**International Conference on Applied Energy 2019**
**Aug 12-15, 2019, Västerås, Sweden**
**Paper ID: 0413**

# MULTI-ROOM OUTDOOR AIR VENTILATION CONTROL STRATEGY IN RESPONSE TO ABNORMAL OCCUPANCY CONDITION

Wenzhuo Li[1], Shengwei Wang[1,*]

1 Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

## ABSTRACT

Conventionally, excessive indoor $CO_2$ condition is related to abnormal occupancy condition and can be solved by increasing overall outdoor air rate through air handling unit (AHU). More energy is consumed to condition and deliver the outdoor air by AHU and deliver outdoor air and fans. To be energy-efficient, this study proposes a multi-room outdoor air coordination strategy in response to abnormal occupancy condition by utilizing wireless sensor network (WSN) technology without increasing overall outdoor air rate through AHU. For critical rooms, a simplified occupancy estimation method is applied, and one-step model-based predictive control for dampers is developed. For non-critical rooms, an optimization problem is formed to reallocate the rest part of overall outdoor air rate. The proposed strategy is applied in a real case in Hong Kong. The reduced highest $CO_2$ and exposure time to undesirable $CO_2$ in critical and non-critical rooms prove the ability of proposed strategy in response to abnormal occupancy condition. And compared with extra energy consumption for AHU and fans in conventional strategy, smaller energy for adjusting dampers proves the energy efficiency of proposed strategy.

**Keywords:** energy efficiency, excessive $CO_2$, multi-zone ventilation, WSN technology, model-based prediction, genetic algorithm (GA)

## NONMENCLATURE

| | |
|---|---|
| *Abbreviations* | |
| ACH | Air change rate |
| AHU | Air handling unit |
| GA | Genetic algorithm |
| HVAC | Heating, ventilation, and air conditioning |
| IAQ | Indoor air quality |
| MV | Mechanical ventilation |
| *Symbols* | |
| C | $CO_2$ concentration |
| G | Emission rate for $CO_2$ from people |
| Q | Outdoor air rate |
| V | Room volume |
| a | initial concentration of $CO_2$ at t=0 |
| b | Sum of outdoor and indoor $CO_2$ emission source |
| m | Number of non-critical rooms |
| n | Occupant number |
| t | Time |

## 1. INTRODUCTION

Air quality in buildings, where human beings spend 80–90% of lifetimes, has significant impact on occupants' health and work efficiency [1, 2]. As an important part of Heating, ventilation, and air conditioning (HVAC) system, mechanical ventilation (MV) system is mainly responsible for controlling indoor air quality (IAQ) by supplying outdoor air to dilute indoor air pollutants. HVAC system accounts for 43% of the commercial building energy consumption, and about 25% of HVAC energy is consumed by MV system [3, 4]. Therefore, maintaining IAQ while saving energy should be considered simultaneously for MV system.

The key parameter that influences the energy consumption and dilution performance of MV system is the outdoor air rate. According to the standard prescribed by the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE),

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

outdoor air rate for a space can be calculated by summing up space size and occupant number multiplied by their corresponding coefficients, which vary by space functions [5]. Since space size is fixed while occupant number is flexible and can fluctuate to a wide range, the outdoor air rate should be determined by the most unfavorable condition (i.e. the maximum occupant number). However, it is not energy efficient, because conditions with lower occupant number are over-ventilated.

In this regard, such a calculation method is more applicable in cases with regular occupancy, which is possibly to be predicted in advance. And the preset outdoor air rates are appropriate for most conditions, except for some abnormal conditions, in which occupant number are beyond normal range and cannot be predicted. For example, staffs who work in office buildings keep regular commuting times and working space, and outdoor air rate can be designed for each time period and space accordingly. However, in meeting rooms, meetings can be arranged temporarily and occupant number can increase far larger than normal value in a short time. Under this condition, the preset outdoor air rate is not enough. And $CO_2$, which is an occupant-related indoor pollutant and a major control indicator for satisfied IAQ [6-8], exceeds the prescribed limit (e.g. 800 ppm as excellent level and 1000 ppm as good level [9]).

