A novel operation approach for the energy efficiency improvement of the HVAC system in meeting rooms through real-time big data analytics

Wenzhuo Li [1], Choongwan Koo [2], Taehoon Hong [3], Jeongyoon Oh [4], Seung Hyun Cha [5], and Shengwei Wang [6]*

[1] Ph.D. Student, Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong (wendy.wz.li@connect.polyu.hk).

[2] Assistant Professor, Division of Architecture & Urban Design, Incheon National University, Incheon, Republic of Korea (*Corresponding Author*, E-mail: cwkoo@inu.ac.kr).

[3] Professor, Department of Architecture and Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea (hong7@yonsei.ac.kr).

[4] Ph.D. Student, Department of Civil and Environmental Engineering, Carnegie Mellon University, PA 15213, United States (jeongyoo@andrew.cmu.edu).

[5] Assistant Professor, Department of Interior Architecture Design, Hanyang University, Seoul, 04763, Republic of Korea (chash@hanyang.ac.kr).

[6] Professor, Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong (shengwei.wang@polyu.edu.hk).

ABSTRACT

Energy efficiency would be improved if the set-point temperature of the HVAC system and occupancy-based control could be considered. However, the equipment failures of the HVAC system, which cause temperature deviation from the designated set-point temperature, were generally ignored. Expensive intrusive sensors to facilitate occupancy-based control could cause privacy issues. By utilizing real-time data, this study conducted the three-phase cyclic process (i.e. monitoring-diagnostic-intervention process) in meeting rooms to solve the aforementioned challenges. The works included (i) basic analysis and control for the set-point temperature of the HVAC system by utilizing the real-time data on temperature; and (ii) advanced analysis and basic control for the effective utilization of the HVAC system by utilizing the real-time data on temperature and CO_2 concentration. Main findings were summarized as follows. The set-point temperature can be estimated by mean temperature. By change point analysis (CPA) in "basic analysis", the set-point temperature in meeting rooms showed skewness towards low temperature (with the median of 22.0 °C and 21.0 °C) rather than recommended range (24–25.5 °C). Accordingly, a "basic control" strategy was developed to estimate the set-point temperature in real time, so as to detect failures in the HVAC system, and provide suggestions about adjusting set-point temperature to the recommended range. On the other hand, the "advanced analysis" showed that HVAC system in meeting rooms were not effectively operated (the *AEURH* were 45.29% and 40.31%), in that unnecessary cooling operation mode was unconsciously provided for empty rooms. Accordingly, an "advanced control" strategy was developed to turn off HVAC system in real time once a room is unoccupied (judged by CO_2 concentration variation).

Keywords: *Real-time big data; Energy efficiency; Set-point temperature of the HVAC system; Change point analysis; Occupancy-based control; CO_2 concentration*

1. INTRODUCTION

As a positive response to global warming, the Chinese government has shown the commitment to reduce the CO_2 emissions per gross domestic product (GDP) in 2030 by 60-65% from 2005 and the energy consumption per GDP in 2030 by 15% from 2005 [1]. It is reported that 20%-40% of the national energy consumption come from the building sector [2]. Especially for Hong Kong, the proportion is over 60%, and a commercial sector accounts for more than half [3]. The heating, ventilating and air-conditioning (HVAC) system has been widely installed and operated in buildings to maintain a comfortable indoor environment, of which energy consumption is estimated to take up the largest proportion (i.e. 25%) of the total energy usages [3]. Thus, there is a large amount of energy saving potential applicable to the HVAC system in office buildings.

The HVAC system is generally controlled by the centralized building energy management system (BEMS) [4], which regulates the set-points (e.g., set-point temperature, set-point volume) and the operation schedule (e.g., on/off condition) of the HVAC system synchronously for the different types of rooms, regardless of their different functions and characteristics. However, it is required to control the HVAC system for the different rooms in accordance with the actual demand, especially for meeting rooms having the unique feature of irregular occupancy. It is estimated to achieve the energy savings by over 20% by carefully determining the set-points and the operation schedules of the HVAC system [5]. Therefore, this study aimed to improve the energy efficiency of the HVAC system in meeting rooms by deploying the optimal operation strategies which consider the set-point temperature and occupancy pattern.

The low-cost sensors and cloud servers have become more accessible due to the rapid growth in the Internet-of-Things (IoT) industry [6-7]. Accordingly, the real-time data opens new opportunities with the valuable information hidden behind these data, which can be effectively used with the advanced computing algorithms and technologies. In this context, there are a growing number of studies on the energy efficiency improvement in buildings by analyzing the real-time data with the emerging methods, such as pattern recognition [8-13], anomaly detection [14-17], model predictive control [18-21], and so on. Tables 1-2 summarize previous studies on the real-time energy efficiency improvement by adjusting the set-point temperature of the HVAC system and by deploying the occupancy-based control of the HVAC system.

First, the set-point temperature is the value at which the indoor temperature finally arrives by the operation of HVAC system, and the dead band is the tolerance range around the set-point temperature at which the HVAC system is not required to respond [22]. As shown in Table 1, many previous studies have proved that the significant energy-saving potential could be achieved by appropriately selecting the set-point temperature of the HVAC system. Ghahramani et al. [22] analyzed the impact of the set-point temperature, dead band, and occupancy schedule on energy-saving potential through the building energy simulation methods. Compared to the annual set-point temperature (i.e. 22.5 °C), the daily set-point temperature (i.e. 19.5-25.5 °C) could save energy by 6.78%-37.03% depending on different climates and building size. Hoyt et al. [23] estimated the energy savings by 29% by increasing the cooling set-point temperature from 22.2 °C to 25 °C. Both of simulations and field studies supported that the adequate range (i.e. low minimum volume set-point) of variable air volume (VAV) system was beneficial in terms of energy savings with the wide range of the set-point temperature.

