Key words:
VAV system, controller set point, optimization, genetic algorithm

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OPTIMAL OPERATION OF VAV AIR-CONDITIONING SYSTEM

The detailed and simplified optimization processes for determining set points of supervisory control of VAV system are proposed and evaluated. Controller set points, such as supply air temperature, supply duct static pressure, and chilled water supply temperature, are determined by these optimization processes in order to minimize energy use while respecting thermal comfort. The detailed optimization process uses the detailed VAV models and genetic algorithm optimization program. The simplified one uses only simple VAV model and certain monitored variables available in the existing control system. The results of the evaluation on existing VAV system show that the proposed detailed or simplified optimization processes, when installed in parallel with a building central control system, will provide optimal operation of VAV system. Although the detailed optimization process performs better that simplified one, the later could be implemented without requiring detailed calculations, including the detailed VAV model and optimization program.

1. INTRODUCTION

The operation of VAV air-conditioning system is a critical activity in terms of optimizing the building's energy use and ensuring the comfort of occupants. Most of the operation of commercial and institutional buildings in Canada is suboptimal, resulting in energy losses. The VAV system performance can be improved through the optimization of controller set points [1, 2, 4]. In the existing HVAC system investigated in this paper, which is installed at the Montreal campus of the *École de technologie supérieure* (ÉTS), each local control of an individual subsystem is individually determined, thus leading to the non-optimal operation. Thus, the proposed detailed and simplified optimization processes could provide a good way to provide optimal opera-

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tion of this and any other system.

2. PROPOSED OPTIMIZATION PROCSSES

2.1. DETAILED OPTIMIZATION PROCESS

The detailed optimization process (DOP) as shown in Figure 1 includes: (*i*) the detailed VAV model, (*ii*) the genetic algorithm optimization program, and (*iii*) an indoor thermal load prediction tool. A simple load prediction tool is applied in this paper, based on the assumption that the indoor sensible loads are equal to the product of the zone airflow rate and the difference between the supply and the zone air temperatures. At each optimization period (i.e., 15 minutes), the genetic algorithm program determine the optimal controller set points using the detailed VAV system model to calculate the energy use considered as the objective function. The development and validation of the detailed VAV model are presented in [3].

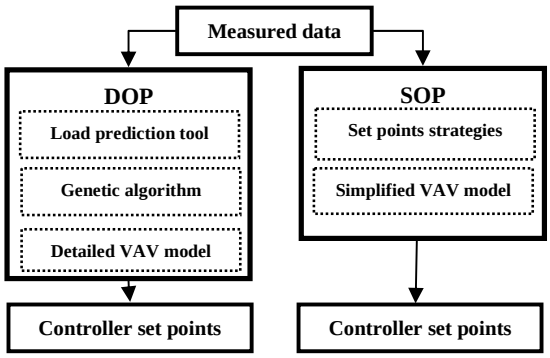

Fig. 1. Schematics of the detailed and simplified optimization processes (DOP and SOP)

2.2. SIMPLIFIED OPTIMIZATION PROCESS

The simplified optimization process (SOP), as shown in Figure 1, consists of: (*i*) controller set point strategies and (*ii*) a simplified VAV model. The SOP is based on the simulation of the response of the VAV system performance to the proposed changes of controller set points. At each simulation step *k*, three new values of supply air temperature set points (Ts_k) are proposed. These values include the current value and the values obtained by increasing or decreasing the current value by a small fixed amount (0.1^{o}C). However, these new values of supply air temperatures should not be set too high as it may provoke under-cooling in certain zones. During a small simulation step, the zone thermal loads are assumed to be constant:

$$Vz_{k-1} \cdot \rho \cdot c_p \cdot (Tz - Ts_{k-1}) = Vz_k \cdot \rho \cdot c_p \cdot (Tz - Ts_k) \quad (1)$$

The specific heat c_p and air density ρ are considered as constant. When the zone under-cooling occurs, its airflow rate (V_z) and air temperature (Tz) should be at their maximum limits (Vz_{max} and Tz_{max}). Using equation above, the high value of supply air temperature set point proposed by SOP should be then limited to:

$$Ts_k \le Tz_{\max} - Ra_k \cdot (Tz_k - Ts_{k-1}) \quad (2)$$

where Ra_k is the ratio of zone airflow rate (Vz_k) to design one (Vz_{des}). For each proposed value of supply air temperature set point, the chilled water supply temperature (Tw_k) [1] and duct static pressure set points (Ps_k) [2] are then determined as following.