### 1.1 Maintain $CO_2$ condition from AHU side

Many previous studies tried to solve excessive indoor $CO_2$ condition by increasing the amount of outdoor air with controlled fan speed or damper valve from air handling unit (AHU) side [10-12]. However, such a conventional strategy for MV system is not energy-efficient, since more energy is required for AHU and fans to condition and deliver outdoor air [14]. Due to the expensive installation and connection fee for wired $CO_2$ sensors, they are typically located at inlet and outlet of AHU, and at a subset of the controlled rooms. The lack of fine-grained information restricts the control action tailored for each rooms. And to fulfill the requirement for critical rooms, other rooms are over-ventilated.

Fortunately, the 21st century has witnessed rapid development of wireless sensor network (WSN) technology with lower application cost. If wireless sensors were installed in every room, detailed condition of each room would be monitored and tailored actions would be taken. As a similar case, Wi-Fi probe enabled system was applied in [13] to estimate occupancy in each room. But outdoor air rate was still adjusted from AHU side, and it failed to take advantage of fine-grained information. Therefore, it is needed to develop an ventilation control strategy in response to abnormal occupancy condition and excessive indoor $CO_2$ by fully utilizing WSN.

### 1.2 Maintain $CO_2$ condition from damper side

In contrast to the strategy from AHU side, ventilation strategy focusing on damper side is expected to take advantage of WSN. Specifically, damper in each room is adjusted separately according to its own IAQ condition monitored by WSN. Since the adjustment of dampers in critical and non-critical rooms are independent, excessive indoor $CO_2$ in critical rooms and over-ventilation in non-critical rooms are avoided by an energy-efficient manner. A relevant study is conducted by Li et al. [15]. After installing real-time environmental sensors for collecting IAQ indicators, they developed a logic-based event-driven control strategy for the real-time removal of excessive $CO_2$ by only increasing outdoor air rate in critical rooms. However, this study did not consider the source of extra amount of outdoor air. Changing fan speed or damper valve from AHU side easily comes to mind, but it causes problems as explained before.

Based on this, this study proposes a multi-room outdoor air ventilation control strategy in response to abnormal occupancy (i.e. excessive indoor $CO_2$ condition) by utilizing WSN technology. It is expected to be energy-efficient, because that dampers in critical and non-critical rooms are adjusted separately, and the overall outdoor air rate keeps unchanged. For critical rooms, one-step model-based predictive control was applied to increase outdoor air rate and reduce excessive $CO_2$. For non-critical rooms, the rest part of overall outdoor air rate from AHU are reallocated by solving an optimization problem, so that $CO_2$ in these rooms can still be maintained. A real case in Hong Kong is chosen to illustrate the feasibility and efficiency of the proposed strategy.

## 2. THE MULTI-ROOM OUTDOOR AIR VENTILATION CONTROL STRATEGY

### 2.1 Overview of the real case

“A” office building in Hong Kong was selected for a case study. A small-scale WSN has been established by installing real-time environmental sensors (AWAIR, of which the technical characteristics can be found in [15]) in one floor of “A” office building. And the collected $CO_2$

data in 15-min interval were used in this study to indicate the ventilation performance.

The schematic diagram of MV system in "A" office building is shown in Fig 1. Outdoor air flows into the building through AHU, and the fan speed determines the overall outdoor air rate. According to design rules, rooms with different functions are supplied with certain amount of outdoor air, which is controlled by individual damper of each room. Due to the limited information for actual outdoor air rate of each room, this study applied $CO_2$-based tracer gas method [7, 8] to estimate air change rate (ACH). ACH is defined as the ratio of outdoor air rate and room volume, thus can reflect the outdoor air rate of each room.

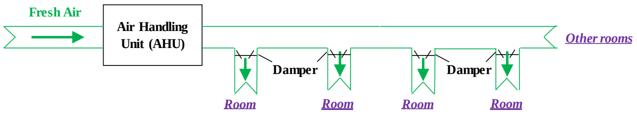

Fig 1 The schematic diagram of MV system in "A" office building

This study considers eight rooms in "A" office building, including one multi-person office (I), two meeting rooms (II and III), one counselling room (IV), two single-person offices (V and VI), one reception desk (VII) and one pantry (VIII). Currently, the default ventilation strategy adopted in "A" office building is on/off control. MV system is operated from 7:30am to 11:00pm in workdays. During operation period, outdoor air rate of each room keeps unchanged regardless whether $CO_2$ is under undesirable level.