Second, the discrepancies between the designed and actual energy consumption in buildings can mainly occur due to the occupants' behaviors. Significant potential in energy savings would be achieved if building services could effectively respond to the occupancy condition. As shown in Table 2, many previous studies have made efforts in developing the occupancy-based control strategies. Labeodan et al. [24] established the wireless sensors and actuators network to facilitate the occupancy-based lighting control. The information from Passive Infrared (PIR) motion sensors and chair sensors were fused to determine the occupants' presence or absence. Wang et al. [25] established the occupancy-profile-based ventilation strategy for multi-zone spaces, enabled by the Wi-Fi technology. Compared to the traditional methods with a fixed outdoor air ratio, the proposed strategy suggested to determine the proper outdoor air ratio by the detected and predicted occupancy level.

Although several studies have been conducted for the energy efficiency improvement by investigating the set-point temperature and occupancy-based control in real time, there were two kinds of challenges to be overcome. First of all, most of previous studies tried to achieve the energy savings by developing the optimal thermostat strategies for the HVAC system, based on the assumption that the actual indoor temperature would reach the designated set-point temperature. However, it is reasonable only if the HVAC system is operated in normal condition. That is, considering the accidental failures of the HVAC system (e.g. the biases of temperature sensor inside, or control signal errors), the designated set-point temperature of the HVAC system would not be always matched with the stable condition. Therefore, it is needed to use the estimated set-point temperature before adjusting it for the energy efficiency improvement, instead of utilizing the value of the set-point temperature from a control panel. On the other hand, most of previous studies tried to achieve the energy savings by developing the occupancy-based control strategies, which used the several methods such as PIR sensors, cameras, Wi-Fi signals, and so on. However, these methods could either cause the high costs or privacy issues. Therefore, alternative ways that are cheaper and unconcerned of privacy issues should be applied to the occupancy-based control strategies for the HVAC system.

To address the aforementioned challenges, a novel operation approach was developed to improve the energy efficiency of the HVAC system in meeting rooms through real-time big data analytics. First, the set-point temperature of the HVAC system was estimated by calculating the mean value of indoor temperature. One of the change point analysis (CPA) models, which could identify changes in the mean value of indoor temperature, was chosen to evaluate the current status of the set-point temperature. Then, the potential equipment failure in the HVAC system was detected by estimating the set-point temperature in real time, and to provide feedbacks to adjust the set-point temperature into the preferred range. On the other hand, the indoor environmental indicators (i.e. temperature and CO_2 concentration) were detected to infer whether the HVAC system was being operated and whether the meeting room was being occupied. Then, the operation condition of the HVAC system was effectively improved by applying the real-time occupancy-based control strategy.

Table 1

Literature review on the real-time energy efficiency improvement by adjusting the set-point temperature of the HVAC system

Author	Area	Building	Time period	Objects	Tools	Method	Main findings
Ghahramani et al. (2016) [22]	The United States	Office	One year	The influence of building size, construction category, climate, occupancy schedule, set-point, and dead band	EnergyPlus, MATLAB software	Building energy simulations, N-way ANOVA analyses	• This paper introduced a systematic approach to study the effects of influential factors on building HVAC energy consumption by using building energy simulations.
Hoyt et al. (2015) [23]	The United States	Office	From November 2010 to August 2012	The influence of cooling set-point, heating set-point, and minimum volume flow rates of VAV on energy-saving of the HVAC system	EnergyPlus version 7.2 and the software JEPlus	Simulation and empirical corroboration	• It is estimated that with the increased cooling set-point, the average cooling energy and total HVAC energy could be saved by 29% and 27% respectively. • Wider set-point range can save energy consumption and satisfy comfort demand by personal controls.
Wang et al. (2013) [26]	The United States	Office	02/01/2010 to 02/28/2011 and 09/01/2011 to 02/28/2012	Temperature set-points, cooling coil stages, damper operation, and optimal start	Portfolio Manager, EnergyIQ, EnergyPlus	Monitoring-based commissioning	• An actual energy saving of 10% was realized through the process of ongoing commissioning.
Yamtraipat et al. (2006) [27]	Thailand	Office	N/A	Adjust room temperature set-point	N/A	Field investigation	• The overall electricity consumption saving would be 804.60 GWh/year, which would reduce the CO_2 by 579.31×10^3 tons/year.
Ghahramani et al. (2014) [28]	The United States	Office	From April 1 to June 20 and from October 1 to October 25 in 2013	The influential factors are indoor temperature, set-point temperature, airflow, outdoor temperature, and subjective thermal comfort vote	N/A	The human interaction for thermal comfort, fuzzy pattern recognition algorithm, Spearman's and Kendall's rank correlation coefficient, regression analysis, and optimization	• The proposed method saved the energy consumption and maintained the thermal comfort at the same time. • The proposed method was based on an optimization problem with a single objective function (i.e. set-point temperature).
Kim et al. (2017) [29]	The United States	Office, commercial building and factory	One week in different seasons	Anomaly detection for set-points and schedules of rooftop units (RTUs)	N/A	Low pass filter, Z-transform, peak detection algorithm, and Bayesian classifier	• The set-point detection and HVAC cycling algorithms were developed based on the peak detection technique, and they could detect the set-points and short cycling of RTUs accurately.
Moon and Han (2011) [30]	The United States	Residential	January 3 and 28, June 27 and July 8	The influence of setback period; set-point temperature; setback temperature on energy-saving of the HVAC system	eQUEST	Computer simulation	• There was large energy-saving potential in both cold and hot-humid climate zones by different thermostat strategies.

