# Impacts of Optimized Cold & Hot Deck Reset Schedules on Dual Duct VAV Systems - Theory and Model Simulation

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**Abstract**

Optimal hot and cold deck reset schedules can decrease simultaneous heating and cooling in VAV AHUs comparing with constant cold deck temperature operation. In this paper, optimization models are developed. The energy impacts are simulated for a typical office building in the hot and humid climate (Galveston, Texas).

The simulation results show that the optimized reset schedules can reduce the cost of AHU energy consumption (cooling, heating and fan power) by 8% to 20% in normal VAV systems when the minimum air flow rate increased from 30% to 70% of the maximum flow.

## Introduction

Simultaneous heating and cooling can be

volume systems [Liu et. al 1994, 1995, 1996]. In a VAV system, the amount of simultaneous heating and cooling is reduced significantly by reducing total air flow when the load is low [SMACNA 1992, Wendes 1994]. The amount of simultaneous heating and cooling depends on the minimum air flow rate under certain cold and hot deck set-points. Since the minimum air flow rate is determined by the indoor air circulation [ASHRAE 1995], simultaneous heating and cooling occurs when the heating or cooling load is low.

In this paper, the optimization models are developed for the VAV box operation. Simulations are performed to investigate the impacts of the optimized hot and cold deck reset schedules on the cost of AHU operations for a typical office building in hot and humid climate

## VAV Box Model

We shall assume:

(1) temperature is controlled at the set point precisely;
(2) Ideal boxes that have zero air leakage;
(3) The maximum hot air flow equals to the maximum cold air flow;
(4) The load ratio varies from -100% (heating load) to 100% (cooling load); and
(5) The mixing air temperature equals 75°F.

When the load ratio is lower than zero (heating), the air flow rates are calculated by Equation 1:

$$a_c = 0$$
$$a_h = -\frac{T_r - T_{c,d}}{T_h - T_r}\dot{q} \qquad (1)$$

$T_{c,d}$ is the design cold air temperature; $T_r$ is the room temperature; and $\dot{q}$ is the load ratio (negative for heating and positive for cooling).

If the hot air flow ratio is lower than the minimum air flow ratio, the cold and hot air flow rates should be determined by Equation 3.

When the load ratio is higher than zero (cooling), the air flow rates are calculated by Equation 2.

$$a_c = \frac{T_r - T_{c,d}}{T_r - T_c}\dot{q} \qquad (2)$$
$$a_h = 0$$

If the cold air flow ratio is lower than the minimum air flow ratio, the air flow ratio is determined by Equation 3.

$$a_{\min} = a_h + a_c$$
$$a_h T_h + a_c T_c = (a_{\min} - \dot{q})T_r + \dot{q}T_{c,d} \qquad (3)$$

Where $a_{\min}$ is the minimum air flow ratio. After the air flow rates are determined, the energy consumption ratio can be determined using Equation 4.

$$E_c = a_c \frac{T_r - T_c}{T_r - T_{c,d}}$$
$$E_h = a_h \frac{T_h - T_r}{T_r - T_{c,d}} \qquad (4)$$

Where $E_c$ is the ratio of the cooling energy consumption to the design cooling energy consumption. $E_h$ is the ratio of heating energy consumption to the design cooling energy consumption.

The VAV box supplies either cold or hot air when the air flow rate is higher than the minimum flow. When the load is low, the VAV box varies the supply air temperature by mixing hot and cold air to maintain the minimum air flow rate. The supply air temperature is determined by Equation 5:

$$T_s = \begin{cases} T_h & a > a_{\min} \quad \dot{q} < 0 \\ T_c & a > a_{\min n} \quad \dot{q} > 0 \\ T_r - \dfrac{\dot{q}}{a_{\min}}(T_r - T_c) & a = a_{\min} \end{cases} \qquad (5)$$

Figure 1 presents a typical cold and hot deck temperature reset schedules. The cold deck temperature is 55°F while the hot deck temperature varies from 100°F to 75°F when the load ratio varies from -0.7 to 0.2. When the heating load is higher than 70% of the design cooling load, the hot deck temperature is 100°F. When the cooling load is higher than 20% of the design load, the hot deck temperature is 75°F.