After applying $CO_2$-based tracer gas method for the $CO_2$ data between July 21 and September 28 in 2017, the default ACH is estimated as 0.3/15-min. Default outdoor air rate ($Q_D$) of each room can be calculated by multiplying room volume (V) with ACH, and they are summarized in Table 1. All of these eight rooms are served by one AHU, thus the sum of $Q_D$ of eight rooms is the overall outdoor air rate that AHU needs to provide ($Q_{AHU}$, 211 $m^3$/15-min).

Generally, staffs who worked in "A" office building keep regular nine-to-five commuting times and constant offices. And the default ventilation strategy performs well in controlling $CO_2$ below a prescribed level. However, in meeting rooms, featured with irregular occupancy patterns, the default ventilation strategy is not applicable any more. As an example shown in Fig 2, $CO_2$ in rooms except for room II (a meeting room) were all maintained to within good level (i.e. lower than 1000 ppm), but $CO_2$ in room II were far beyond 1000 ppm during a meeting period. To solve excessive $CO_2$, the multi-room outdoor air ventilation control strategy is proposed. It includes ventilation strategies for critical and non-critical rooms as follows.

Table 1 $Q_D$ of eight office rooms

| Room | I | II | III | IV | V | VI | VII | VIII | $Q_{AHU}$ |
|---|---|---|---|---|---|---|---|---|---|
| V ($m^3$) | 240 | 120 | 47 | 32 | 66 | 30 | 90 | 72 | |
| $Q_D$ ($m^3$/15-min) | 72 | 36 | 15 | 10 | 20 | 9 | 27 | 22 | 211 |

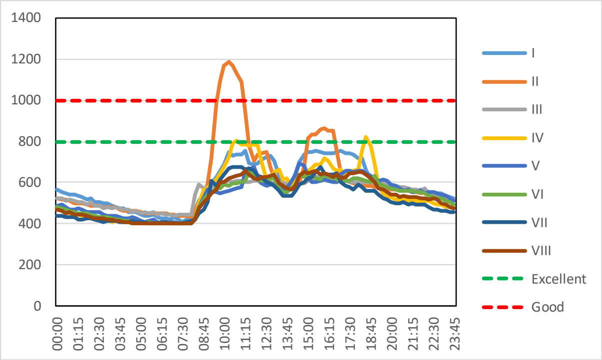

Fig 2 $CO_2$ in eight office rooms on 1 August 2017 with default ventilation strategy

## 2.2 *The ventilation strategy for critical rooms*

The proposed ventilation strategy for critical rooms is a one-step model-based predictive control. The time step in this study is 15-minute. If the predicted $CO_2$ at the next time step is higher than a certain value (i.e. 800 ppm in this study), rooms will be regarded as critical rooms. And outdoor air rate in critical rooms will be increased as small as possible to assure that the predicted $CO_2$ at next time step can be lower than 800 ppm.

The prediction model for $CO_2$ is based on mass balance equation (refer to Equation (1)). $CO_2$ at each time *t* is integral solution of Equation (1) from *t*=0 to *t*=t, and can be expressed as Equation (2) with parameters of *a* and *b*. $CO_2$ at (t+1) can be predicted by $CO_2$ at t and (t-1): a is $CO_2$ at t, and n at t equals to n at (t-1). Then with the trial and error method, the smallest value that outdoor air rate in critical rooms should be increased to can be found.

The occupancy estimation in prediction method is based on an assumption that occupant number is the same between two consecutive time steps. Although such a simplified estimation method is not as accurate as the direct monitoring method, it is reasonable in real cases. Generally, meeting participants do not enter room just at the same time, but arrive successively before the start time of meeting. That is, prior to reaching the maximum occupant number, which also corresponds to the highest $CO_2$, occupant number in previous time step can already been identified as larger than normal value. If outdoor air rate was increased at t, $CO_2$ at (t+1) would not as high as that under default ventilation strategy.

$$\frac{dC}{dt} = \frac{1}{V}(QC_{out} - QC + G) \qquad (1)$$

$$C = (a - b)e^{-ACH \cdot t} + b \qquad (2)$$

$$b = C_{out} + \frac{n \cdot G}{Q} \qquad (3)$$

where, C is indoor $CO_2$ concentration (ppm); t is time of day; V is room volume ($m^3$); Q is outdoor air rate ($m^3$/15-min); $C_{out}$ is outdoor $CO_2$ concentration (i.e. 473 ppm); G is emission rate for $CO_2$ from people ($3.75 \times 10^{-3}$ $m^3$/15-min); a is initial concentration of $CO_2$ at t=0 (ppm); b is the sum of outdoor and indoor $CO_2$ emission source (ppm);and n is occupant number.

