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Multi-zone outdoor air coordination through Wi-Fi probe-based occupancy sensing

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ABSTRACT

As most urban residents spend an average 90% of their time in buildings, it is crucial for building residents to monitor and maintain a comfortable indoor environment and air quality. Controlling the indoor carbon dioxide (CO2) concentration level is the major objective of mechanical ventilation systems to ensure healthy indoor air quality (IAQ). Current methods utilize proportional–integral–derivative (PID) controllers and multi-zone equations to operate ventilation systems in large spaces based on ASHRAE Standard 62. However, this approach suggests to determine the fresh air supply rate primarily based on CO2 level without considering occupancy. This often results in insufficient fresh air or energy waste in unnecessary mechanical operations in unoccupied building zones. Therefore, this study proposes a ventilation strategy based on occupancy profiles that captured by a Wi-Fi probe enabled occupancy sensing system. Based on the detected occupancy profiles, the proposed ventilation strategy and other two conventional strategies were compared in a two-day experiment conducted a multi-zone space. The comparison results in the experiment show that the proposed approach could maintain a CO2 concentration level lower than 1000 ppm for 94% (weekday) and 80% (weekend day) of day time for all zones. At the same time, the proposed strategy saved about 44.26% (weekday) and 55.5% (weekend day) of ventilation energy consumption when compared to the fixed rate ventilation strategy and saved about 23.6% (weekday) and 46.1% (weekend day) of ventilation energy consumption when compared to the multi-zone equation strategy.

1. Introduction

Indoor air quality has been regarded as an urgent and essential issue for building residents' health, given most urban residents spend an average 90% of their time in buildings [1]. In general, a livable indoor environment is free from toxic gas, and the major concern for IAQ is the level of carbon dioxide concertation. High CO2 concentration obstruct respiration by reducing oxygen saturation of blood and results in asphyxiation, dizziness, and sleepiness [2]. In most buildings, mechanical ventilation is a typical method to maintain acceptable indoor air quality by introducing non-polluted outdoor air in buildings [3]. More fresh air requires more energy consumption by fan drives and air pumps. Many studies show that 30% or more of annual cooling/heating energy is consumed by handling the fresh air into a typical commercial building [4–6]. As energy demand and IAQ level is a trade-off in most commercial buildings [7], improving the operation efficiency of ventilation system becomes a critical and inevitable issue for facility managers.

Being proposed in recent years, demand-controlled ventilation (DCV) suggests a feasible solution to properly balance the IAQ and energy saving with just sufficient air flow [8–11]. DCV relies on accurate CO2 detection and optimized PID controller to operate ventilation systems based on the extract need of occupants. However, CO2 concentration does not directly reflect the occupants need, since its level is often affected by various reasons. Also, the variation of CO2 concentration is slow and lags behind the occupants' mobilization. Therefore, this paper proposed a Wi-Fi probe based occupancy detection and prediction to implement DCV so that unnecessary ventilation if unoccupied indoor zones can be avoided. The proposed solution also can be utilized in the heating and air conditioning control of building HVAC systems.

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Nomenclature

$V_{oa.z,i}$	The outdoor air amount of zone i
R_p	The outdoor air requirement for per occupant
$P_{z,i}$	The number of occupant in zone i
R_a	The outdoor air requirement for per area
$A_{z,i}$	The area of zone i
$V_{sa,z,i}$	The supply air amount of zone i
$X_{z,i}$	The outdoor air fraction of zone i
V_{room}	The volume of zone i
$C_{z,i}(t)$	The CO2 concentration of zone i
C_{sa}	The CO2 concentration of supply air
S	The CO2 generation of per occupant
$V_{ra,z,i}$	The return air amount of zone i
C_{ra}	The CO2 concentration of return air
C_o	The CO2 concentration of outdoor air
$V_{oa,tot}$	The total outdoor air amount for the multi zones
$V_{sa,tot}$	The total supply air amount for the multi zones
$X_{uncorrect}$	The uncorrected outdoor air fraction for the zones
$Z, X_{critical}$	The outdoor air fraction for the critical zone
X_{OA}	The corrected outdoor air fraction for the multi zones
$TPM\|_t$	The transfer probability matrix
P_t^{in-out}	The probability of occupant' status from "in" to "out"
P_t^{in-in}	The probability of occupant' status from "in" to "in"
P_t^{out-in}	The probability of occupant' status from "out" to "in"
$P_t^{out-out}$	The probability of occupant' status from "out" to "out"
N_{in-out}	The frequency of occupant' status from "in" to "out"
N_{in-in}	The frequency of occupant' status from "in" to "in"
N_{out-in}	The frequency of occupant' status from "out" to "in"
$N_{out-out}$	The frequency of occupant' status from "out" to "out"
$P_{z,i}^{t+1}$	The number of occupants in zone i at time t+1
$P_{z,i}^{t}$	The number of occupants in zone i at time t
$P_{z,i}^{\Delta t}$	The number of occupants in zone i in time window (Δt)
$f_{z,i}$	The outdoor air requirement proportion of zone i
$V_{oa,z,i}^{t+1}$	The outdoor air amount of zone i at time t+1
$V_{sa,z,i}^{t+1}$	The supply air amount of zone i at time t+1
$X_{z,i}^{t+1}$	The outdoor air fraction of zone i at time t+1
$X_{critical1}$	The outdoor air fraction for the critical zone 1
$X_{critical2}$	The outdoor air fraction for the critical zone 2
W_{cost}	The energy consumption of the system
$Q_{outdoor}$	The cooling load of outdoor air
W_{fan}	The energy consumption of primary air fan
β	The coefficient of the fan
M	The flow rate of the fan

2. Background

2.1. CO2-based DCV methods

The classic ventilation strategy utilizes a fixed minimum outdoor air rate or minimum outdoor air percentage based on the building space [12]. Other strategies utilized variable air volume (VAV) systems to adjust the supplied air amount to minimize the energy cost of mechanical ventilation [13–16]. Both ventilation strategies often result in energy wastes because of over-ventilation than the actual demands when reliable occupancy information is unavailable. In mixed fresh air and conditioned air ventilation systems, sensible temperature-based air-side and enthalpy-based air-side economizers strategies have been demonstrated effective in past decades [13]. Both strategies take the dry-bulb temperature of the outdoor air, recirculated air, and mixed air as control signals to adjust the outdoor air flow rate. In recent years, CO2-based demand-controlled ventilation strategies have been proposed to determine the amount of outdoor air supply [5,12,19–26]. CO2-based DCV strategies adjust the required outdoor air flow rate based on monitored CO2 concentration in a building zone. Nassif et al. utilized DCV to control flow rate at return air ducts and found CO2-based DCV performed better than conventional a fixed rate ventilation [12]. Nielsen and Drivsholm installed a high resolution CO2 sensor and implemented DCV in a residential house and reported a 35% of fan energy saving [27]. In the study, 43% of power from the ventilation fan and heating could be saved when the CO2 concentration level was controlled under 950 ppm with a low ventilation rate. Although CO2-based DCV strategies are effective in maintain CO2 concentration in single zone, overventilation or underventilation are often been observed in multi-zones because of small coverage to CO2 sensors and occupants' mobility.

To coordinate outdoor air flow rates in a multi-zone space, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommend Standard 62–2007 to calibrate the flow rates with multi-zone equations [28]. The multi-zone equations approach identifies a critical zone, which requires the highest outdoor air fraction, among all zones and take it as the reference for all air handling units (AHUs). Mumma and Bolin compared fixed flow rate and temperature-based strategies with the multi-zone equations approach with VAV systems and found that the multi-zone equations approach recommended by ASHRAE performed best [29]. Wang et al. also confirmed similar conclusions in several on-site experiments in Hong Kong [6,11,21,23]. In Wang et al.'s study, the researchers found reliable CO2 detection is pivotal in finding proper outdoor air ratios for multi-zones [11,23]. However, CO2 concentration varies in different zones, when unoccupied zone is selected as critical zone, the required flow rate can be dramatically exaggerated and finally results in energy wastes. Therefore, accurate and reliable occupancy profile detection in zones is the premise of proper and effective ventilation control.

