, as shown in Figure 13 (b), energy cost savings mainly occur when daily average OAHR is low. From the results, it can be inferred that most of the energy cost saving potential can be expected in partial load periods, when extreme cooling, heating, and dehumidification is not required.

In spite of the energy performance improvement of the OC, there were a total of 5 days (i.e., 1 day each in 3B cooling, 4A heating, 4A shoulder, 4C cooling, 6A shoulder) when the daily energy cost saving was negative. These days, ironically, the RBC outperformed the OC. The red diamond in Figure 13 represents such data of January 30th in climate zone 4A. Figure 14 gives the evidences that the GA searched almost every space within the boundaries, which implies that the optimal SAT derived by the GA is the global optimum for this day. In this regard, the thermal lag caused by the building mass might be a potential reason to affect the results. Therefore, further investigations on the OC with different prediction horizons (PH) (e.g., PH = 3 hours, 6 hours, etc.) will be required as a future study.

Lastly, in addition to the energy performance analysis, spot checks on zone air temperature and relative humidity were conducted. Figure 15 (a) and (b) are histograms to represent the air temperature and relative humidity for the multi classroom 1 (MC 1) throughout the entire periods. As shown in Figure 15 (a), with the proposed control (i.e, OC), the zone air temperatures under all the climate conditions are well maintained between the heating setpoint (HTG SP) and the cooling setpoint (CLG SP). Similarly, Figure 15 (b) shows that the zone relative humidity can be controlled within the dehumidifying setpoint (i.e., 60%). It implies that the
OC has the potential to operate the DOAS in an energy-efficient way without violating indoor air temperature and humidity levels.

Conclusion and Future Work
This paper presented an optimal control (OC) strategy for dedicated outdoor air system (DOAS) supply air temperature (SAT) control sequence under six different climate conditions (i.e., ASHRAE climate zones 2A, 3B, 4A, 4C, 6A, and 6B). To address its effectiveness, EnergyPlus-based primary school models equipped with DOAS and fan-coil units (FCUs) were developed. Then, A Genetic Algorithm (GA) was adopted to find the optimal DOAS SAT control sequence in terms of minimizing the energy cost of the overall HVAC system (i.e., DOAS + FCU) operations in three representative months (i.e., heating, cooling, shoulder seasons). As a result, it turned out that an energy cost saving potential ranging from 1.3 % to 63.3 %, depending on climate zones and seasons, could be expected from adopting OC over a typical RBC, without violating occupants comfort level (e.g., air temperature and humidity constraints).

Limitations and future work are listed as follows. First, the presented results are limited to one DOAS system configuration (i.e., primary school with DOAS + FCU). In order to derive more general observations about the optimal DOAS SAT, the ongoing and future work will involve further investigations on the effectiveness and scalability of the proposed optimization technique for different DOAS system configurations (e.g., DOAS unit with terminal units of heat pump, DOAS units with desiccant wheel, etc.). Next, regardless of the optimal control’s outstanding performance, running optimizations for every timestep is time consuming and the relationship between the inputs (e.g., outdoor air conditions, internal heat gains, etc.) and the outputs (i.e., optimal SAT) are difficult to be interpreted by building operators. In this regard, additional investigations on optimization-informed rule extractions will be conducted as a follow-up to develop implementable and interpretable control strategies. Last but not least, this paper is limited to simulation-based studies, suggesting additional experiments for applying and validating the suggested OC in existing DOAS systems.

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