Table 2

Literature review on the real-time energy efficiency improvement by deploying the occupancy-based control of the HVAC system

Author	Area	Building	Time period	Objects	Time scale	Tools	Method	Main findings
Labeodan et al. (2016) [24]	Netherlands	Office	Three weeks	Energy saving for lighting system	N/A	Passive Infrared motion sensors and chair sensors	Experimental study	• Energy was saved by means of occupancy-driven lighting control.
Wang et al. (2018) [25]	Hong Kong	Multi-zone office	A regular weekday, a weekend day, and a holiday	CO_2 concentration and energy consumption	1 minute	Trnsys platform, Wi-Fi Probe devices, and overhead camera	Computer-based simulation	• Occupancy profile was obtained by the Wi-Fi probe technology, and it was used to determine proper outdoor air portions for multi-zone office. • The proposed method could save energy largely while sacrifice the IAQ slightly, which performs better than the traditional methods.
Manjarres et al. (2017) [31]	Spain	Office	63 days in summer and 46 days in winter	Save energy by optimal schedule operation of the HVAC ON/OFF and mechanical ventilation	1 hour	Python	The random forest (RF) regression techniques	• The HVAC ON/OFF and mechanical ventilation (MV) operation schedule could be predictively controlled based on 24-h ahead prediction of indoor temperature by RF regression techniques.
Moon and Kim (2016) [32]	South Korea	Hotel	From June 1st to September 30th in 2014	Reduce the cooling energy consumption and improve thermal comfort	1 min	TRNSYS and MATLAB software	ANN and simulation	• One ANN model predicted the cooling energy consumption needed to restore the indoor temperature to normal set-point temperature from the unoccupied period to occupied period. • Another ANN model predicted the time to restore indoor temperature to normal set-point temperature.
Yang and Becerik-Gerber (2014) [33]	The United States	Office	From January to April in 2013	Save energy by operating HVAC according to occupancy profile, and by rearranging occupants to different zones	3 minutes	OpenStudio	ARMA, NN, Markov chain, logit regression, bootstrapping-derivative method, k-means clustering, and simulation	• The occupancy-profile-based HVAC schedules could save 9% of energy. • Room reassignment was achieved by “P rule”, "S rule" and "C rule" in clustering process. • Further 8% energy was saved by coupling occupancy-profile-based control schedule with room reassignment.
Nagarathinam et al. (2017) [34]	Indian	Open-plan office	From 1 October in 2015 to 31 January in 2016	Thermal comfort (i.e., PPD) and energy consumption	1 and 15 minutes	N/A	Temperature and humidity prediction	• Considering the spatial variation of mean radiant temperature and occupancy, a model based predictive control was developed to regulate the dynamic temperature set-point via the PID controller.
						EnergyPlus and MLE+	Simulation	
						MATLAB	Optimization	
Nikdel et al. (2018) [35]	The United States	Office	N/A	The efficiency of occupancy-based HVAC controls in energy cost, fossil fuels consumption and gas emissions	N/A	EnergyPlus	Computer simulation	• The occupancy-based control performed effectively in energy cost, fossil fuels consumption and gas emissions, and the performance improvement varied across different climate zones and HVAC systems.

2. MATERIALS AND METHODS

2.1. Research framework

A complete process should be implemented for the dynamic energy performance management in buildings, such as a three-phase cyclic process (i.e. monitoring-diagnostic-intervention) [36]. Li et al. [37] has successfully applied the three-phase cyclic process concept (i.e. monitoring-diagnostic-intervention process) into the indoor environmental quality (IEQ) improvement by removing the excessive pollutants and by preventing the dew condensation on the diffuser of the HVAC system.

As shown in Fig. 1, this study also applied the three-phase cyclic process (i.e. monitoring-diagnostic-intervention) for achieving the energy efficiency improvement in meeting rooms by estimating the set-point temperature and by improving the effective utilization of the HVAC system in real time. Depending on the complexity of the analysis methods and control strategies, this study classified two aspects (i.e. basic and advanced in diagnostic and intervention phases). That is, the three phases were implemented as follows: (i) monitoring phase, real-time data collection; (ii) diagnostic phase, basic and advanced analyses; and (iii) intervention phase, basic and advanced control strategies.

- *(i) Monitoring phase (refer to section 2.2):* A real-time sensor network has been established to collect the real-time indoor environmental data. Temperature and CO_2 concentration, as indoor environmental indicators, were collected in this phase.
- *(ii) Diagnostic phase (refer to section 2.3):* Depending on the complexity of the analysis methods (e.g. the number of indicators, the way how it is considered, etc.), two kinds of analyses (i.e. basic and advanced analyses) were conducted. First, as explained in Section 2.3.1, the basic analysis was conducted by considering the only one environmental indicator (i.e. temperature). The set-point temperature of the HVAC system was estimated to judge whether it has been maintained within a proper range (for energy saving and thermal

comfort). Second, as illustrated in Section 2.3.2, the advanced analysis was conducted by considering two environmental indicators (i.e. temperature and CO_2 concentration). The effective utilization of the HVAC system was evaluated by investigating whether the HVAC system was turned off after occupants have left meeting rooms).

- *(iii) Intervention phase (refer to section 2.4):* Depending on the complexity of the control strategies (i.e. the number of indicators, the way how it is considered, etc.), two kinds of control strategies (i.e. basic and advanced controls) were developed. First, as explained in Section 2.4.1, the operational parameter (i.e. the set-point temperature of the HVAC system) was estimated to detect the possible equipment failure and to provide proper suggestions for energy saving and thermal comfort. Second, as illustrated in Section 2.4.2, the operational parameter (i.e. the shutdown of the HVAC system) was considered to avoid the unnecessary operation of the HVAC system when meeting rooms were not occupied; and thus, the effective utilization of the HVAC system could be achieved.

