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Simulation and analysis of load shifting and energy saving potential of CO_2-based demand-controlled ventilation in a sports training center

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Abstract. This paper aims to evaluate and characterize the impact of optimizing the operation of the HVAC system through maintaining dynamic CO_2-based Demand-Controlled ventilation (DCV) on the electricity load profile and energy consumption of the sports training center of Leibniz University Hannover. The actual ventilation control scheme, in which the operation of the HVAC system is operated with a two-stage volume flow controller based on indoor CO_2 concentration is improved through two steps to avoid overventilation and reduce power consumption. For this purpose, a detailed multi-zone model of the sports center and energy supply system has been developed in TRNSYS. In the first step, a multi-stage control scenario is implemented considering the occupancy schedules and indoor CO_2 concentration measurement data. In the second step, based on an indoor CO_2 concentration model, a predictive control scenario is developed and applied. Aiming at characterizing the influence of these operation scenarios on the power consumption of the building, the annual electricity load profiles of the simulation cases will be analyzed and compared with the actual load profile of the building based on the technical planning documents and data provided by building management system (BMS). Simulation results show that utilizing predictive CO_2-based DCV leads to a reduction of the peak load electricity by almost 2 kW and the base load by 5 kW as well as decreasing the annual energy consumption by 40 %.
Keywords: Simulation, TRNSYS, HVAC, CO_2-based DCV, Sports center, Load shifting, Energy Saving

1. Introduction

Heating, Ventilation, and Air-conditioning (HVAC) systems account for a significant part of the energy consumption in none-residential buildings. Roughly three million none-residential buildings in Germany are equipped with around 420,000 HVAC plants; Optimizing the operation of these plants is estimated to reduce over 20% of the entire power consumption which results in saving about 200 PJ primary energy demand [1]. Due to the large air-handling systems in none-residential buildings with high occupancy levels, a considerable part of the power consumption in HVAC systems dedicates to the mechanical ventilation. Hence the performance of the air-handling systems can influence the entire electrical load and energy consumption of the building significantly and can play a crucial role in load shifting and energy saving scenarios. Maintaining indoor air quality (IAQ) through demand-controlled ventilation (DCV) in these buildings is a well-known approach that offers significant energy saving potential through avoiding overventilation. By this method, efficient ventilation rates are supplied based on standard occupancy schedules in each zone. However, since the schedules deviations can result in overventilation and consequently increasing power consumption of the air-handling units, DCV strategy should be optimized in terms of accuracy and energy efficiency. As CO_2 concentration is considered to be the major factor of human comfort for IAQ [2], CO_2 concentration level is considered as an indicator for IAQ. Hence recent DCV control methods including sensor-based methods have been focused on maintaining CO_2concentration level within a certain comfort range [3]. Utilizing a dynamic and intelligent CO_2 based-DCV in correlation with the occupancy patterns of the zones in none-residential buildings could offer a substantial reduction in energy consumption and peak load shaving. The investigated object in this study is the sports center of Leibniz University Hannover which consists of four floors including office spaces, sauna, gym, and sports halls with approximately 5900 m² net.

2. Model Development

In order to evaluate the impact of different ventilation scenarios on the performance of the air-handling systems, a detailed multi-zone thermal model of the sports center building together with the HVAC system is developed by means of TRNSYS tool [3] and validated based on the energy consumption data provided by BMS.

2.1. Air Distribution Model

Considering the use profiles, set-point temperatures and orientations of different sections, the building is divided into 51 thermal zones which are modeled in detail. The significant part of the 27000 m³/hr supplied air flow rate by the central HVAC system is dedicated to the 7 largest zones of the building including sport halls on the ground floor, service area on the first floor, fitness center on the second floor and seminar room in the third floor; These zones and their detailed ventilation data are presented in Table 1. A simplified schematic of the HVAC system is illustrated in Figure 1. As it is seen the supplied air from the central ventilation system is distributed between the zones through supply/exhaust air flaps in each zone; these air flaps are regulated by indoor CO_2 sensors in each zone.