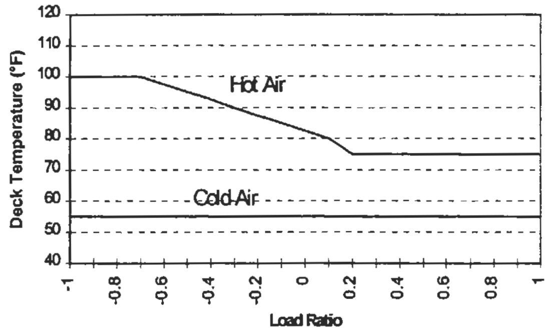


Figure 1: A Typical Cold and Hot Deck Reset Schedule for A VAV System

Figure 2 presents the simulated air flow rates under the typical cold and hot deck reset schedule when the minimum air flow rate is 50% of the maximum air flow rate. The simultaneous heating and cooling occurs when the heating load is lower than 90% of the cooling design load and the cooling load is lower than 50% of the design load.

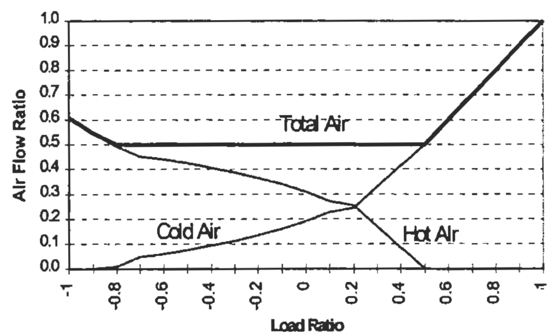


Figure 2: Simulated Air flow Ratio for a Typical VAV Terminal Box (The Minimum Air Flow Rate Is 50% of the Design Flow)

The energy consumption can be significantly reduced by resetting the cold and hot air temperature based on supply air temperature. The optimal hot deck can be determined by equation 6.

$$T_h^{\,0} = T_r - \frac{\dot{q}}{a_{\min}}\left(T_r - T_{c,d}\right) \qquad (6a)$$

$$T_h = \begin{cases} 100 & T_h^{\,0} > 100 \\ T_h^{\,0} & \\ T_{mix} & T_h^{\,0} < T_{mix} \end{cases} \qquad (6b)$$

The optimal cold deck temperature can be determined by equation 7.

$$T_c^{\,0} = T_r - \frac{\dot{q}}{a_{\min}}\left(T_r - T_{c,d}\right) \tag{7a}$$

$$T_c = \begin{cases} 60 & T_c^{\,0} > 60 \\ T_c^{\,0} & \\ T_{c,d} & T_c^{\,0} < T_{c,d} \end{cases} \tag{7b}$$

Figure 3 presents the optimized cold and hot deck reset schedules. These schedules minimize the simultaneous heating and cooling as well as the fan power consumption. The high limit of the cold deck temperature is required for the room humidity control. The hot deck temperature is decreased to 75°F when the heating load is lower than 10%. The cold deck temperature remains 60°F until the cooling load is higher than 40%.

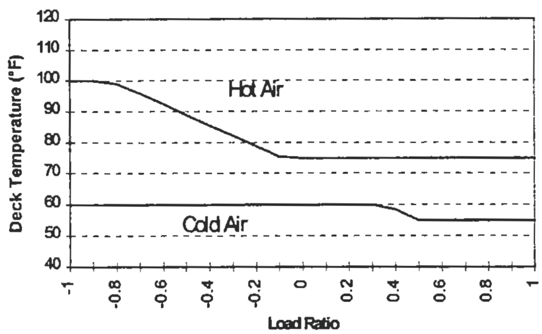


Figure 3: The Optimized Cold and Hot Deck Reset Schedule (The Minimum Air Flow Rate is 50% of Design Flow)

Figure 4 presents the simulated air flow under the optimized cold and hot deck reset schedules. The simultaneous heating and cooling is limited to a load range of -10% to 40% due to the optimal reset schedule.

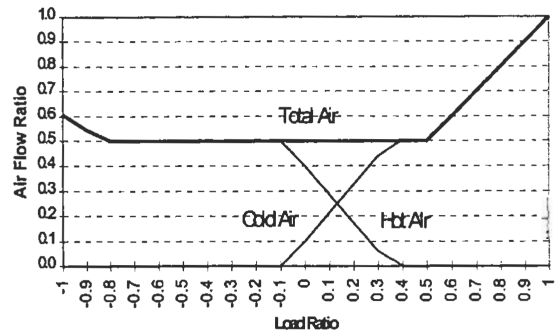


Figure 4: Simulated Air Flow Rate Under the Optimized Cold and Hot Deck Reset Schedules (The Minimum Air Flow Rate is 50% of the Design Flow)

A VAV system has several terminal boxes that often have different load ratios at the same time. Therefore, the optimization is often performed by trail and error method using a sophisticated simulation software.