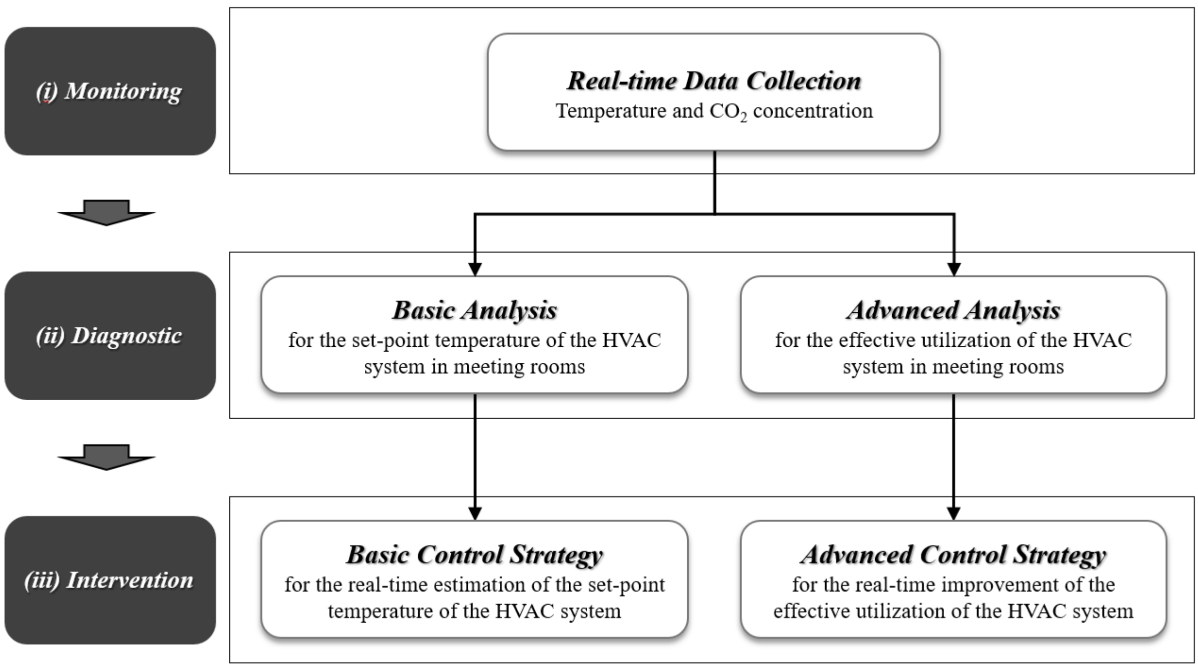

Fig. 1. Three-phase cyclic process for the energy efficiency improvement of the HVAC system in a meeting room

2.2. Monitoring phase: real-time data collection

The field measurement was conducted in Hong Kong (latitude: 22°15’ N; longitude: 114°15’ E) from 31 July through 30 September in 2017, which was a typical summer season for the cooling operation of the HVAC system. This study targeted two meeting rooms (i.e. a large meeting room and a small meeting room) in "A" office, in which the real-time environmental sensors (AWAIR) were installed. The staff members in "A" office have used these two meeting rooms for a cooperative work in an irregular manner.

The centralized HVAC system was operated in "A" office, and the control panel was located in each room for the individualized control by occupants. Accordingly, the set-point temperature and on/off condition of the HVAC system could be controlled in two ways (i.e. centralized control and individualized control). First, the on/off condition of the HVAC system could be generally controlled by the BEMS with a fixed operation schedule. Considering the nine-to-five working schedule, the HVAC system was preset to be automatically turned on at 7:00am and turned off at 23:00pm during working days, and to be stopped during holidays. On the other hand, occupants could turn on/off the HVAC system and adjust the set-point temperature of the HVAC system via the control panel depending on their preference.

The environmental sensors (AWAIR) can collect the environmental indicators (i.e. temperature, humidity, CO_2 concentration, volatile organic compounds (VOCs), and micro dust) in near real time. The sensor collects the environmental data in one-minute interval; but, the data are automatically calculated to the 15-minute averaged value and saved in a cloud server, from which users can download the dataset. According to the study by De Mauro et al. [38], a dataset that is characterized by high volume, high velocity and high variety can be defined as a "Big Data". The five kinds of indicators (i.e. temperature, humidity, CO_2 concentration, VOCs, and micro dust) in two meeting rooms were investigated with a large amount of dataset (i.e. every 15 minutes) in a nearly real-time resolution (i.e. every one minute) from 31 July through

30 September in 2017. Since it exactly corresponds to "High Volume", "High Velocity", and "High Variety", the real-time IEQ dataset collected by the environmental sensors (AWAIR) in this study can be defined as a "Big Data". It should be noted that two indicators (i.e. temperature and CO_2 concentration) were mainly investigated, and the other indicators (i.e. humidity, VOCs and micro dust) were briefly introduced in relevant sections. Table 3 shows the specifications of the environmental sensor (AWAIR), including time intervals, indicators, measurement ranges and uncertainties.

Table 3
Summary of the specifications of the environmental sensor (AWAIR)

Sensor	Time interval	Indicators	Measurement range and uncertainty
Environmental sensor (AWAIR)	one minute for data collection; 15 minutes for data download	Temperature	5-60 °C with the uncertainty of ±0.2 °C
		Humidity	20-80% with the uncertainty of ±2%
		CO_2	400-5000 ppm with the uncertainty of ±75 ppm
		VOCs[a]	Vary for individual gas
		Micro dust	N/A

Notes: [a] The sensor tests for a number of common VOCs, including carbon monoxide, ethanol, hydrogen, methane, ammonia and isobutene.