Table 1. Description of the thermal zones of the building

Zone	Description	Volume [m³]	Max. Capacity [Person]	$q_{supply,design}$ [m³/h]	ACPH [1/h]	Natural Infiltration [1/h]	$C_{CO2, setpoint}$ [ppm]
Z.1	Martial Arts Hall	1752	65	3060	1.7	0.37	600
Z.2	Multipurpose Hall	1750	50	3060	1.7	0.39	600
Z.3	Climbing Hall	1964	35	1600	0.8	0.28	600
Z.4	Dance Studio	1754	70	3120	1.8	0.44	600
Z.5	Service Area	229	33	820	3.6	1.05	600
Z.6	Fitness Center	3020	110	11000	3.6	0.59	600
Z.7	Seminar Room	251	24	700	2.8	0.28	600

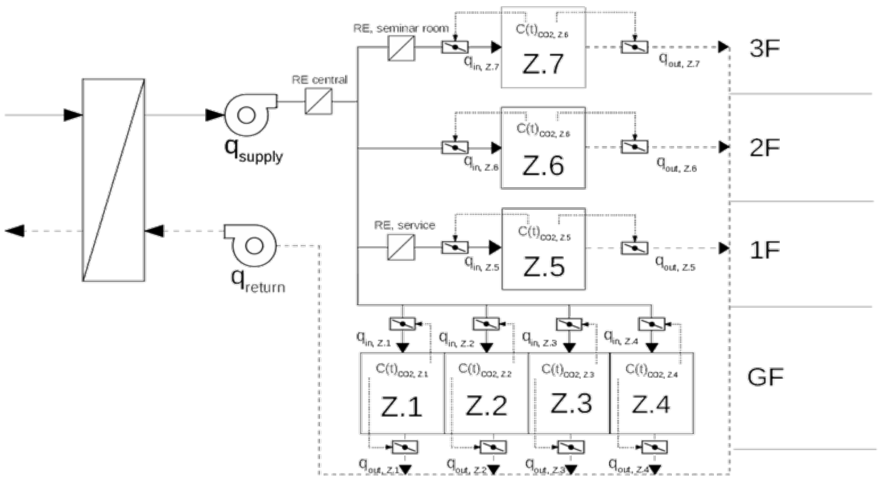

Figure 1. Simplified schematic of the HVAC system supplying eight zones

$q_{in,Zi}$ and $q_{out,Zi}$ are inlet and outlet air flow rates of each zone and $C(t)_{CO2,Zi}$ is the CO_2 concentration in each zone at the time t measured by CO_2 sensors in each zone.

2.2. Control Scenarios

Basically, three control scenarios are considered to be implemented in the HVAC model as follows:

1) **Baseline control scenario:** This is the current control scheme applied for the ventilation system, in this case, the air flaps are regulated through two-stage control based on $C(t)_{CO2,Zi}$ and $C_{CO2,Set}$:

$$q_{supply} = \begin{cases} 0.65 \times q_{supply,design}, & C(t)_{CO_2} < C_{CO_2,Set} \\ q_{supply,design}, & C(t)_{CO_2} \geq C_{CO_2,Set} \end{cases} \quad (1)$$

Where the supply air flow rate (q_{supply}) is set to 0.65 of the design flow rate ($q_{supply,design}$) when indoor CO_2 concentration ($C(t)_{CO_2}$) is below set point ($C_{CO2,Set}$) and if $C(t)_{CO_2}$ exceeds $C_{CO2,Set}$, q_{supply} is set to $q_{supply,design}$; Thereby the power consumption of the ventilation system is maximized which causes an increase of the peak electrical load of the building. In this stage the first goal is to reduce the power consumption and consequently peak load of the building by modifying the ventilation control strategy; Therefore, the second control strategy is introduced in second step.

2) **Multi-Stage control scenario:** In this case, the air flaps are regulated in several stages based on indoor CO_2 concentrations; Since the occupancy schedule of the zone has a direct correlation with the CO_2 generation in the zone the opening degrees of the air flaps are designed according to the average occupancy rates of each zone. Figure 2. represents the weekly occupancy schedules of some of the zones.