2.2. Occupancy based ventilation control

Although numerous demand-based HVAC controls system introduced several occupancy detection methods, high-resolution occupancy information is extremely difficult to acquire [30–32]. Many researcher have recognized the importance of occupancy information in joint optimization of building energy consumption and IAQ [32,33]. Brandemuehl and Braun adopted DCV strategy and shown that the amount of energy saving highly depended on the schedule of occupancy [34]. Other researchers also concluded that zone-climate control based on occupancy feedback is more suitable to regulate the indoor climate in commercial buildings [35–37]. Also, the occupancy information reveals the occupants' behavior and how they use the building service systems [38].

Since accurate occupancy information is difficult to access, current ventilation control methods mainly rely on two rough occupancy estimation approaches. The first approach utilizes occupancy diversity factors based on building types and functional zones that recommended by ASHRAE Standard 90.1–2007 [39]. Occupancy diversity factors are developed based on the historical data that collected from ASHRAE Research Project 1093 and widely implemented in building load analysis and energy simulations. Researchers found this rough occupancy estimation could results in as high as 40% energy consumption variation compared with actual demand [40]. The second approach used CO2 concentration level to assess occupancy, given human exhale CO2 during breathing [23,41]. However, there are extensive sources of CO2 in buildings and the deploy cost of CO2 sensors and flow meters is prohibitively high. Therefore, facility managers normally take the worst scenario as the control baseline and often over-ventilate indoor space. Such control strategy selects a zone with highest CO2 concentration and fresh air demand, called critical zone, as the reference to determine the setting points for mechanical ventilation systems. Therefore, the choice of critical zone significantly affects the energy consumption of HVAC systems. When the ventilation demand of critical zone is much higher than other zones, the ventilation system will introduce excessive outdoor air flow and waste energy. Also, the dilution process of CO2 is slow and impedes the responsive and fast selection of critical zones. Therefore, for CO2-based strategies, the selection of critical zones is essential in optimizing HVAC operation.

2.3. Organization of this study

To propose a high-resolution occupancy detection approach and improve CO2-based control strategy, this study utilized Wi-Fi probes to scan the Wi-Fi network requests and responses and to determine number of occupants in a specific zone. For achieve such goal, this study explored existing occupancy profile based ventilation strategies, developed an Wi-Fi probe enabled occupancy sensing algorithm to determine the critical zone, implemented the control logic in ventilation operation, and compared the proposed approach with conventional strategies in a two-day experiment.

In this paper, Section 3 explores three conventional ventilation strategies and proposed a new ventilation strategy based on Wi-Fi probe technology. Section 3 also introduces the proposed control optimization and control process in detail. Section 4 shows the data analysis and experimental ventilation tests and reports the outcomes of CO2 concentration levels in each zone during two typical days. Section 5 further discusses application, implication, and limitations of the proposed method. The last section concludes this study.

3. Methdology

3.1. Outdoor air supply for building spaces

To circulate the sufficient outdoor fresh air into building spaces, the ASHRAE Standard 62.1 2010 recommend to use multiple spaces equations to calculate the outdoor air rates for building zones. Indoor air pollutants, such as CO2, are generated by both occupants (and their activities) and building facilities. Thus, the ventilation demand includes a human-related component (to dilute contaminants from people and their activities) and an space-related component (to dilute contaminants from non-occupant-related sources). Eq. (1) calculates the outdoor air amount required in zone i as a function of the number of zone occupants $P_{z,i}$ and the zone floor area $A_{z,i}$.

$$V_{oa.z,i} = R_p * P_{z,i} + R_a * A_{z,i} \tag{1}$$

Where, R_p and R_a can be determined based on the occupancy types in ASHRAE Standard 62.1. For each zone in a building space, the outdoor air ratio $X_{z,i}$ can be determined by,

$$X_{z,i} = \frac{V_{oa,z,i}}{V_{sa,z,i}} \tag{2}$$

Where $V_{sa,z,i}$ is the supply air flow rate of zone i.

In practice, the outdoor air ratio in each zone can be different, since each zone has its unique occupancy pattern. When multiple zones are served by one air handling unit, their outdoor air ratio is same but the air flow rates are subject to their VAV terminals [42]. For a typical VAV system, the conditioned air circulation in one zone can be simplified as process that shown in Fig. 1. When assuming CO2 only comes from occupant respiration and outdoor air, the CO2 generation (S') from the occupant is constant and the CO2 concentration (C_o) of outdoor air varies slightly.

The air that supplied into space is assumed to be well-mixed. The variation of CO2 concentration over time in one zone can be calculated based on mass balance equation,

$$V_{room}\frac{dC_{z,i}(t)}{dt} = V_{sa,z,i}C_{sa} + P_{z,i} * S - V_{ra,z,i}C_{ra} - V_{oa,z,i}C_{ra} \tag{3}$$

While in the AHU, mass balance of CO2 can be simplified as

$$V_{oa,z,i}C_o + V_{ra,z,i}C_{ra} = V_{sa,z,i}C_{sa} \tag{4}$$

Where,$C_{z,i}$ is the indoor CO2 concentration of zone i; C_{ra} is the CO2 concentration at return duct level of zone i. If assuming CO2 concentration at return air ducts remains the same as the CO2 concentration of indoor air at breathing level, we can simply Eq. (3) as,

$$V_{room}\frac{dC_{z,i}(t)}{dt} = V_{oa,z,i}C_0 + P_{z,i} * S - V_{oa,z,i} * C_{z,i} \tag{5}$$

Where, V_{room} is the volume of the room. At the steady-state,

$$C_{z,i} = \frac{P_{z,i} * S}{V_{oa,z,i}} + C_o = \frac{P_{z,i} * S}{V_{sa,z,i} * X_{z,i}} + C_o \tag{6}$$

If the air in the room is well-mixed and the occupants' activities are consistent in the zone, which occupants' CO2 emition rate is stationary.

3.2. Control strategies of ventilation systems

To maintain a good indoor air quality with less energy consumption, various control strategies have been developed to optimize primary fan operation and outdoor air cooling or heating. To simplify this multi-objective optimization problem, this study designed a ventilation option strategy with a fixed CO2 level to minimize energy consumption for occupied building zones. In *Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places*, the Environmental Protection Department of Hong Kong suggests two CO2 levels, Excellent Level (CO2 concentration lower than 800 ppm) and Good Level (CO2 concentration lower than 1000 ppm), for IAQ assessment [43]. The Good Level (1000 ppm) is also the acceptable IAQ level that recommended by the ASHRAE Standard 62 [28]. Therefore, in the propose strategy and comparisons, this paper takes1000 ppm as the control threshold.

3.2.1. Strategy 1 – Minimum outdoor air ratio

Minimum outdoor air ratio strategy setup a fixed outdoor air ratio to fulfill the requirements of a building at full occupancy load under the design condition. The dampers' positions can be adjusted to maintain the ratio [44]. Energy can be wasted when the occupancy load is low; while poor IAQ can present in some zones when the occupancy load is high and ratio is too conservative [12].

3.2.2. Strategy 2: CO2-based demand control at return air duct

As mentioned before, it is widely accepted that the ventilation systems should adjust outdoor air flow rate in response to CO2 sensors' research at return duct. This strategy modulates outdoor air dampers with PID controller based on a comparison between detected CO2 concentrations and its setting points. In general, this strategy can effectively maintain the CO2 concentration level at return duct levels less than or equal to setting points. It is the most widely adopted control strategy for commercial building nowadays.