### 2.3 *The ventilation strategy for non-critical rooms*

The basic point of the proposed ventilation strategy for non-critical rooms is the reallocation of outdoor air, with the prerequisite that overall outdoor air from AHU is unchanged. When more outdoor air is supplied to critical rooms as determined by section 2.2, outdoor air rate to other rooms is reduced. And reallocating the rest of outdoor air should meet the following two requirements. First, $CO_2$ should be kept lower than 800 ppm for non-critical rooms as well as possible, though smaller outdoor air rate than default value is provided. Second, adjustment of dampers, which controls the change of outdoor air rate in each room, between two consecutive time steps should be as small as possible. Accordingly, an objective function is formed as Equation (4), with the constraint of adjustable range for outdoor air rate in non-critical rooms. Such an optimization problem is solved by the genetic algorithm (GA) in Matlab.

$$\min_{Q_{i,t}} \frac{1}{m}\sum_{i=1}^{m}\left(\frac{|C_{i,t+1} - 800|}{800} + \frac{|Q_{i,t} - Q_{i,t-1}|}{Q_{Tot}}\right) \qquad (4)$$

subject to $Q_{i,t} \in [0, Q_{D,i}]$

$$\sum_{i=1}^{m} Q_{i,t} = Q_{AHU} - Q_{C,t}$$

where, m is the number of non-critical rooms; $C_{i,t}$ is $CO_2$ in the $i^{th}$ non-critical room at t; $Q_{i,t}$ is outdoor air rate in the $i^{th}$ non-critical room at t; $Q_{D,i}$ is default outdoor air (refer to Table 1) in the $i^{th}$ non-critical room; $Q_{AHU}$ is the overall outdoor air rate that AHU needs to provide, 211 $m^3$/15-min as shown in Table 1; and $Q_C$ is outdoor air rate in critical rooms at t determined in section 2.2.

## 3. RESULTS AND DISCUSSION

The excessive $CO_2$ in eight office rooms on 1 August 2017 is selected as an example that is solved by the proposed multi-room outdoor air ventilation control strategy. This section is based on this example.

### 3.1 *Outdoor air rate and $CO_2$ in critical rooms*

As shown in Fig 2, there were two critical rooms on 1 August 2017 considering 800 ppm as the limit, including room II (i.e. meeting room) and IV (i.e. counselling room). Considering the more evident efficiency of proposed strategy on excessive $CO_2$, only results of room II is explained in detail here. Fig 3 shows outdoor air rate and corresponding $CO_2$ in room II on 1 August 2017 with two ventilation strategies (i.e. default and proposed strategies).

With the default ventilation strategy, outdoor air rate keeps a constant value of 36 $m^3$/15-min from 7:30am to 11:00pm (refer to Table 1). $CO_2$ was higher than 800 ppm from 9:30am to 11:15am (a total of 105 minutes), and from 3:00pm to 4:30pm (a total of 90 minutes). The highest $CO_2$ was 1186 ppm at 10:15am.

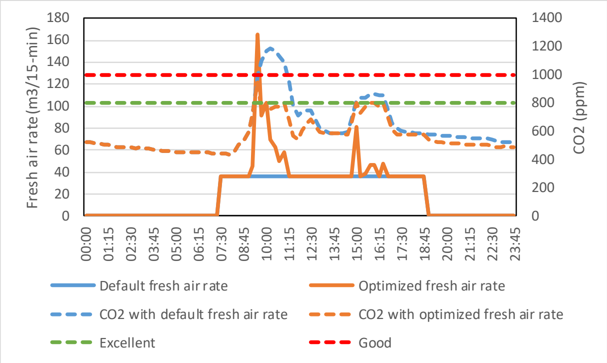

Fig 3 Outdoor air rate and corresponding $CO_2$ in room II on 1 August 2017 with two ventilation strategies

With the proposed ventilation strategy, outdoor air rate deviates far from the default value between 9:15am and 11:00am, and fluctuates close to the default value from 3:00pm to 4:30pm. $CO_2$ was higher than 800 ppm at 9:30am (less than 15 minutes), and at 16:30 (less than 15 minutes). The highest $CO_2$ was 956 ppm at 9:30am. It should be noticed that excessive $CO_2$ condition is not prevented completely. This is due to the assumption in section 2.2 that occupant number at t is the same with that at (t-1). Despite the error in occupancy estimation, such an assumption informs MV system to change operation mode before $CO_2$ condition becoming worse.