**VAV System & Optimization**

A VAV AHU often serves several rooms or zones. However, these zones can often be grouped as two types: interior zone and exterior zone. In this investigation, a two-zone VAV system is simulated.

The conditioned floor area is 200 feet long and 50 feet wide. The conditioned area has only one exterior wall which is 200 feet long by 10 feet high. 20% of the exterior wall area is windows with a heat transfer value of 1 Btu/ft$^2$/°F/hr. The opaque wall has a heat transfer value of 0.1 Btu/ft$^2$/°F/hr. The whole area is separated into two zones: interior zone and exterior zone. The interior zone is 200 feet long and 30 feet wide while the exterior zone is 200 feet long and 20 feet wide.

The internal gain due to lighting and office equipment is 1.5 W/ft$^2$. The occupancy density is 200 square feet per person. The designed maximum air flow is 1 cfm/ft$^2$. The outside air intake is 20 cfm/person or 0.1 cfm/ft$^2$.

The AHU has two terminal boxes for the interior and the exterior zones, respectively. A constant outside air intake is maintained regardless of the total air flow rate. Both heating and cooling coils have enough capacity to maintain the cold and hot deck set-points.

The supply air fan has a capacity of 10 kW with a VFD to maintain the supply static pressure. The fan power consumption is calculated by equation 8.

$$q_{kw} = 10\left(\frac{cfm}{cfm_{\max}}\right)^3 \tag{8}$$

Where $q_{kw}$ is the fan power consumption, cfm is the air flow rate, and $cfm_{max}$ is the designed air flow rate.

In the base cases, the cold deck temperature is 55°F regardless of the ambient temperature. The hot deck temperature varies from 110°F to 75°F when the ambient temperature increases from 40°F to 75°F. When the ambient temperature is lower than 40°F, the hot deck temperature remains at 110°F.

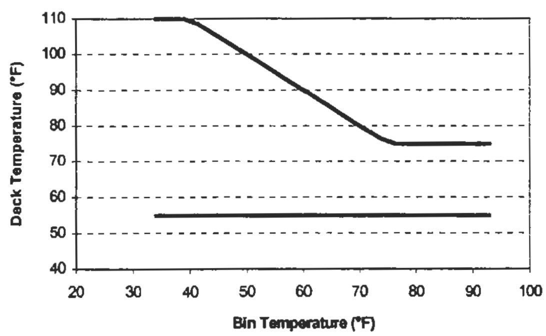


Figure 5: Cold and Hot Deck Temperature Versus the Ambient Temperature for Base Case or Normal VAV System

The optimal cold and hot deck temperatures are determined by using "AirModel"[Liu, 1997]. The "Air Model" is a software package designed specially for optimizing AHU operation and detecting faults of the AHU operation.

Under the optimized cold and hot deck reset schedules, the AHU has the minimum energy cost (heating, cooling, and fan power). The room relative humidity is controlled at 55% or lower.

In the model simulation, neither economizer nor humidifier are considered. The room temperature is 73°F. The AHU operates 24 hours per day. Both solar heat gain and moisture production are neglected. The air leakage through a closed air damper is 5% of the total air flow rate. The energy prices are: \$0.027/kWh for electricity (fan and pump power), \$4/MMBtu for heating (hot water), and \$4/MMBtu for cooling (chilled water).

Table 1 presents the Bin weather data (Galveston, Texas) generated by using the national weather station measured hourly data in 1994. The first column is the dry ambient temperature. The second column is the coincident dew point. The third column is the number of hours under each bin