For a single room, this strategy could achieve good IAQ with less energy consumption. However, for ventilation in multi-zone

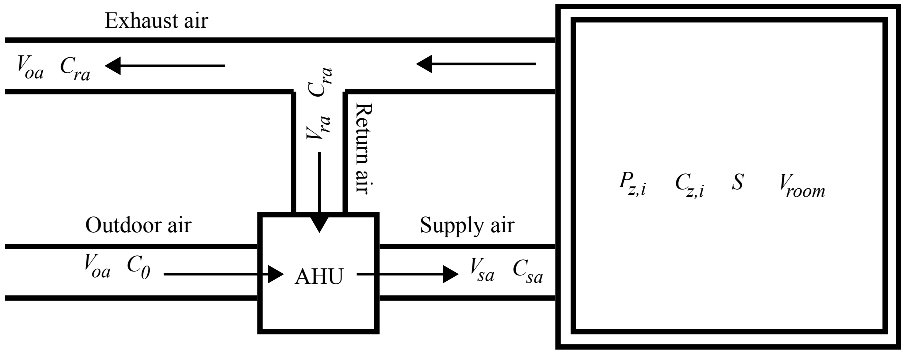

Fig. 1. Illustration of a typical AHU working process.

spaces, this strategy subject to two major constraints: (1) CO2 concentration is an indirect indicator of occupancy and could mislead the selection of the critical zone. (2) the CO2 concentration level that monitored at the return air duct is the result of mixed air from all zones, so its value can be easily distorted.

3.2.3. Strategy 3: Multi-zone ventilation equations

For multi-zone ventilation operation, ASHRAE recommend a set of equations to determine the proper ratio of outdoor air. The strategy aims to calculate corrected ratios to satisfy the unique ventilation and thermal requirements for each zone based on zone specifications. The total outdoor air amount can be derived from air flow rate at each zone.

$$V_{oa,tot} = \sum_i V_{oa,z,i} = \sum_i R_p * P_{z,i} + R_a * A_{z,i} \tag{7}$$

$$V_{sa,tot} = \sum_i V_{sa,z,i} \tag{8}$$

The uncorrected fraction of the outdoor air flow rate is

$$X_{uncorrect} = \frac{V_{oa,tot}}{V_{sa,tot}} \tag{9}$$

The fraction of outdoor air flow rate for the critical zone is

$$Z = X_{critical} = max\left\{X_{z,i}\right\} = max\left\{\frac{V_{oa,z,i}}{V_{sa,z,i}}\right\} \tag{10}$$

Then corrected setpoint of the outdoor air flow rate can be determined by

$$X_{OA} = \frac{X_{uncorrect}}{1 + X_{uncorrect} - Z} = \frac{\frac{\sum_i R_p*P_{z,i}+R_a*A_{z,i}}{\sum_i V_{sa,z,i}}}{1 + \frac{\sum_i R_p*P_{z,i}+R_a*A_{z,i}}{\sum_i V_{sa,z,i}} - max\left\{\frac{R_p*P_{z,i}+R_a*A_{z,i}}{V_{sa,z,i}}\right\}} \tag{11}$$

The major challenge of this strategy is to properly select the critical zone and make reasonable corrections for each zone. Occupancy information is the most critical reference for critical zone selection, and CO2 concentration is a valid indicator for occupancy level. Therefore, in this strategy, critical zone is the one that has highest CO2 concentration level.

3.2.4. Strategy 4: Supervisory occupancy prediction based multi-zone control (Proposed strategy)

This strategy, proposed in this paper, is based on the predictive occupancy information through the received Wi-Fi signals. Since the selection of the critical zone could dramatically affect the system settings and energy consumption, the proposed strategy utilizes the detected and predicted occupancy level rather than CO2 concentration as the reference. Given the slow dilution process of CO2, the change of CO2 concentration level often significantly lags behind human breathing and mechanical ventilation. Therefore, this study utilized a more responsible Wi-Fi detected occupancy profiles. Fig. 2 illustrates a scheme of occupancy detection systems based on Wi-Fi probe and environmental sensors. In the proposed method, the Wi-Fi probe actively attempts to record the signal request and response from users, even if no connection between the Access Points (AP) and user tags. Also, the unique MAC addresses of users' device is logged as the occupants' identity. With a Markov time window, the signal processing system can estimate occupants' locations in a given space or zone[45,46].

In conventional single-zone Markov chain model, either an "in" tag or an "out" tag is assigned to the temporal occupancy statuses. A transfer probability matrix is calculated with historical records to represent the probability of status changes from time t to time $t+1$.

$$TPM|_t = \begin{bmatrix} P_t^{in-out} & P_t^{in-in} \\ P_t^{out-out} & P_t^{out-in} \end{bmatrix} (t > 1) \tag{12}$$

where $TPM|_t$ is the transfer matrix at t. P_t^{in-out} and P_t^{in-in} denote the observed probability that one occupant whose status is "in" will change to "out" or remain "in" at the next time period. P_t^{out-in} and $P_t^{out-out}$ denote the observed probability that one occupant whose status is "out" will change to "in" or remain "out" at the next time period. These probabilities can be calculated with observable conditional probabilities. For example,

$$P_t^{out-in} = P(observedstate = in|observedstate = out) \quad (t > 1) \tag{13}$$

Then, with Bayes' theorem,

$$p^{in-in} = \frac{\sum N_{in-in}}{\sum N_{in-in} + \sum N_{in-out}} p^{out-in} = \frac{\sum N_{out-in}}{\sum N_{out-out} + \sum N_{out-in}} \tag{14}$$

To extend the current approach for a multi-zone space, for zone i, the total number of occupants in one time window is $P_{z,i}^{\Delta t}$. Then, the probability of $(P_{z,i}^{t+1})$ at time t+1 is

$$P_{z,i}^{t+1} = \sum_{n=1}^{P_{z,i}^{t}} 1 * p^{in-in} + \sum_{n=1}^{P_{z,i}^{\Delta t} - P_{z,i}^{t}} 1 * p^{out-in} \tag{15}$$

With Eqs. (5) and (6), outdoor air flow rate requirement in zone i can be formulated as:

$$X_{z,i} = \frac{C_{z,i} - C_o}{P_{z,i} * S} * V_{sa,z,i} \tag{16}$$

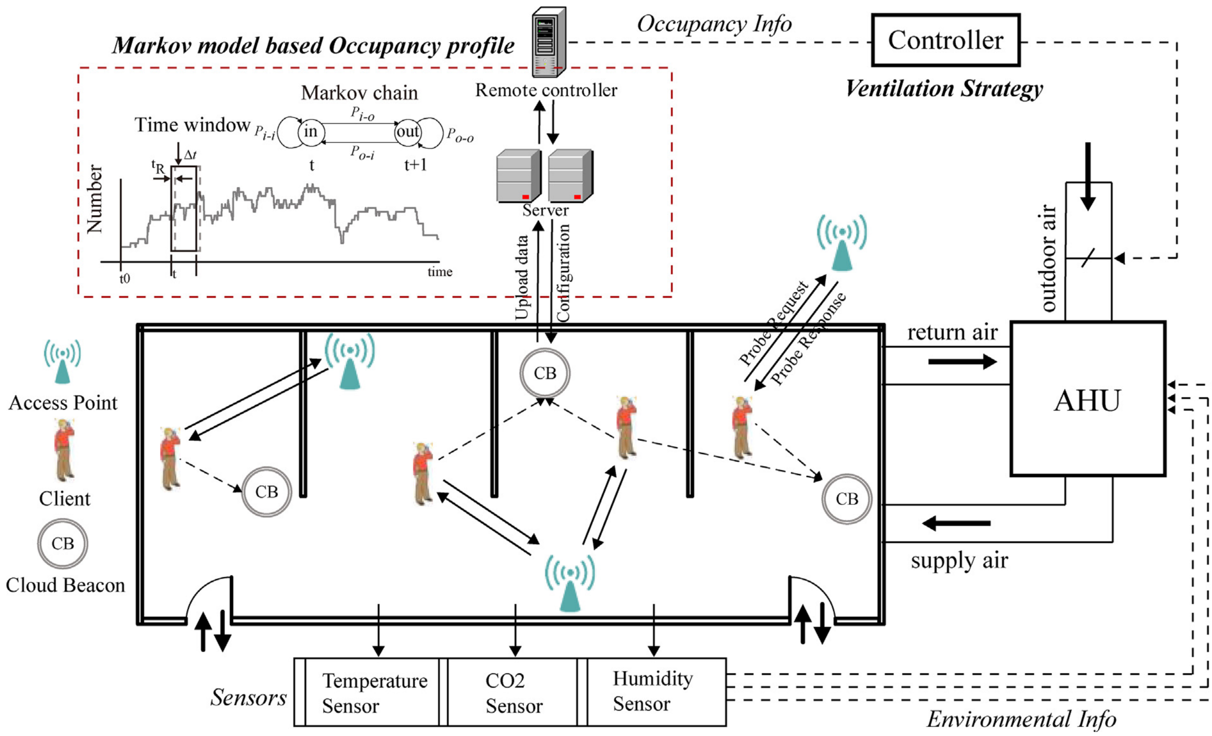

Fig. 2. Scheme of Wi-Fi probe based occupancy detection system.