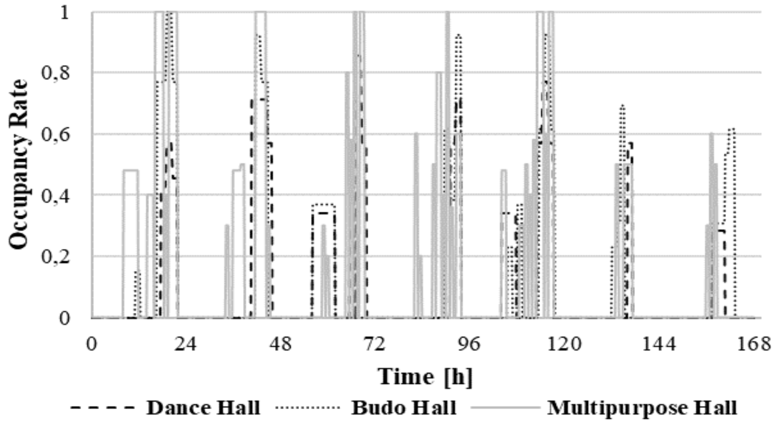

Figure 2. Weekly occupancy rates of three zones in the summer semester

Assuming constant outdoor CO_2 concentration, $C_{CO2,amb} = 450$ ppm, and considering $C_{CO2,Set} = 600$ ppm the control interval for $C(t)_{CO_2}$ will be [450, 600]; This interval is divided into four subintervals based on the occupancy rate profiles shown in Figure 2; Thereby the air volumetric flow rate (q_{supply}) is increased stepwise respectively through controlling the opening degrees of the air flaps as follows:

$$q_{supply} = \begin{cases} q_{base} = 0.2 \times q_{supply,design}, & C(t)_{CO_2} \leq 450 \text{ ppm} \\ 0.4 \times q_{supply,design}, & 450\, ppm < C(t)_{CO_2} \leq 500 \text{ ppm} \\ 0.6 \times q_{supply,design}, & 500\, ppm < C(t)_{CO_2} \leq 550 \text{ ppm} \\ 0.8 \times q_{supply,design}, & 550\, ppm < C(t)_{CO_2} \leq 600 \text{ ppm} \\ q_{max} = 1 \times q_{supply,design}, & 600\, ppm < C(t)_{CO_2} \end{cases} \quad (2)$$

Where the base supply air flow rate (q_{base}), which is applied to dilute the none-occupant-related pollutants, is set to 20% of the design air flow rate ($q_{supply,design}$) during none-occupied periods of the zone where the $C(t)_{CO2}$ is almost equal to the $C_{CO2,amb}$; On the other hand when the $C(t)_{CO2}$ exceeds the $C_{CO2,\ setpoint}$ which is 600 ppm the supply air flow rate is increased to the design air flow rate.

3) **Predictive control scenario:** The aim of developing this control scenario is to avoid the negative impacts on the ventilation rate and power consumption of the HVAC system caused by inaccuracies and measurements deviations of the CO_2 sensors by reducing the dependencies on CO_2 sensors. In

this case the CO_2 predictive model developed and validated in [3] is applied for each zone; This model consists of two parts for generation and decay of CO_2 represented in equations (3) and (4):

$$CO_2\ generation\ prediction: \quad C(t)_{CO_2} = (\frac{S}{q_0})[1 - e^{-K(t-t_i)}] + C_i \tag{3}$$

$$CO_2\ decay\ prediction: \quad C(t)_{CO_2} = C_i[1 - e^{-K(t-t_g)}] + C_g \times e^{-K(t-t_g)} \tag{4}$$

Where:

$$S = R \times N(t) \tag{5}$$

$$K = q_0/V \tag{6}$$

$S[\frac{l}{h}]$ represents the CO_2 generation by the occupants and is calculated based on R as CO_2 generation rate per person according to the standard shown in Table 2 and $N(t)$ as occupancy schedule. $K[\frac{1}{h}]$ is air exchange per unit and q_0[m³/s] and $V[m^3]$ are natural ventilation rate and the volume of the zone respectively. t_i is the time at which the CO_2 generation begins and C_i is the indoor CO_2 concentration at this time and t_g is the time at which CO_2 generation ends and C_g is the indoor CO_2 concentration at this time.

Table 2. CO_2 generation rate per person based on activity level [4]

Type of Work	CO_2-Emission [l/h]
Sedentary Work	15 - 20
Light Work	20 - 40`
Medium-Heavy Work	40 – 70
Heavy Work	70 - 110

Applying the above model and using the given parameters of the zones, the indoor CO_2 concentration tend for each zone is developed. The multi-stage ventilation is then operated based on the CO_2 concentration profiles of the zones. The annual simulations under these ventilation control strategies are carried out in 15 minutes-time steps and the results are discussed in the next part.