### 3.2 *Outdoor air rate and $CO_2$ in non-critical rooms*

Fig 4 shows outdoor air rate in eight office rooms on 1 August 2017 with proposed ventilation strategy. There are two time periods that outdoor air rate in non-critical

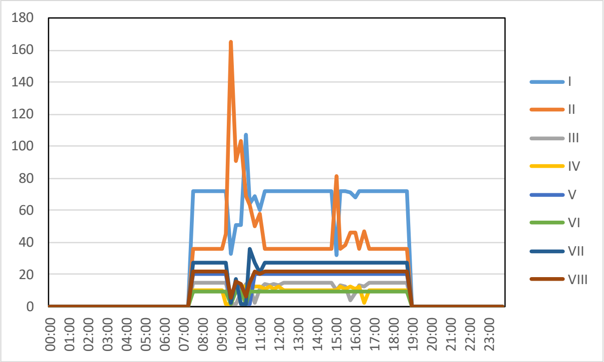

Fig 4 Outdoor air rate in eight office rooms on 1 August 2017 with proposed ventilation strategy

rooms fluctuates, and they are matched with the periods when outdoor air rate in critical rooms fluctuates. During rest of the time, all rooms keep their default outdoor air rates as Table 1.

Fig 5 shows $CO_2$ in eight office rooms on 1 August 2017 with proposed ventilation strategy. In non-critical rooms, $CO_2$ was higher than 800 ppm in room I at 10:15am (less than 15 minutes); and in room VII at 10:30am (less than 15 minutes). The highest $CO_2$ was 856 ppm in room VII at 10:30am.

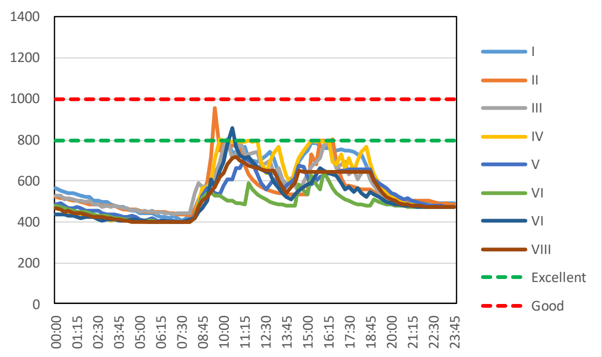

Fig 5 $CO_2$ in eight office rooms on 1 August 2017 with proposed ventilation strategy

### 3.3 Discussion

The main findings of this study are explained in aspects of IAQ control and energy saving.

For IAQ control, the proposed strategy both control the highest $CO_2$ and the exposure time to undesirable $CO_2$. For the example of critical rooms mentioned in section 3.1 (i.e. room II on 1 August 2017), the highest $CO_2$ is reduced from 1186 ppm to 956 ppm; and the exposure time to undesirable $CO_2$ (i.e. higher than 800 ppm) is reduced from 195 minutes (105 minutes+ 90 minutes) to less than 30 minutes (15 minutes+ 15 minutes). By reallocating outdoor air, the outdoor air rates in non-critical rooms are smaller than default values. But IAQ is not deteriorated too much, since $CO_2$ only excess 800 ppm for a small extent, short period and limited rooms.

For energy saving, the proposed strategy is expected to be more energy-efficient than conventional strategy. The conventional strategy control excessive $CO_2$ by increasing the overall outdoor air rate through AHU, thus more energy are consumed to condition and deliver outdoor air. By contrast, the proposed strategy aims at reallocating outdoor air among critical and non-critical rooms, without changing the overall outdoor air rate through AHU. More energy are required to control dampers, but they are expected to be smaller than that consumed by AHU and fan in conventional strategy.