2.3. Diagnostic phase: basic and advanced analyses

Since the HVAC system is a major way to maintain a comfortable indoor environment in two meeting rooms of this study, the real-time dataset for the environmental indicators can be used to investigate the operation condition of the HVAC system, and the potential of the energy efficiency improvement of the HVAC system. Considering the complexity of analysis methods (e.g. the number of indicators, the way how it is considered, etc.), the diagnosis for the energy efficiency of the HVAC system was conducted in two ways: (i) "basic analysis" for the set-point temperature of the HVAC system in meeting rooms by utilizing temperature; and (ii) "advanced analysis" for the effective utilization of the HVAC system in meeting rooms by utilizing temperature and CO_2 concentration.

2.3.1. Basic analysis for the set-point temperature of the HVAC system in meeting rooms

The set-point temperature of the HVAC system can be adjusted by occupants through the control panel of the HVAC system. As a reference for occupants to determine the set-point temperature of the HVAC system, there are different regulations or standards in different climates [27]. According to the "Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places" [39] enacted by the government in Hong Kong, the excellent class of indoor temperature was defined within the range of 20–25.5 °C while the good class was defined with the fixed range of the upper limit at 25.5 °C. The Guidance Notes were mainly intended to create a thermally comfortable indoor environment (i.e. temperature and humidity). Meanwhile, the "Energy Saving Charter 2017" [40] launched by Environment Bureau in Hong Kong rather focused on the energy-saving issue. The Energy Saving Charter appealed to the business and community organizations for maintaining an averaged indoor temperature within the range of 24-26°C in Hong Kong during the summer season (i.e. from June to September).

By thoroughly considering the aforementioned regulation standards, four classes of indoor temperature (i.e. Class 1-Class 4, divided by 20 °C, 24 °C, and 25.5 °C) were established as shown in Table 4. Four ranges have different characteristics in terms of the energy saving and thermal comfort issues, which can be usefully applied to determine the set-point temperature of the HVAC system. The details can be explained by class as follows.

Table 4
Characteristics for energy saving and thermal comfort by class

Classification	Temperature range	Energy saving	Thermal comfort
Class 1	Higher than 25.5 °C	+[a]	-[b]
Class 2	24–25.5 °C	+[a]	+[a]
Class 3	20–24 °C	-[b]	+[a]
Class 4	Lower than 20 °C	-[b]	-[b]

Notes: [a] "+" means that when the indoor temperature is within the specific range of the class (i.e. Class 1-Class 4), it could be matched with the levels of the objectives (i.e. energy saving and thermal comfort). For example, if the indoor temperature is at 26 °C (which is higher than 25.5 °C, namely in Class 1), the energy saving could be achieved. In addition, [b] "-" means that *when the indoor temperature is within the specific range of the class (i.e. Class 1-Class 4), it could not be matched with the levels of the objectives (i.e., energy saving and thermal comfort). For example, if the indoor temperature is 26 °C (which is higher than 25.5 °C, namely in Class 1), occupants could not be satisfied with the indoor thermal comfort because the indoor temperature is too high.*

- *Class 1 (higher than 25.5 °C):* This class could contribute to the energy saving in accordance with the regulation standard [40], but the thermal comfort requirement could not be met with the regulation standard [39]. That is, the energy saving could be achieved by turning off the HVAC system in summer; however, the temperature could not be satisfied in terms of the thermal comfort. This is because the indoor temperature increases with the heat transfer from ambient environment; but, it could not be cooled by the HVAC system.
- *Class 2 (24–25.5 °C):* This class could meet the regulation standards set by the government in Hong Kong [39-40] in terms of both of the energy saving and thermal comfort issues. That is, the set-point temperature of the HVAC system should be adjusted within the range of 24–25.5 °C as a preferred standard to simultaneously achieve two objectives.
- *Class 3 (20–24 °C):* This class could meet the thermal comfort requirement set by the government in Hong Kong [39]; however, the more energy would be consumed to keep the indoor temperature within the range of 20–24 °C (Class 3) compared to that of 24–25.5 °C (Class 2). This class (Class 3) is especially necessary and meaningful for such occupants as children, elderly, and patients, who are very sensitive to the indoor temperature.
- *Class 4 (lower than 20 °C):* This class could meet neither the energy saving nor the thermal comfort issues in terms of the indoor temperature. If the indoor temperature was set within the range of this class, occupants would feel cold rather than cool, and other indoor environmental problems (e.g. condensation [37]) could happen. In other words, more energy could be consumed without obtaining occupant' satisfaction. Thus, the set-point temperature below 20 °C could be meaningless and should be avoided.

It is a time-consuming way to record all the values from the control panels of the HVAC system for investigating the set-point temperature of the HVAC system. In addition, the values displayed on the control panels could deviate from the actual value controlled by the HVAC system (i.e. performance gap) due to the equipment failure inside the HVAC system [41-43]. Moreover, the historical values of the set-point temperature of the HVAC system in two meeting rooms were not recorded. Thus, it is needed to apply an alternative and indirect way to estimate the set-point temperature by using the real-time indoor temperature (which were measured by the environmental sensors in two meeting rooms).

In contrast to the set-point temperature of HVAC system designated by occupants, a dead band could occur by the relevant properties of equipment or be preset by managers' rules of thumb. In the cooling operation of the HVAC system, the relationship between the set-point temperature and the dead band can be explained as follows: (i) if the indoor temperature reaches or exceeds the maximum temperature (which can be established at the set-point temperature plus a half of dead band), the HVAC system starts operating to cool the indoor air; (ii) if the indoor temperature reaches or is below the minimum temperature (which can be established at the set-point temperature minus a half of dead band), the HVAC system stops operating. In this way, the HVAC system would be intermittently operated to maintain the indoor temperature within the dead band around the set-point temperature (refer to the blue dotted area in Fig. 2); and accordingly, the indoor temperature could be fluctuated within the dead band. Thus, this study adopted an indirect way to calculate the averaged indoor temperature and regarded it as the set-point temperature of the HVAC system.