3. Results and Discussions

In the first step, the impact of the ventilation control scenarios on the inlet air flow rate of the zones is investigated; Figure 3 illustrates the variation of the supply air flow rate of the multipurpose hall under third control scenario against indoor CO_2 concentration model during the first week of November; As it is seen the air flow rate is set to 716 m³/h which is the minimum flow rate when the CO_2 generation is zero by starting CO_2 generation and rising CO_2 concentration the air flow rate is increasing until maximum flow rate, 3060 m³/h, where $C_{CO2,\ setpoint}$ is exceeded, by mitigating CO_2 concentration the air flow rate is reduced stepwise; It can be observed that under this control scheme the ventilation system is able to maintain the CO_2 concentration level below the set point while modifying the ventilation air flow rate.

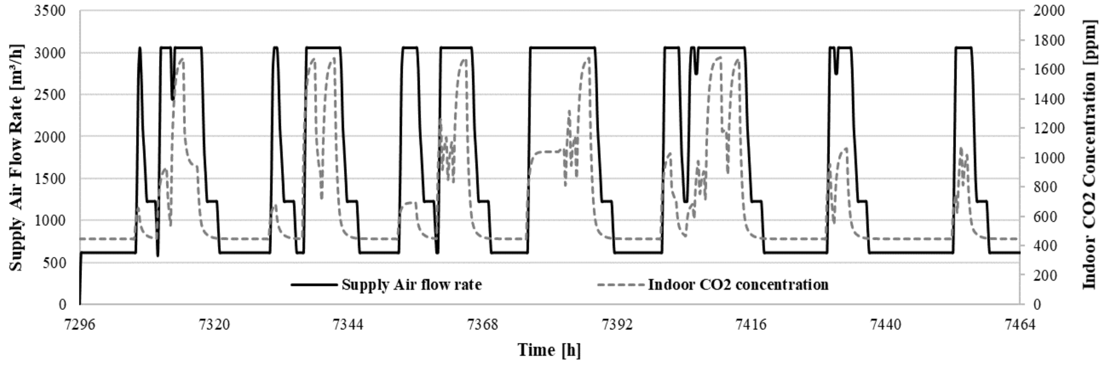

Figure 3. Air volume flow rate versus model-based indoor CO_2 concentration in the multipurpose hall during the first week of November

Figure 4 compares the supply air flow rate of the multipurpose hall under each ventilation control scheme, it is seen that through replacing the current double-stage control strategy (scenario 1) by multi-stage control scenario (scenario2) the current supply air flow rate (black line) is strongly reduced (gray line) during the low occupancy periods; Utilizing the predictive control scheme (scenario3) results in further decrement of the volume flow rate (dotted line) during the periods where there is no deviation between scheduled and real occupancies or the hall is over-occupied; On the other hand when the hall is under-occupied (less than scheduled occupancy) supply flow rate under the third ventilation scenario is less than the one under second scenario.

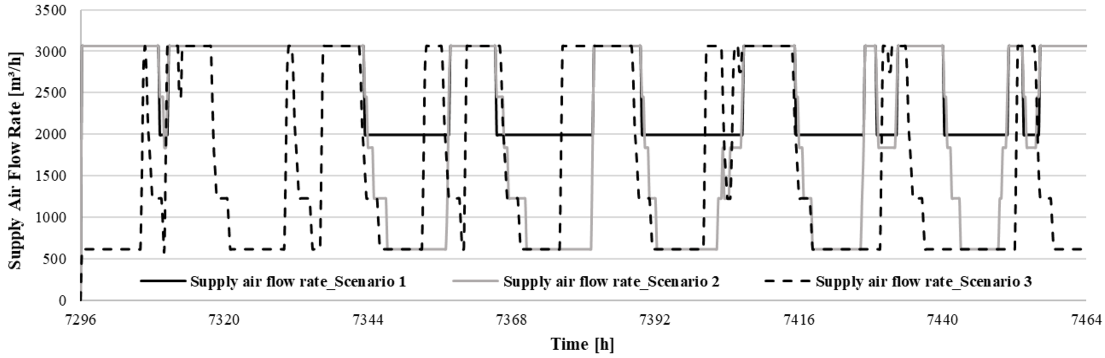

Figure 4. Comparison of supply air flow rate in the multipurpose hall under three ventilation scenarios during the first week of November 2017

The impact of lowering ventilation air flow rates on the load profile and power demand of the ventilation system is discussed in Figures 5-6. The overall electrical load profile of the ventilation system for the first week of November 2017 is illustrated in Figure 5; It can be observed that operating the ventilation system under scenario 1 results in the highest electrical load level compared with other control schemes, as it is expected from the ventilation rates, using multi-stage ventilation control in the second scenario reduces the power consumption at low occupant periods (grey curve) while integrating the third ventilation scenario (dotted curve) leads to the further reduction of power consumption during the periods with no occupancy deviation as well as over-occupied periods .