With Eq. (16), it is possible to find out the necessary ventilation requirements for each zone. If all zones served by the same AHU, then the total required outdoor air amount is

$$V_{oa,tot} = \sum_{i} V_{oa,z,i} \tag{17}$$

Therefore, it could find outdoor air requirement proportion for zone i as

$$f_{z,i} = \frac{V_{oa,z,i}}{V_{oa,tot}} \tag{18}$$

The aggregated uncorrected outdoor air fraction for the AHU is

$$X_{uncorrect} = \sum_{i} f_{z,i} * X_{z,i} \tag{19}$$

Similar to Eq. (1) and Eq. (15), the predicted outdoor air requirements for zone i at next time period $(t+1)$ are

$$V_{oa,z,i}^{t+1} = R_p * P_{z,i}^{t+1} + R_a * A_{z,i} \tag{20}$$

$$X_{z,i}^{t+1} = \frac{V_{oa,z,i}^{t+1}}{V_{sa,z,i}^{t+1}} \tag{21}$$

For the critical zone selection, this study proposed to select two critical zones, who have the highest and second highest demand based on predicted occupancy level. The fraction of at maximum load for first critical zone is

$$X_{critical1} = max\left\{X_{z,i}^{t+1}\right\} = max\left\{\frac{V_{o,z,i}^{t+1}}{V_{s,z,i}^{t+1}}\right\} \tag{22}$$

For second critical zone is

$$X_{critical2} = max\left\{X_{z,i}^{t+1} - \left\{X_{critical1}\right\}\right\} \tag{23}$$

Then, the averaged fraction for both critical zone is

$$Z = \frac{1}{2}\left(X_{critical1} + X_{critical2}\right) \tag{24}$$

The selection of second critical zone intends to avoid the exaggerated and biased demand when the demand the first critical zone is much higher than all other zones. Then the corrected fraction can be calculated through

$$X_{OA} = \frac{X_{uncorrect}}{1 + X_{uncorrect} - Z} = \frac{\sum_i f_{z,i} * X_{z,i}}{1 + \sum_i f_{z,i} * X_{z,i} - \frac{1}{2}\left(X_{critical1} + X_{critical2}\right)} \tag{25}$$

3.3. System control optimization

In a typical VAV-enabled AHU system, all VAV boxes deliver conditioned air uniformly to each thermal zone. Fig. 3 shows a sample system configuration that can implement all four ventilation strategies discussed in Section 3.2. This paper used all four strategies for comparison purpose based on an on-site experiment. The test space has seven individual office rooms and is assumed to be well-insulated. The primary fan unit supplies outdoor air with single ratio for the entire multi-zone space. The ASHRAE recommended multi-zone ventilation equations strategy (Strategy 3) to use occupancy profile that derived from CO2 concentration, however, in this study, Strategy 3 used Wi-Fi probe detected occupancy.

Fig. 4 shows the detailed flow chart of the proposed ventilation control strategy. The presence and number of occupants determine the operation mode and setting points of VAV boxes.

In Phase I, the Wi-Fi probe identifies the unoccupied rooms. If a room is occupied, the inference algorithm could estimate the number of occupants and calculate the minimum required outdoor air flow rate according to ASHRAE standards. Phase II aims at determining the primary fraction of outdoor air for the satisfactory IAQ level (1000 ppm) with Eq. (16). Two critical zones will be selected to assess the uniform outdoor air flow ratios for all VAV terminals. Then, the corrected fraction can be computed with Eq. (25). Phase III utilizes the derived system setting and delivery the fresh air into spaces with the mechanical system as shown in Fig. 3. The energy

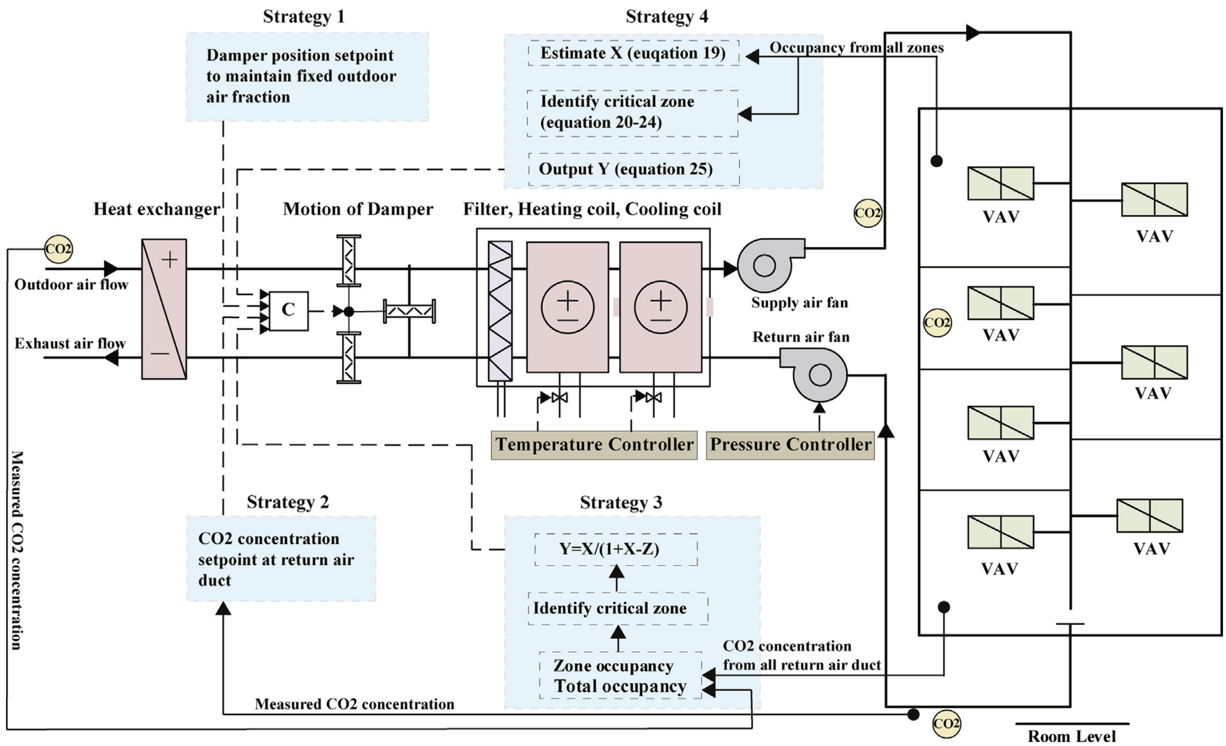

Fig. 3. Mechanical system configuration and four ventilation strategies.

consumption of the primary fan and cooling coil then can be estimated or monitored in this phase. In addition, a cost function is formulated to assess the prediction accuracy [11].

$$\min(W_{cost}) = \min\left(W_{fan} + Q_{outdoor}/COP\right) \tag{26}$$

In the equation, the cooling load of outdoor air $Q_{outdoor}$ can be estimated by the air flow rate and air enthalpy of outdoor air and supply air. The power consumption of primary air fan (W_{fan}) can be determined by affinity law, as shown in Eq. (27). W_{fan} is proportional to the cubic of flow rate M. For simplicity, the coefficient β was set as 0.6 in the study.

$$W_{fan} = \beta M^3 \tag{27}$$

4. Data analysis and results

4.1. On-site experiment and occupancy detection

To validate the proposed control strategy, an on-site experiment was conducted in a graduate students office on campus at City University of Hong Kong. The experiment tested three typical days, including a regular weekday, a weekend day, and a holiday. The scanning frequency of Wi-Fi Probe devices is set as one minute. For every minute, the Wi-Fi requests and responses of occupants' internet device were recorded even if these devices did not connect to the Wi-Fi AP. There are 6–7 access points covered the entire experiment space. In the experiment space, there is an open office with a maximum design capacity of 68 seats, however, during the experiment, only about 25 seats were taken by the long-term occupants. The actual occupancy profiles were also monitored by an overhead camera that installed above the entrance. The energy loads of the room include geometry and thermal load, occupants' load, and utility loads (such as, the computer and lights). Both the actual occupancy and predicted occupancy were used to identify critical zones and validate the effectiveness of the four strategies. Fig. 5 shows the comparison between the actual occupancy using camera and the detected occupancy using Wi-Fi Probe.