$$Ps_k = \left(Ra_k^2\right)_{highest} \cdot Ps_{des} + a_{ps} \cdot (0.98 - \theta_{k-1}) \quad (3)$$

$$Tw_k = Ts_k - PLR \cdot (Ts - Tw)_{des} + a_v \cdot (0.98 - \theta v_{k-1}) \quad (4)$$

The highest Ra value is considered above. The part load ratio PLR (current cooling coil load to design one) is calculated from the cooling coil water or air side depending on measured data. The difference $(Ts\text{-}Tw)_{des}$ of investigated system at design conditions equals 5°C. When the cooling coil valve opening (θv_{k-1}) or VAV box position (θ_{k-1}) at previous time ($_{k-1}$) are less than 99% and greater than 97%, the term a_v or a_{ps} equal zero. Otherwise, they have a fixed value {$a_v = 0.01(Ts\text{-}Tw)_{des} = 0.05^oC$, and $a_{ps} = 0.01\ Ps_{des} = 2.5\ Pa$}.

The simplified component VAV models are used to determine their new energy demands resulting from the three proposed supply air temperature set points (Ts_k). Fan energy demand is a function of the fan airflow rate (Vf) and of fan total static pressure. The latter is equal to the sum of the duct static pressure set point (Ps) and the remaining duct static pressure drop, which is a function of the fan airflow rate and the flow coefficient C_f determined at design conditions. The relation between the current and previous fan energy demands ($\dot{W}f$) is given by:

$$\dot{Wf}_k = \dot{Wf}_{k-1} \cdot \frac{Vf_{k-1} \cdot \left(Ps_{k-1} + C_f \cdot Vf_{k-1}^2\right)}{Vf_k \cdot \left(Ps_k + C_f \cdot Vf_{k-1}^2\right)} \quad (5)$$

The fan airflow rate (Vf) is equal to the sum of the zone airflow rates (Vz) that are calculated by rearranging equation 1. The zone and fan airflow rates are limited by

their maximum and minimum values. Chiller energy demand could be presented only as a function of chilled water supply temperature *Tw* [4]:

$$\dot{Wc}_k = \dot{Wc}_{k-1} \cdot \left[1 + Cc \cdot \left(Tw_{k-1} - Tw_k\right)\right] \tag{6}$$

The parameter *Cc* can be obtained at design system operation and is approximately constant for a chiller. The zone reheat is turned on when the zone airflow rate reaches its minimum limit (Vz_{min}), and air temperature in the zone is decreased to a minimum level (Tz_{min}). Using equation 1 (with reheats), the zone reheats ($\dot{Wz}$) could be determined by zone energy balance:

$$\dot{Wz}_k = \dot{Wz}_{k-1} + Vz_{\min} \cdot c_p \cdot \rho \cdot \left[\left(Ts_{k-1} - Ts_k\right) + \left(Tz_{\min} - Tz_{k-1}\right)\right] \tag{7}$$

If the zone reheat is not used at a previous time ($\dot{Wz}_{k-1} = 0$), the effect of the supply air temperature decrease on the local reheat is seen only when the air zone temperature is close to Tz_{min}. If the difference (Tz_{k-1}-Tz_{min}) is less than the value of the change in the supply air temperature set point ($Ts_{k-1} - Ts_k$), the zone reheat will take a negative value, which then converts to zero. When the zone reheat is used at a previous time ($\dot{Wz}_{k-1} \neq 0$), the last term of the equation above becomes 0 (Tz_{min}=Tz_{k-1}). Equations 5, 6, and 7 show the system component energy demand variations in response to the variations of the controller set points. Three supply air temperature values are proposed at each simulation time, and the associated total energy demand is simulated in each case. The selected value then corresponds to the least total energy demand.

3. EVALUATION AND DISCUSSION

The detailed (DOP) and simplified (SOP) optimization processes are evaluated using the existing HVAC system installed at the *École de technologie supérieure (ÉTS)* campus. Air-handling units of multi-zone VAV systems meeting the load for 68 west perimeter zones are investigated. Controller set points are determined by the following three supervisory control strategies:

- Strategy $\mathbf{S_1}$: controller set points are exactly the same as in the existing system
- Strategy $\mathbf{S_2}$: controller set points are determined by the SOP
- Strategy $\mathbf{S_3}$: controller set points are determined by the DOP.