## 4. CONCLUSIONS

A multi-room outdoor air ventilation control strategy in response to excessive $CO_2$ caused by abnormal occupancy condition is developed. Dampers in critical and non-critical rooms are adjusted separately to reallocate outdoor air without changing the overall outdoor air rate from AHU. For critical rooms, a simplified occupancy estimation method is applied, and one-step model-based predictive control for dampers can reduce excessive $CO_2$ in advance. For non-critical rooms, the rest part of outdoor air are reallocated by solving an optimization problem to maintain $CO_2$ in these rooms. The proposed strategy is applied in a real case in Hong Kong. And it is proved to perform well in maintaining $CO_2$ both in critical and non-critical rooms without consuming more energy.

As a supplementary study of [15], which only focused on event-driven control logic in critical rooms, this study further solves optimization problems for control strategies in non-critical rooms. It combines WSN technology with centralized optimization method. However, considering huge amount of data from WSN to be input to central optimizer, centralized control may not applicable anymore. Therefore, the follow-up research will focus on distributed optimization method and distributed control, which are tractable solutions for large-scale problems.

## ACKNOWLEDGEMENT

This work was supported by the Hong Kong PhD Fellowship Scheme. This work was supported by the National Research Foundation of Korea grant funded by the Korean government (MSIP; Ministry of Science, ICT & Future Planning) (NRF-2018R1C1B4A02022690). This work was supported by a grant (18CTAP-C1117226-03) from Technology Advancement Research Program

(TARP) funded by Ministry of Land, Infrastructure and Transport of Korean government.

## REFERENCE

[1] Sarbu I, Sebarchievici C. Aspects of indoor environmental quality assessment in buildings. Energy and Buildings. 2013;60:410-9.

[2] Li W, Koo C, Cha SH, Lai JH, Lee J. A conceptual framework for the real-time monitoring and diagnostic system for the optimal operation of smart building: A case study in Hotel ICON of Hong Kong. Energy Procedia. 2019;158:3107-12.

[3] Ghahramani A, Zhang K, Dutta K, Yang Z, Becerik-Gerber B. Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings. Applied Energy. 2016;165:930-42.

[4] Ben-David T, Rackes A, Waring MS. Alternative ventilation strategies in U.S. offices: Saving energy while enhancing work performance, reducing absenteeism, and considering outdoor pollutant exposure tradeoffs. Building and Environment. 2017;116:140-57.

[5] ASHRAE S. Standard 62.1-2016 e Ventilation for Acceptable Indoor Air Quality, American Society for Heating. Refrigeration, and Air-Conditioning Engineers, Inc. 2016.

[6] Ganesh HS, Fritz HE, Edgar TF, Novoselac A, Baldea M. A model-based dynamic optimization strategy for control of indoor air pollutants. Energy and Buildings. 2019.

[7] Lu T, Knuutila A, Viljanen M, Lu X. A novel methodology for estimating space air change rates and occupant CO2 generation rates from measurements in mechanically-ventilated buildings. Building and Environment. 2010;45:1161-72.

[8] Macarulla M, Casals M, Forcada N, Gangolells M, Giretti A. Estimation of a room ventilation air change rate using a stochastic grey-box modelling approach. Measurement. 2018;124:539-48.

[9] Indoor Air Quality Management Group of the Government of the Hong Kong Special Administrative Region. Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places. 2003.

[10] Xu X, Wang S. An adaptive demand-controlled ventilation strategy with zone temperature reset for multi-zone air-conditioning systems. Indoor and Built Environment. 2007;16:426-37.

[11] Sun Z, Wang S, Ma Z. In-situ implementation and validation of a CO2-based adaptive demand-controlled ventilation strategy in a multi-zone office building. Building and Environment. 2011;46:124-33.

[12] Xu X, Wang S, Sun Z, Xiao F. A model-based optimal ventilation control strategy of multi-zone VAV air-conditioning systems. Applied Thermal Engineering. 2009;29:91-104.

[13] Wang W, Wang J, Chen J, Huang G, Guo X. Multi-zone outdoor air coordination through Wi-Fi probe-based occupancy sensing. Energy and Buildings. 2018;159:495-507.

[14] Lü X, Lu T, Viljanen M, Kibert CJ. A new method for controlling CO2 in buildings with unscheduled opening hours. Energy and Buildings. 2013;59:161-70.

[15] Li W, Koo C, Cha SH, Hong T, Oh J. A novel real-time method for HVAC system operation to improve indoor environmental quality in meeting rooms. Building and Environment. 2018;144:365-85.