4.2. Comparison between the control strategies

To compare the performance of all control strategies, this study composed a simulation model with Trnsys platform. The model simulated the dynamics of the mechanical system and reported IAQ and energy consumptions for all four control scenarios. The underlying building model has seven 10m x 10m x 3m zones. The supply air temperature was assumed as 19 °C and indoor air temperature was set as 25 °C for all zones. A PID controller serves to determine the supply air flow rate to maintain the acceptable indoor thermal comfort. To simplify the control loop, the heat transfers at the building envelope were ignored and the schedule of other heat sources, such as computers, lighting, was assumed to change concordantly with occupancy variations. The outdoor air CO2 concentration was assumed as 360 ppm and the CO2 generation rate of an occupant as 5 × 10-6 m3/s. In the model, the infiltration of outdoor air was negligible. The only source of CO2 is occupants and the generation rate of CO2 for each occupant is a constant. The simulation period starts from 08:00 am to 23:00 pm in a weekday and a weekend day. The initial CO2 concentration level of all zones is assumed to be the same as outdoor air. The Strategy 1 has a fixed ratio of 25% as the designed minimum ventilation requirements for all seven zones.

Fig. 6 and Fig. 7 show the simulated outdoor air flow rates for the whole space in two days. It can be observed from the figures that Strategy 1 requires the highest outdoor air flow rate while Strategy 2 reports the minimum rate for both days. The area under the curve represents the total volume of outdoor air for all zones through a day. Table 1 summaries the peak outdoor air flow rate and total outdoor air amount required for the both days. It can be found that the peak outdoor air flow rate on the weekday is Strategy 3 and the value is close to Strategy 4. This

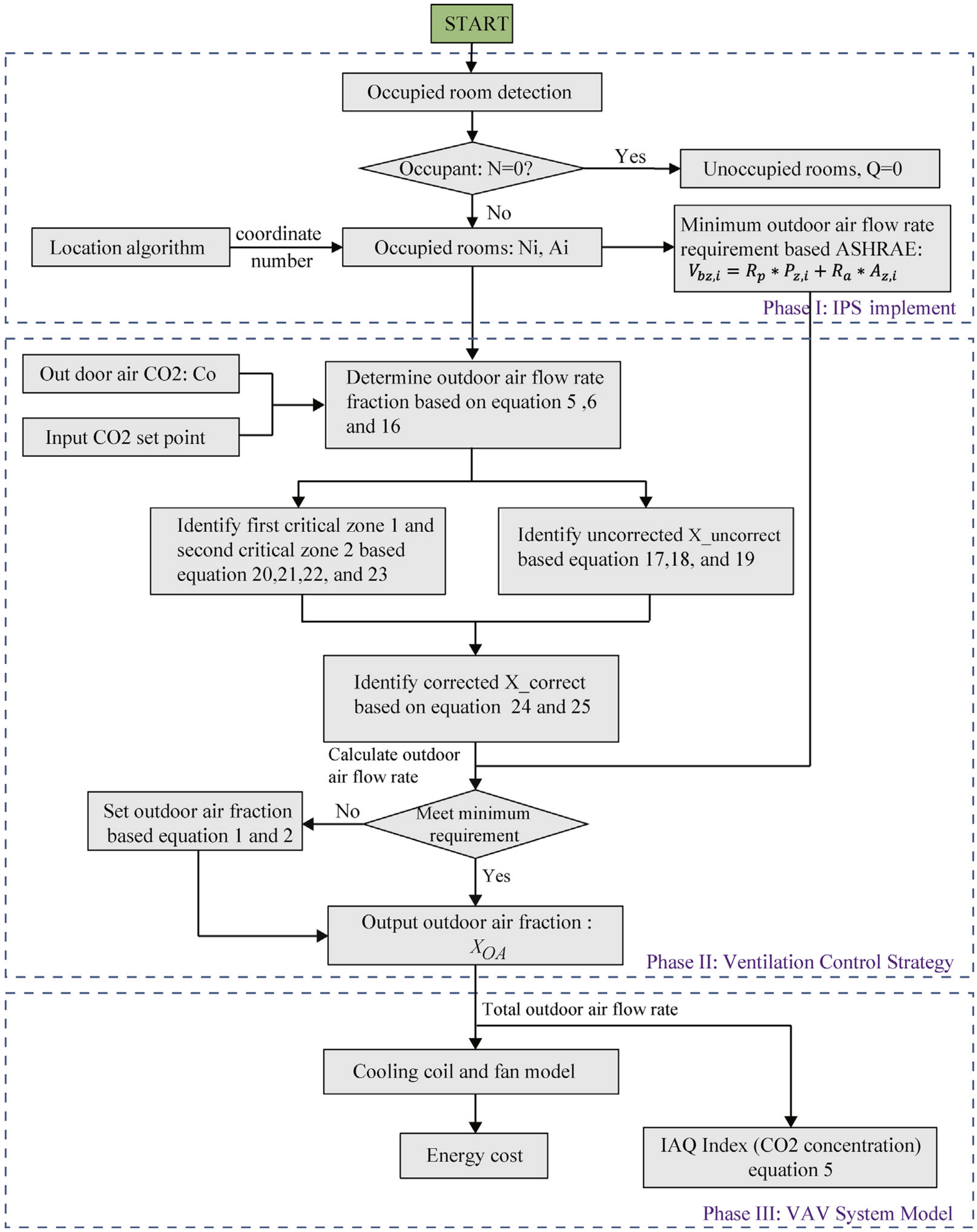

Fig. 4. The proposed supervisory control algorithm.

Table 1
The peak flow rate and total amount of outdoor air required in the whole weekday and weekend day.

	Weekday		Weekend day	
	Peak outdoor air flow rate (L/s)	Total outdoor air flow rate for 7 zones (m3)	Peak outdoor air flow rate (L/s)	Total outdoor air flow rate for 7 zones (m3)
S1	1769.43	69483	1087.5	49281
S2	925.78	30516	435.00	19716
S3	1237.72	51060	856.31	41136
S4	1211.40	38907	647.67	21939

suggests that the multi-zone equations strategy and the proposed strategy perform similar when the zones reach maximum ventilation load (or highest occupancy). However, when partial loads are more frequently observed, the proposed Strategy 4 use less energy compared with the multi-zone equations strategy. Such condition is more popular during the weekend days. In addition to energy consumption, the IAQ for these strategies were further discussed.