Table 1: Bin Weather Data Generated By Using National Weather Station Measured Data in 1994

| Dry Bulb (°F) | Coincident Dew Point (°F) | Hours |
|---|---|---|
| 34.1 | 27.9 | 8 |
| 36.5 | 33.3 | 36 |
| 38.9 | 34.7 | 81 |
| 41.4 | 35.4 | 105 |
| 43.7 | 36.6 | 169 |
| 46.4 | 37.3 | 171 |
| 48.9 | 39.4 | 238 |
| 51.3 | 43.8 | 236 |
| 53.8 | 47.2 | 353 |
| 56.3 | 49.6 | 304 |
| 58.9 | 52.9 | 429 |
| 61.3 | 55 | 483 |
| 63.8 | 59.6 | 532 |
| 66.2 | 61.9 | 568 |
| 68.7 | 64.3 | 602 |
| 71.1 | 66.3 | 494 |
| 73.7 | 68.2 | 454 |
| 76.3 | 69.6 | 353 |
| 78.9 | 71.9 | 443 |
| 81.4 | 75.1 | 706 |
| 83.6 | 76.2 | 887 |
| 86.2 | 76.6 | 456 |
| 88.7 | 76.3 | 405 |
| 91 | 75.9 | 219 |
| 93 | 75.5 | 28 |

**Simulation Results**

Both base and optimization simulations are performed for different minimum air flow rates: 0.3, 0.4, 0.5, 0.7, 0.9, and 1.0 cfm/ft$^2$.

Table 2 summarizes the simulation results. The energy cost savings increase from 8% to

28% when the minimum air flow increases from 30% to 100% (constant volume system). The cooling energy savings increases from 5% to 27%, and the heating energy saving increases from 80% to 96%. The optimized hot and cold deck increases fan power consumption when the minimum air flow is lower than 50%. Note that the heating energy consumption was extremely low (5% to 14%) compared with the cooling energy consumption in the case simulated. When the actual heating consumption is higher in mild climates, the potential saving of the optimized reset schedule will increase significantly.

Figures 6 to 9 present and compare the detailed results when the minimum air flow rate was 0.5 cfm/ft$^2$.

Figure 6 presents the optimized deck temperature as a function of the outside air temperature when the minimum air flow rate is 50%. The optimized hot deck temperature varies from 73°F to 78°F when the ambient temperature is increased from 35°F to 85°F. The hot deck temperature equals to the mixing air temperature when the ambient temperature is higher than 85°F. The optimized cold deck temperature varies from 55°F to 62°F. The optimized hot deck temperature is significantly lower than the base hot deck temperature while the optimized cold deck temperature is significantly higher than the base cold deck temperature when the ambient temperature is lower than 80°F.

Table 2: Summary of Simulated Annual Energy Consumption Under Different Minimum air Flow Rate

| Minimum Air Flow (%) | | 100% | 90% | 70% | 50% | 40% | 30% |
|---|---|---|---|---|---|---|---|
| Cooling | Base | 1,424 | 1,221 | 1,077 | 946 | 901 | 887 |
| MMBtu/yr | Optimized | 1,040 | 1,002 | 927 | 865 | 847 | 842 |
| Heating | Base | 219 | 223 | 160 | 88 | 60 | 48 |
| MMBtu/yr | Optimized | 8 | 18 | 25 | 17 | 11 | 9 |
| Fan Power | Base | 86,600 | 63,131 | 29,704 | 10,876 | 6,608 | 6,012 |
| kWh/yr | Optimized | 86,600 | 63,131 | 29,704 | 11,481 | 7,740 | 7,276 |
| Cost | Base | 10,109 | 8,522 | 6,609 | 5,140 | 4,673 | 4,537 |
| $/yr | Optimized | 7,294 | 6,524 | 5,274 | 4,440 | 4,221 | 4,181 |
| Savings | Cost | 28% | 23% | 20% | 14% | 10% | 8% |
| % | Cooling | 27% | 18% | 14% | 9% | 6% | 5% |
| | Heating | 96% | 92% | 85% | 81% | 82% | 80% |
| | Fan Power | 0% | 0% | 0% | -6% | -17% | -21% |

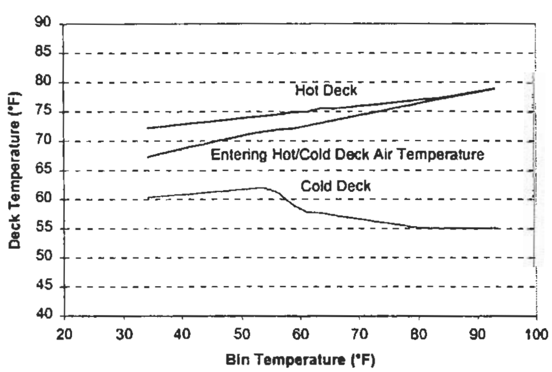


Figure 6: Deck Temperature Versus the Ambient Temperature for Both Base and the Optimized Cases (The Minimum Air Flow Rate Was 50% of the Maximum Air Flow)

Figure 7 compares room relative humidity levels under both the base and the optimized case. When the ambient temperature is lower than 55°F, the room relative humidity levels are the same for both the base and the optimized cases. When the ambient temperature varies from 55°F to 80°F, the relative humidity level is higher in the optimized case while it is still lower than 55%. When the ambient temperature is higher than 80°F, the relative humidity levels were the same for both the base and the optimized cases.