Meanwhile, the change point analysis (CPA) can be used to distinguish the different time periods by considering the set-point temperatures of the HVAC system. The CPA is a univariate statistical analysis technique, which can detect the points where the statistical properties of a sequence of data (e.g. time-series data) change [44]. The CPA has been applied in many fields, for example, the fault detection of operational performance in buildings [16], the estimation of occupancy conditions [45, 46], and the exchange rate regime analysis in finance [47]. Since the mean temperature, one of the statistical properties, was determined to be regarded as the set-point temperature of the HVAC system, the CPA model that analyzes the mean change could be applied in this study. The problem on the change point detection for distinguishing the different set-point temperatures of the HVAC system in a day can be described as follows.

The dataset on the indoor temperatures was collected in 15-minute interval by the environmental sensors, and the default operation schedules of the HVAC systems in two meeting rooms were automatically controlled from 7:00 through 23:00. Thus, the 64 datasets of the indoor temperatures between 7:00 to 23:00 were used as inputs for the CPA model. Let the time-series data of the indoor temperatures and the data for each sampling time (15-minute interval) denoted by T and T^i, respectively (where i=1, 2,…, 64). According to Equation (1), T was separated into different segments by considering the different change points (θ_1, θ_2,…, θ_j) [45]. The adjacent segments can be featured with various statistical properties, which was determined to be the mean value of the indoor temperatures for 15-minute interval in this study. There are lots of available algorithms for the CPA model, some of which are integrated into algorithm packages. In this study, the "changepoint" R package, which was developed by Killick and Eckley [48-51], was adopted for the CPA model. The function (i.e. "cpt.mean()") to identify the changes in mean values was chosen, in which the parameters were selected with the Schwartz information criterion (SIC) as a penalty and the power of the pruned exact linear time (PELT) as a method.

$$T = \begin{cases} T_1(i, w_1) + e_1(i), \ 1 \le i < \theta_1 \\ T_2(i, w_2) + e_2(i), \ \theta_1 < i < \theta_2 \\ \qquad \cdots \cdots \\ T_j(i, w_j) + e_j(i), \theta_{j-1} < i \le 64 \end{cases} \qquad \text{Eq.(1)}$$

where, $T_k(i,w_k)$ is the function to describe the statistical property of the k^{th} segment; i is the sampling time; w_k is the parameter vector; and $e_k(i)$ is the error term of the k^{th} segment, k=1, 2,…, j.

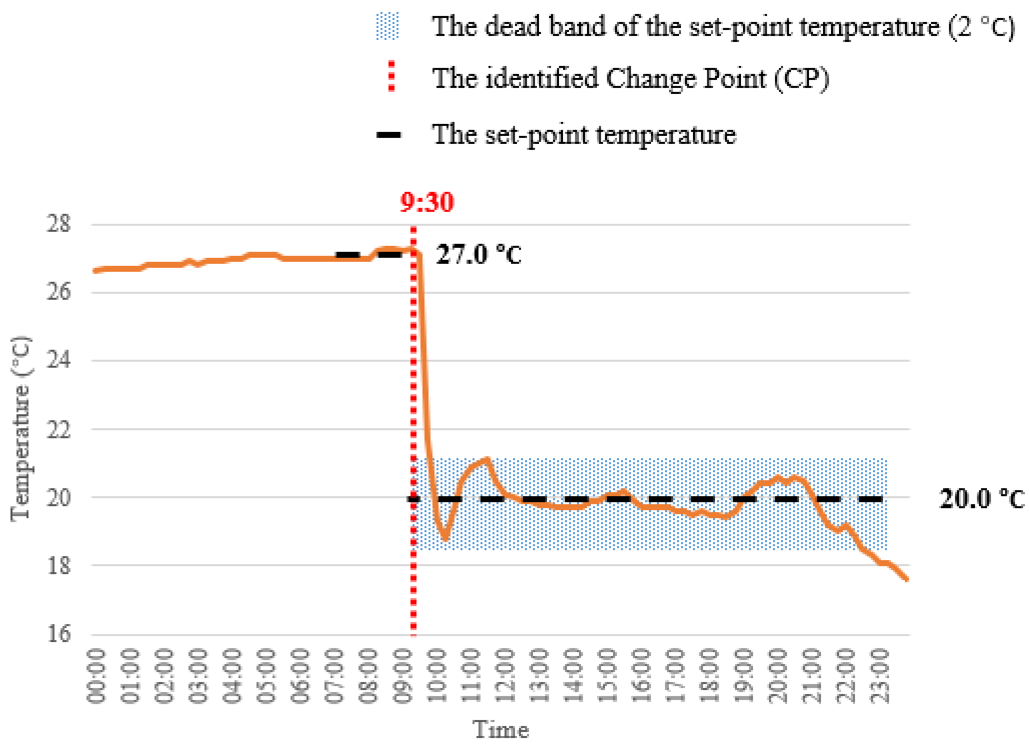

Fig. 2. Application of the CPA model for distinguishing the different set-point temperatures in the large meeting room (for the case of 15 August 2017)