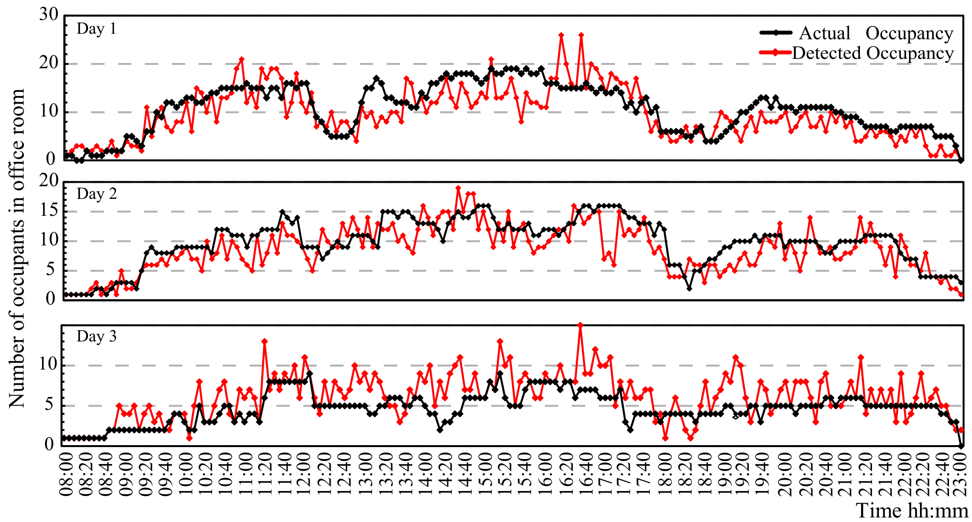

Fig. 5. The detected occupancy profiles and actual occupancy profiles during the experiment.

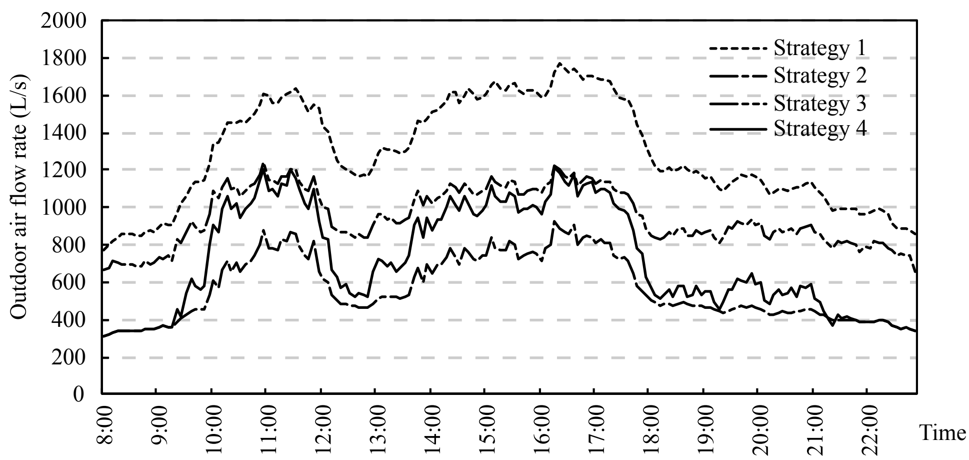

Fig. 6. Outdoor air flow rates of all zones during the weekday.

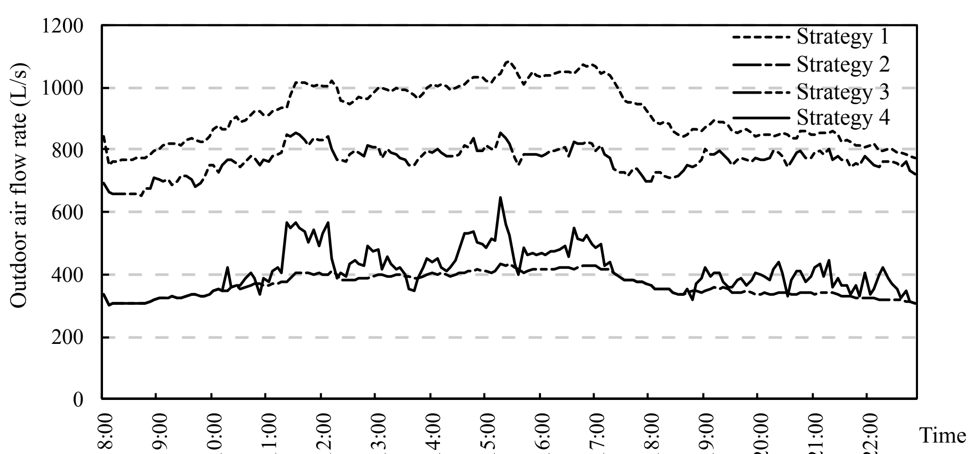

Fig. 7. Outdoor air flow rates of all zones during the weekend day.

4.3. IAQ analysis

4.3.1. Weekday

Fig. 8 to Fig. 11 show the CO2 concentration level of the simulated model in a typical weekday. All four strategies reach acceptable IAQ level (1000 ppm) for most zones. All ventilation strategies selected zone 6 and zone 3 as the critical zones. Fig. 8 shows that Strategy 1 successfully maintained the CO2 concentration lower than 900 ppm for all zones. Zone 7 was "unoccupied" before 10:30, so its CO2 concentration remains same at the beginning of the weekday. The total outdoor air amount required by Strategy 1 for the whole day is 69483m^3.

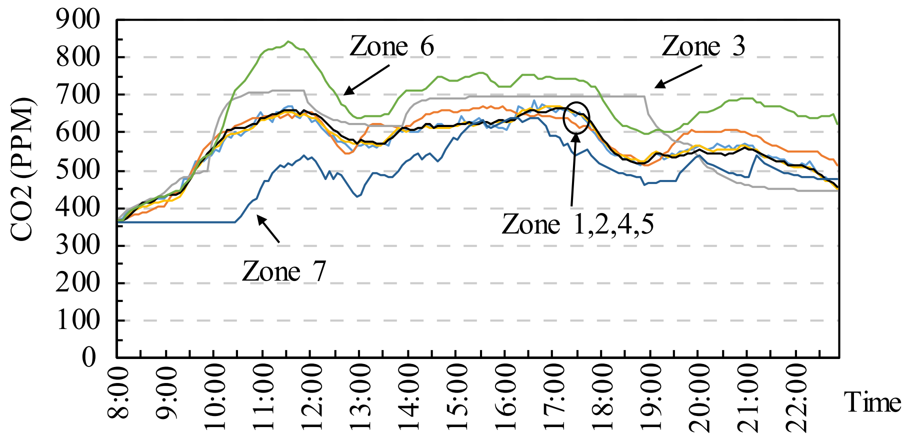

Fig. 8. CO2 concentration levels in all zones under Strategy 1 during the weekday.

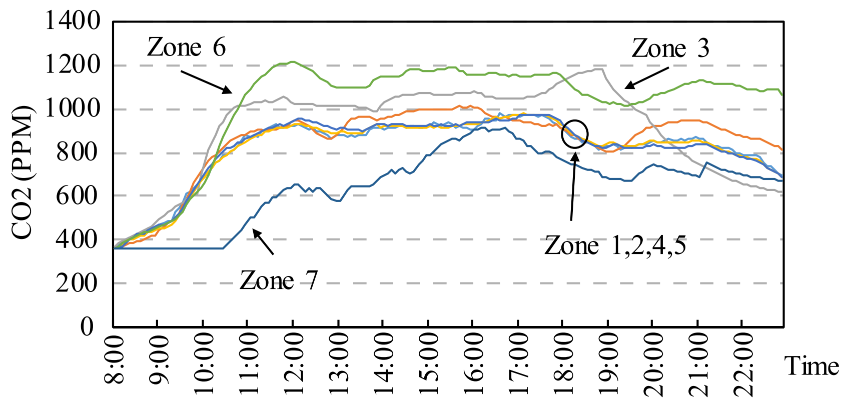

Fig. 9. CO2 concentration levels in all zones under Strategy 2 during the weekday.

Fig. 9 shows the results of Strategy 2. Zone 1, 2, 4, 5, and 7 satisfied the 1000 ppm threshold during the occupied period. However, CO2 concentration in zones 3 and 6 are higher than 1000 ppm but lower than 1200 ppm for most of the day. Deficiency in occupancy information results in challenges to maintain an acceptable the IAQ in critical zones. However, Strategy 2 is a conservative strategy with much lower energy consumption, since the total outdoor air amount in a day (30516 m^3) is less than half of the Strategy 1′s flow rate.