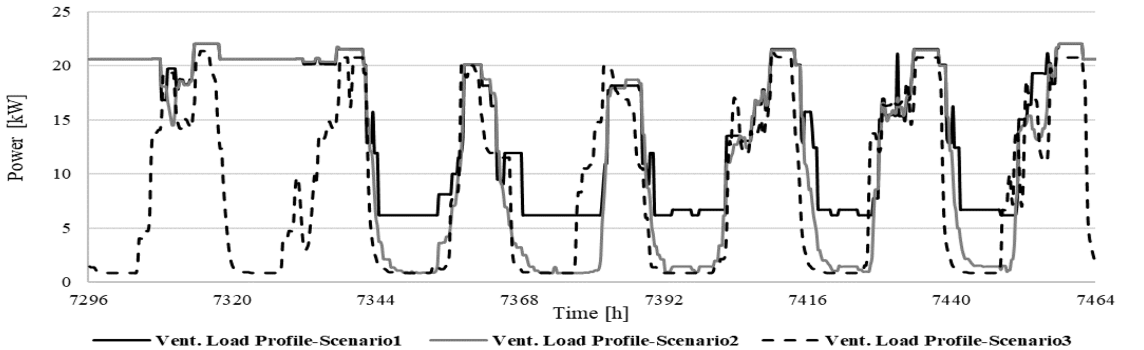

Figure 5. Electrical load profiles of the ventilation system under three scenarios during the first week of November 2017

The annual load duration curves (LCD) presented in Figure 6 indicate that applying the predictive control strategy for the ventilation system reduces the peak load of electricity by almost 2 kW and the base load by 5 kW compared with other scenarios, it can be also seen that the peak load operation length of the ventilation system under predictive scenario is roughly 700 hours shorter than the operation scenarios and the base load operation period is roughly 2050 hours longer than the operation under multi-stage scenario; However during 1221 hours of the system operation under average load the power demand under the third scenario exceeds the one under the second scenario.

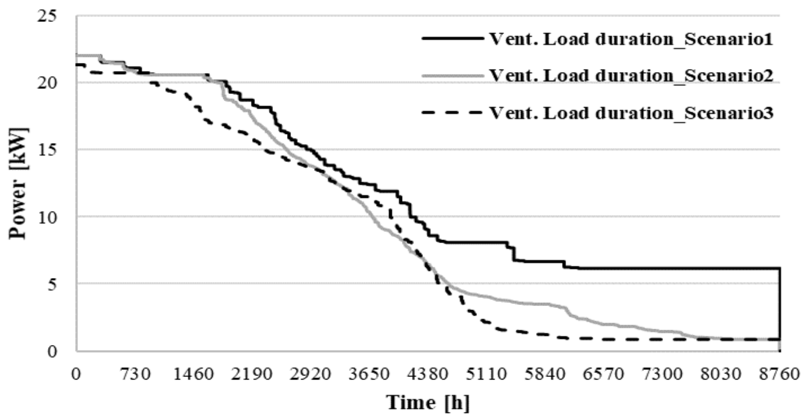

Figure 6. Annual load duration curves of the ventilation system under three scenarios in 2017

Shifting load profile and reducing the operation hours of the ventilation system lead to lower energy consumption; Table 3 proves that applying multi-stage and predictive control schemes can reduce the annual energy consumption by 14% and 40% respectively; Thus the predictive control scenario is the most energy efficient way among all control methods.

Table 3. Annual energy consumption of the ventilation system for different control scenarios

Control Scenario	Annual Energy Consumption of the Ventilation System [MWh]
Scenario 1	33.56
Scenario 2	28.74
Scenario 3	20.01

4. Conclusion and further works

A CO_2 DCV strategy for a validated thermal model of sports center of Leibniz University Hannover is improved within two steps using multi-stage control and indoor CO_2-concentration model, according to the simulation results the proposed predictive control system delivers a good performance in load shifting and energy saving compared with the current control scheme. However, further developments are necessary specifically in terms of indoor air moisture which is also an important issue in sports centers.

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