In the existing system (Strategy $\mathbf{S_1}$), the chilled water supply temperature and duct static pressure set points are constant at 7°C and 250 Pa, respectively. The supply air temperature set point, in this strategy, changes linearly within the 13 to 18°C range (function of outdoor temperature and fan airflow rate). However, in strategies $\mathbf{S_2}$ and $\mathbf{S_3}$,

this set point is not limited to 18°C and the lowest supply duct static pressure and highest chilled water supply temperature set points are limited (150 Pa and 11°C, respectively). The evaluations are done for three weeks under different weather conditions (summer, midseason, and winter), but are presented here only for three different days (Day#1, Day#2, and Day#3) respectively. Figures 2 and 3 show the energy demands and supply air and chilled water temperature set points.

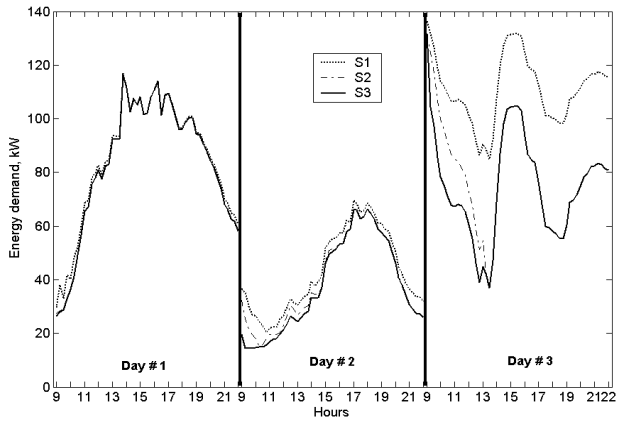

Fig. 2. *Energy demands for three investigated days*

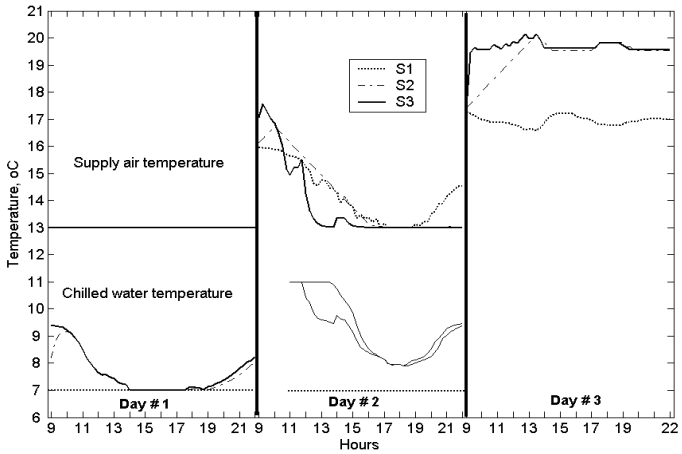

Fig. 3. *Supply air and chilled water temperature set points for three days*

On Day#1, the supply air temperature and resulting duct static pressure set points for two strategies, $\mathbf{S_2}$ and $\mathbf{S_3}$, are the same. Given that the thermal loads, and consequently the zone airflow rates, are relatively low on Day#2 and Day#3, the duct static pressure set points are at their lowest value (i.e. 150 Pa) for $\mathbf{S_2}$ and $\mathbf{S_3}$, and so they are not illustrated. It should be noted that the cooling coil valve is closed before 11:00 on Day#2. On

winter days (Day #3), great energy savings are obtained by the DOP and the SOP. Comparing the results obtained by DOP and SOP, strategies $\mathbf{S_2}$ and $\mathbf{S_3}$, the DOP performs better that SOP. On Day#3, since these two strategies start at 9:00 using real set point values (17°C), the SOP, strategy $\mathbf{S_3}$, needs a certain amount of time to reach the optimal values determined by the DOP due to a small incremental change in supply air temperature. This could also happen when the thermal loads change significantly. However, the SOP could be implemented without requiring detailed calculations, including the detailed VAV model and optimization program. Comparing the results obtained by the SOP and DOP with exiting strategy $\mathbf{S_1}$, the energy savings obtained for three weeks is 16.2% when the SOP is applied and 16.6% when the DOP is applied, versus the energy used by existing system.

4. CONCLUSION

The detailed and simplified optimization processes are proposed and evaluated using an existing VAV system. The evaluation results showed that the energy savings obtained for three weeks is 16.2% when the simplified optimization process SOP is applied and 16.6% when the detailed one DOP is applied, versus the energy used by existing system. However, although the DOP performs better that simplified one when the thermal loads change significantly, the SOP could be implemented without requiring detailed calculations, including the detailed VAV model and optimization program.

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