Fig. 2 shows an example of the CPA model to distinguish the different set-point temperatures in the large meeting room on 15 August 2017. The datasets on the indoor temperatures collected in 15-minute interval between 7:00 to 23:00 were numbered in order from 1 to 64, and they were used as the inputs of the function "cpt.mean()" in the "changepoint" R package. After running the "R" programming language, the 11^{th} data (i.e. temperature at 9:30) was identified as the change point, which could be intuitively checked in Fig. 2. Thus, the dataset on the indoor temperatures between 7:00 to 23:00 were divided into two segments with different mean values (i.e. the averaged set-point temperature), which were 7:00-9:15 (the first segment) and 9:30-23:00 (the second segment). The mean value in the period of 7:00-9:15 (the first segment) and 9:30-23:00 (the second segment) were 27.13 °C and 20.00 °C, respectively (refer to the shaded area in Table 6). Since the set-point temperature of the HVAC system could be adjusted with the increment of 0.5 °C via its control panel, the calculated mean temperature should be rounded to the first decimal place with the value of 0 or 5. For example, the calculated mean temperature of 27.13 °C was rounded to 27.0 °C, and 20.00 °C was rounded to 20.0 °C. In this way, the change points of the set-point temperatures were determined by 9:30, indicating 27.0 °C between 7:00-9:15 (the first segment) and 20.0 °C between 9:30-23:00 (the second segment) (refer to Fig. 2 and the shaded area in Table 6).

The set-point temperature is a concept that can be applied to the premise where the HVAC system is operating. As explained earlier, there are four classes in terms of the indoor temperature by considering the regulation standards set by the government in Hong Kong. Assuming that if the indoor temperature lied in Class 1 (i.e. higher than 25.5 °C), the HVAC system could be inferred to have been turned off. If the indoor temperature lied in Class 3 (i.e. 20–24 °C), the level of thermal comfort for occupants could be satisfied; but, the potential of energy savings could be more increased. Therefore, in the example shown in Fig. 2, it could be inferred: (i) the HVAC system was not operated between 7:00-9:15 (the first segment); and (ii) the energy saving could be achieved if the set-point temperature between 9:30-23:00 (the second segment) would be increased to Class 2 (i.e. 24–25.5 °C) from Class 3 (i.e. 20–24 °C).

The CPA model was applied to each day during the whole measurement period (from 31 July through 30 September in 2017) for two meeting rooms. The detailed analysis results on the different set-point temperatures in small and large meeting rooms can be found in Tables 5-6. It should be noted that the abovementioned results were based on a set of specific parameters (i.e. SIC as a penalty and PELT as a method) in the function "cpt.mean()" of the "changepoint" R package. The sensitivity of the CPA model (i.e. the number of identified change points) can differ depending on the type of penalty and method. It is still an open question to select the appropriate penalty and method, and the CPA with the specific penalty and method can be generally validated by plotting the original data and identified change points. The intention of this study is to discover the possibility in applying the CPA model in the estimation of the set-point temperature rather than the optimization of the configuration in the function "cpt.mean()" of the "changepoint" R package, which could be further considered in the follow-up studies.

2.3.2. Advanced analysis for the effective utilization of the HVAC system in meeting rooms

Occupants can have an effect on the indoor environment in both ways: (i) passive way (e.g. heat generation, moisture generation, CO_2 emission, and pollutant emission); and (ii) active way (e.g. controlling electronic equipment) [52]. To remove these artificial impacts and to maintain a comfortable indoor environment, it is a reliable and essential way to operate the HVAC system in hot and humid regions, such as Hong Kong [53]. Accordingly, the indoor environmental indicators (e.g. temperature, humidity, CO_2 concentration, VOCs and micro dust) can be maintained within an appropriate comfortable range. However, considering the gap between the amount of influence from occupants and the capacity of the HVAC system, it is not easy to identify the exact cause of the change in the indicators. The main features of the indicators can be explained in terms of the HVAC system and occupancy as follows:

- *Temperature*: Compared to the capacity of the HVAC system in a cooling mode, the increase in the indoor temperature by occupants' activities would be a negligible amount. Thus, the variation of the indoor temperature can be used as a proxy indicator to judge whether the HVAC system would be operated. That is, if the indoor temperature would continuously decrease or be kept at a low level for over a certain time, it could be judged that the HVAC system would be operated; otherwise, it would be turned off.

- *Humidity*: The HVAC system of this study has a limited dehumidification capacity; and the moisture generated from occupants' activities would not be significant in office buildings. That is, the variation of the indoor humidity would not be significantly affected by the operation of the HVAC system nor occupants' activities. Thus, it is not feasible to refer the variation of the indoor humidity as a proxy indicator in judging whether the HVAC system would be operated or whether the meeting room would be occupied by person.
- *CO_2 concentration*: When a meeting room is occupied by person, the CO_2 concentration would generally increase due to the metabolic process [45, 54-56]. Even if the mechanical ventilation of the HVAC system would be operated to bring a certain amount of fresh air, the CO_2 emissions from occupants could evidently contribute to the increase in the CO_2 concentration [57, 58]. Thus, the CO_2 concentration can be used as a proxy indicator to judge whether the meeting room would be occupied by person.
- *Other pollutants (e.g. VOCs and micro dust):* On one hand, the occupant-related activities could cause the increase in the concentration of indoor air pollutants, such as VOCs and micro dust [59-62]. On the other hand, the concentration could considerably depend on the ventilation capacity of the HVAC system [63-65]. However, it is very difficult to identify the relative significance for the indoor air pollutants between the operation of the HVAC system and occupants' activities. That is, the concentration of VOCs and micro dust could move in different ways (increase or decrease) when the operation of the HVAC system and occupants' activities would simultaneously occur. For example, some of the occupants' activities (e.g. spraying air freshener and cleaning a personal desk) could cause the increase in the concentration of indoor air pollutants despite the operation of the HVAC system. In this regard, it is not feasible to refer the concentration of indoor air pollutants as a proxy indicator in judging whether the HVAC system would be operated or whether the meeting room would be occupied by person.

In this point of view, this study adopted two indicators for the advanced analysis as follows: (i) temperature to judge whether the HVAC system would be operated and (ii) CO_2 concentration to judge whether the meeting room would be occupied by person.