Strategy 3 was designed to eliminate the deficiency of strategy 2 and focus on improving IAQ in critical zones. Fig. 10 shows the CO2 concentration level that adopted Strategy 3 in all zones. Compared with Strategy 2, zones 3 and zone 6 reached satisfactory level of ppm. The total outdoor air amount required in Strategy 3 is about 51060 m^3. The multi-zone equations strategy guarantees that all zones' IAQ satisfy the required level with small additional energy consumption. As shown in this model, Wi-Fi probe enabled occupancy detection approach can be integrated with the multi-zone equations method and effectively improve IAQ with a slight increase in energy consumption.

Fig. 11 shows the results of the proposed Strategy 4. Based on the strategy, the outdoor air flow rate is corrected by two sequential critical zones identified by the occupancy prediction model. The total outdoor air flow amount required under Strategy 4 is about 38907 m^3 during the day. Except for Zone 3 during 18:00 to 19:00, almost all zones satisfy the required IAQ level. Compared with Strategy 3, though scarifying one hour's qualified IAQ, this strategy can save 23.8% energy consumption.

4.3.2. Weekend day

Different from weekdays, during weekend days, it is more often to observe occupied zones. This section discussed the simulated results of a typical Saturday. Fig. 12 to Fig. 15 show the CO2 concentration level of all zones with different strategies. With decreased occupancy load, the required outdoor air flows were also reduced. In Fig. 12, the same Strategy 1 results in lower CO2 concentrations in each zone than that on a weekday. The total amount of outdoor air required is about 49281 m^3 for the whole day. All zones have CO2 concentration under 800 ppm (Excellent Level). Zone 3 was regarded as the critical zone at the beginning of the day and dropped during afternoon with decreased occupancy. Zone 7, on the contrary, became the critical zone in the later day.

Fig. 13 shows the results that utilized Strategy 2. Except Zone 7, all zones' CO2 concentration are maintained under acceptable level. Zone 7 has 20.1% of occupied time that IAQ exceeds 1000 ppm and as high as 1200 ppm. The total outdoor air flow rate required under Strategy 2 is about 19716 m^3.

As shown in Fig. 14, under Strategies 3, all zones reach excellent IAQ level (less than 800 ppm). The total outdoor air amount required is 41136 m^3 for the whole day. Strategy 3 satisfied the same standard as Strategy 1 with less outdoor air and lower energy consumption. Therefore, Strategy 3 is more preferable compared with Strategy 1.

For Strategy 4 in Fig. 15, IAQ for most zones are acceptable. Zone 7 have a CO2 concentration higher than 1000 ppm for 13.96% of the occupied time after 20:00 pm The total outdoor air amount required in strategy 4 is about 21939 m^3. Compared with Strategy 2, there is a 10.1% increase in total amount but, in exchange, the unstratified time for Zone 7 was reduced by 6% and CO2 con-

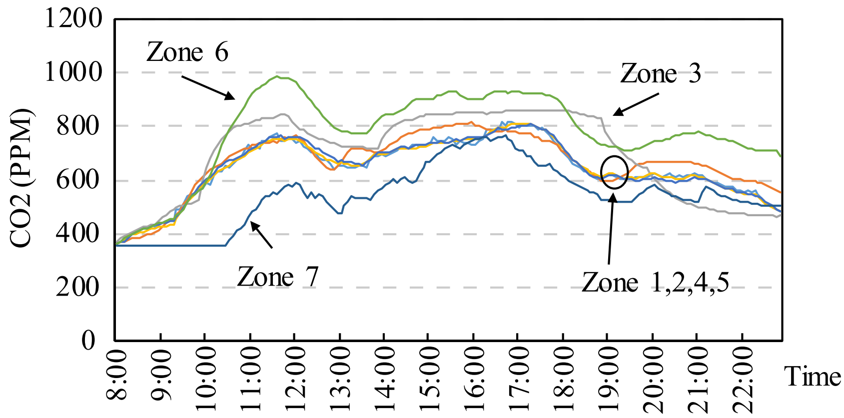

Fig. 10. CO2 concentration levels in all zones under Strategy 3 during the weekday.

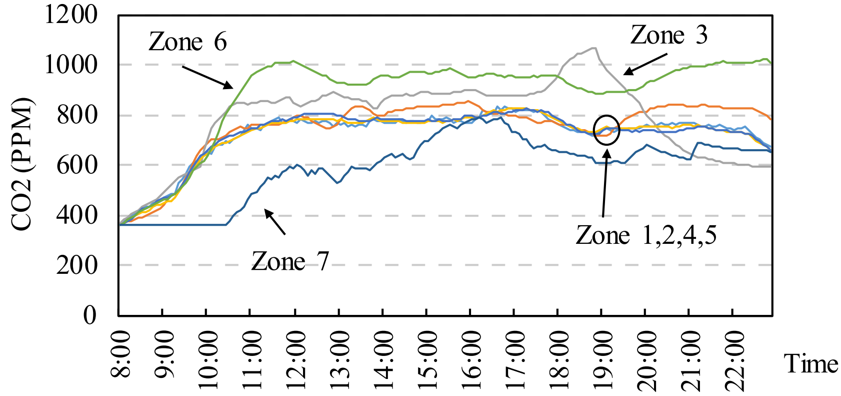

Fig. 11. CO2 concentration levels in all zones under Strategy 4 during the weekday.

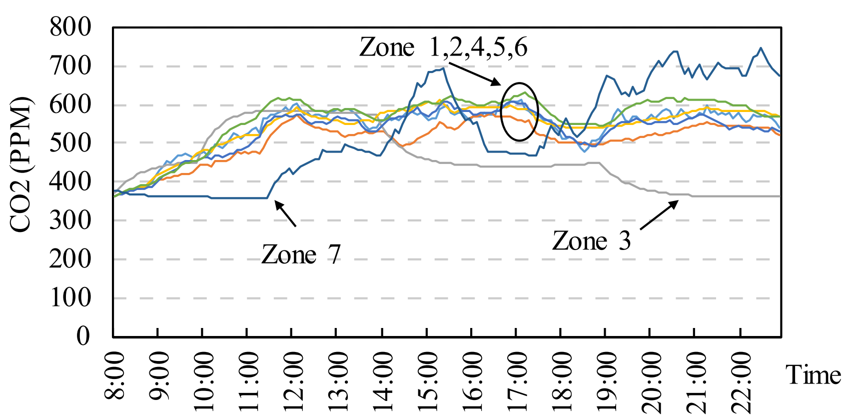

Fig. 12. CO2 concentration levels in all zones under Strategy 1 during the weekend day.

certation is close to 1000 ppm. When compared with Strategy 3, if acceptable IAQ level is selected to save energy, Strategy 4 could be preferable.

4.4. Energy consumption analysis

The energy consumption of the cooling coils of the AHU is estimated over the simulated two days. Both days are typical cooling day and the energy consumers include primary fan and cooling coils. Table 2 summaries the simulated results.

The Strategy 2 has lowest energy usage by scarifying the IAQ level in critical zones. Strategy 3 can effectively reduce the CO2 concertation to acceptable level with 27% less energy consumption than the baseline (Strategy 1) in a weekday. Compared with Strategy 1 and Strategy 3, the proposed Strategy 4 could achieve even higher energy saving, 44.26% and 23.6% reduction, respectively. However, as discussed in previous section, such saving results in a short period of unsatisfied IAQ in the critical zone. In contrast to the weekday, for the energy consumptions on a typical weekend day, Strategy 3 has less energy reduction than Strategy 1, however, Strategy 4 can save even more energy. This can be explained by the fact that the weekend day has higher chance for a zone to be unoccupied, since the rationale of Strategy 4 is to identify unoccupied zone and avoid to provide unnecessary service.