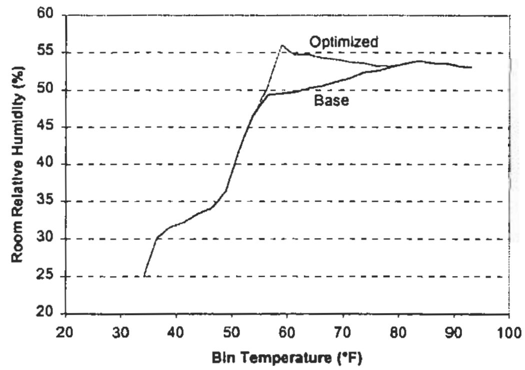


Figure 7: Simulated Room Relative Humidity Versus the Ambient Temperature for Both Base and the Optimized Cases (The Minimum Total Air Flow Rate is 50% of the Maximum Air Flow)

Figure 8 compares operation cost (heating, cooling, and fan power) under both base and the optimized cold and hot deck operation schedules. When the ambient temperature is lower than 74°F, the optimized energy consumption is significantly smaller than the base consumption. The lower energy cost are due to simultaneously reduced heating and cooling when the ambient temperature is lower than 55°F.

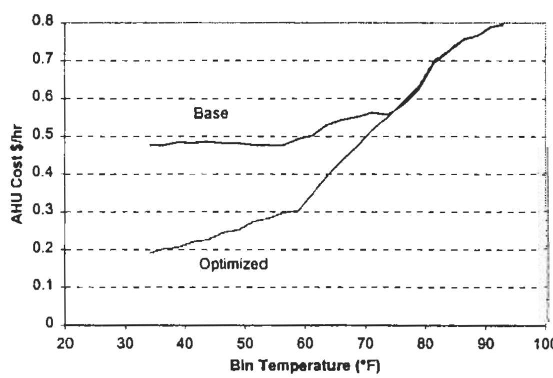


Figure 8: Simulated Hourly Energy Consumption (Heating and Cooling) Versus the Ambient Temperature (The Minimum Total Air Flow Is 50% of the Maximum Air Flow)

Figure 9 compares the annual energy cost under each Bin temperature. The annual cost is determined as the product of the hourly cost (Figure 8) and the number of hours for each Bin. The majority of annual savings occurs when the ambient temperature is within 35°F to 70°F because of the high number of hours.

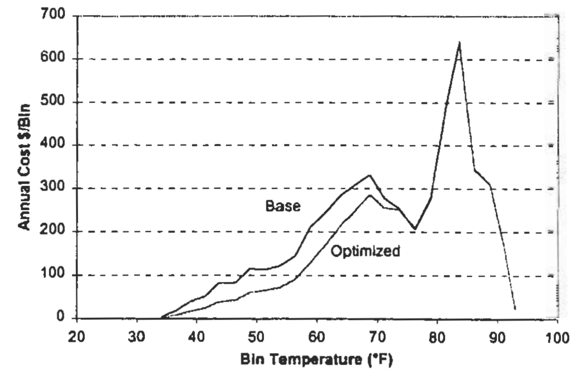


Figure 9: Simulated Annual Energy Consumption Under Each Bin Temperature (The Minimum Total Air Flow Is 40% the Maximum Total Air Flow)

**Conclusions**

The simultaneous heating and cooling occurs when the heating load is lower than 90% of the cooling design load and the cooling load is lower than 50% of the design load when the typical cold and hot deck reset schedule are used in a VAV box with 50% of the maximum air flow rate. Significant amount of simultaneous heating and cooling can be reduced by optimizing the hot and the cold deck reset schedules.

The simulation results in a typical office building at Galveston, Texas show that the optimized reset schedules can reduce the cost of AHU energy consumption (cooling, heating, and fan power) by 8% to 20% in normal VAV systems, when the minimum air flow rate increased from 30% to 70% of the maximum flow.

**Acknowledgment**

This work was supported by the Texas State Energy Conservation Office through the LoanSTAR program. The authors are appreciated the comments from the following colleagues:

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