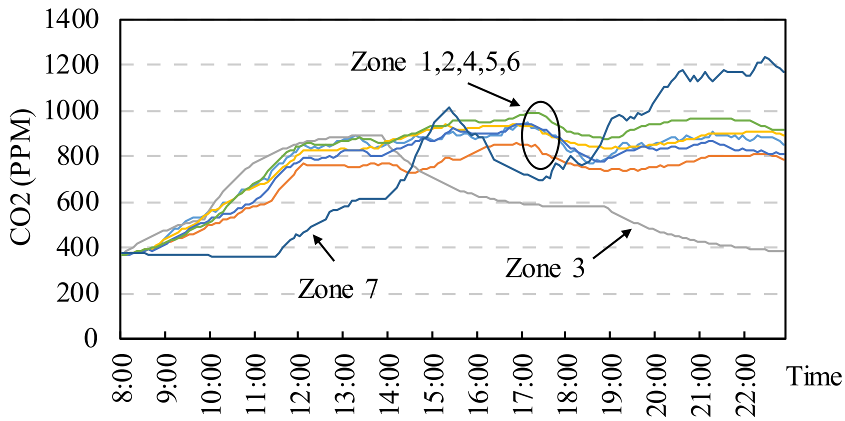

Fig. 13. CO2 concentration levels in all zones under Strategy 2 during the weekend day.

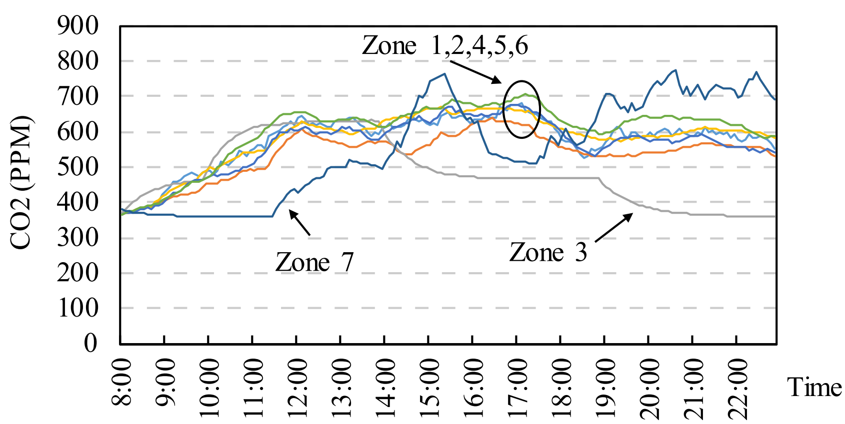

Fig. 14. CO2 concentration levels in all zones under Strategy 3 during the weekend day.

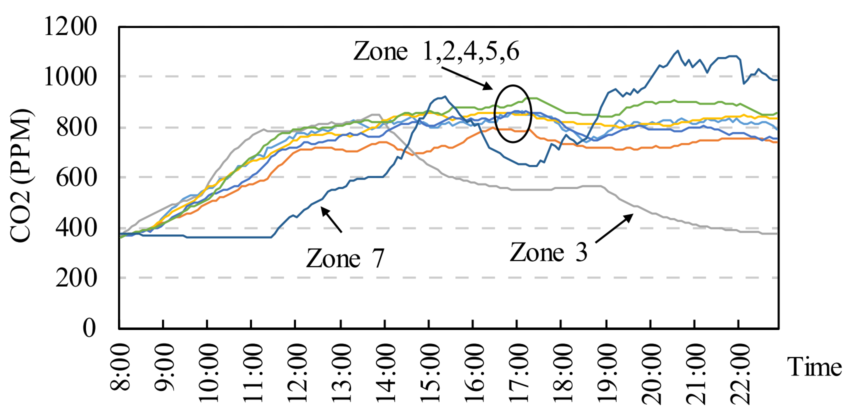

Fig. 15. CO2 concentration levels in all zones under Strategy 4 during the weekend day.

Table 2
Energy consumptions of strategies 1–4 of a typical weekday and weekend day .

Energy Consumption Sectors (kWh)		Weekday				Weekend day			
	S1	S2	S3	S4	S1	S2	S3	S4	
Sum of Primary Fan and Cooling Coil		294.77	113.08	215.17	164.30	113.64	31.69	93.81	50.49
Energy Saving* (Baseline)	(S1)	/	/	27%	44.3%	/	/	17.4%	55.5%
	(S3)	/	/	/	23.6%	/	/	/	46.1%

* Note: For S3, the baseline of energy saving is S1; for S4, the baseline of energy saving is S1 and S3.

5. Discussion

This study compared IAQ and energy consumption of the proposed strategy with three conventional ventilation strategies for two typical days. Strategy 1 takes one destined maximum outdoor air fraction to regulate the system ventilation, while Strategy 2 mainly focuses on energy saving and uses the CO2 concentration levels at the return duct as its control standard. Although simple and effective, both strategies neglected the occupancy conditions of a space, especially when the space composed by multiple thermal zones. Many researchers have found the occupancy information and occupants' behaviors could significantly impact the HVAC load and IAQ requirements [47–50]. Therefore, ASHRAE Standard 62 recommends a multi-zone control strategy based on each zone's occupancy condition. As illustrated in this study, Strategy 3 and Strategy 4 can achieve a satisfactory IAQ level with great amount of energy conservation. In addition, Strategy 4 was found more versatile in balance the IAQ and energy consumption based on predicted occupancy information.

Different from exiting approach, the proposed strategy also utilized the predicted occupancy to select two critical zones. The corrected outdoor air fraction is computed by averaging the requirement of both critical zones. By doing so, the first critical zone's IAQ may not be guaranteed over the whole day, but this effectively avoid the potential distortion caused by the first critical zone's deviated high value. In addition, the detection of unoccupied zones can be easily removed from the critical zone candidates and will not waste ventilation service. As shown in the simulation, although 6% (weekday) and 20.1% (weekend) of time in one zone may have a CO2 concertation slightly higher than 1000 ppm, 23.6% (weekday) and 46.1% (weekend day) can be saved through the proposed strategy.

This study employed Wi-Fi probe to count the number of occupants in a zone and used the detected occupancy profile as control reference. Although the simulation results suggest a good performance under the experiment setting, this strategy still subject to several limitations. The first limitation is caused by the Wi-Fi probe technology. Since the occupancy detection is highly relying on the occupants' Wi-Fi tag or smart phone, if they do not use Wi-Fi network or have multiple phones, the occupancy detection algorithm can be misled and report inaccurate occupants' number. Therefore, to overcome the constraint of the Wi-Fi probe technology, it is essential to integrate the other occupancy detection approaches, such as environment sensors or motion sensors, to cross-reference the proposed strategy. The second limitation is related to the selection of the second critical zone. Taking the average of both critical zone as control reference can result in long time low IAQ in the first critical zone. If the building space have few zones, the propose strategy may not able to save a large amount of energy to compensate the loss of low IAQ. Therefore, the propose strategy is preferable when the underling space have many zones or the requires outdoor air fractions are similar in all zones. Another limitation is related to the simplification of our model. This study modeled the strategies for the fan-coil system and mainly focuses on the ventilation flow rate, however, in many HVAC systems, both the ventilation system and the heating and air conditioning system are integrated together. The mixed fresh air is heated or air conditioned before been delivered into buildings, therefore, the occupancy detection should determine not only the outdoor air amount but also the preferable indoor temperature [35,36,51]. In addition, the building thermal load also depends on equipment operation, lighting, building envelope, and other heat sources. Therefore, in reality, the optimization of building HVAC is a multi-objective problem and requires further and more rigorous investigation.

6. Conclusions

This study proposed an occupancy-profile based multi-zone control strategy to operate building ventilation system. In this strategy, the Wi-Fi probe technology is implemented to detect real-time and high-resolution occupancy information to determine proper outdoor air portions for all thermal zones of a given building space. To validate the proposed approach, this study conducted an onsite experiment to gather occupancy information for two typical days and used this data simulated the energy and ventilation performance of four different strategies. The results suggest that the proposed the strategy can maintain IAQ in most zones and save up to 55% of energy consumption compared with traditional fixed minimum air flow rate strategy, but it also results in unqualified IAQ in 6% to 20.1% of operation time in the critical zone. The proposed method also shown better performance than the ASHRAE recommended the multi-zone equations control strategy.

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