- *Temperature*: If the indoor temperature would decrease for more than 30 minutes or be kept at lower than 25.5 °C (which is the upper limit of excellent class and good class for the indoor temperature in guidance notes [39]), the HVAC system of a meeting room would be judged as being operated; otherwise, it would be judged as being turned off. Accordingly, it is possible to exclude the occasional fluctuation caused by disturbance. For example, although the HVAC system in a meeting room would be turned off, the indoor temperature could decrease for over a certain time (but shorter than 30 minutes) by letting the cooled air from other rooms transferred through the opened door of the meeting room.
- *CO_2 concentration*: If the CO_2 concentration would increase for more than 30 minutes, occupants would be regarded to have come into a meeting room (i.e. a meeting has been started). Meanwhile, if the CO_2 concentration would decrease for more than 30 minutes, occupants would be regarded to have left a meeting room (i.e. a meeting has been finished). In this regard, it is possible to exclude the occasional fluctuation caused by disturbance. For example, emptying the trash can could have an effect on the increase in the CO_2 concentration for over a certain time (but shorter than 30 minutes).

By considering the real-time data of indoor temperature and CO_2 concentration simultaneously, it is possible to evaluate the effective utilization of the HVAC system in a meeting room. If the HVAC system would operate during a meeting, it would be regarded as meaningful to maintain a comfortable indoor environment for occupants, indicating that the HVAC system would be effectively operated. Otherwise, it should be judged that the HVAC system would not be properly operated, indicating that the potential of the energy efficiency improvement of the HVAC system in a meeting room could be found.

Fig. 3 shows the real-time data on indoor temperature and CO_2 concentration in the large meeting room on 25 September 2017, with which the evaluation process could be illustrated.

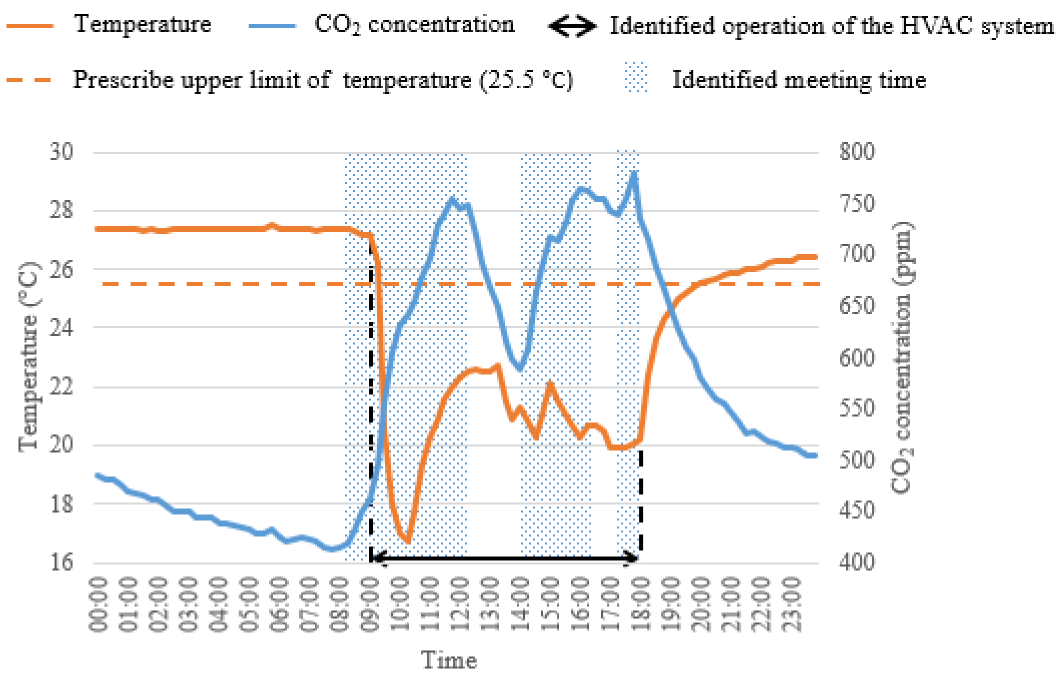

Fig. 3. The real-time data on indoor temperature and CO_2 concentration in the large meeting room (for the case of 25 September 2017)

- *Operation duration of the HVAC system (ODH)*: It can be calculated by considering the variation of indoor temperature as a proxy indicator (refer to the orange-colored solid line in Fig. 3). The indoor temperature started to decrease for more than 30 minutes since 9:00 am, and it has been kept below 22.5 °C until 10:00 am. Then, it started to increase for more than 30 minutes since 10:00 am; but it has been kept below 22.5 °C until 13:00 pm. Then, it started to decrease for more than 30 minutes since 13:00 pm, and it has been kept below 22.5 °C until 18:00 pm. Then, it started to increase since 18:00 pm. As a result, the HVAC system could be identified as being operated from 9:00 am through 18:00 pm (refer to the black-colored solid arrow line in Fig. 3), and the *ODH* is calculated as 9.0 hours.
- *Duration of meeting (DM)*: It can be calculated by considering the variation of the CO_2 concentration as a proxy indicator (refer to the blue-colored solid line in Fig. 3). As shown

in the blue-colored shared area of Fig. 3, three meetings were held in the meeting room: (i) 8:00 am - 12:00 pm; (ii) 14:00 pm - 16:00 pm; and (iii) 17:30 pm - 18:00 pm. The aim of the evaluation process is to analyze the effective utilization for the HVAC system, indicating whether the HVAC system was operated during meetings. Accordingly, the only meeting time when the HVAC system was being operated in a cooling mode was considered. Thus, the meeting times to be used for calculating duration of meeting (*DM*) were updated as first meeting from 9:00 am to 12:00 pm (3 hours), the second meeting from 14:00 pm to 16:00 pm (2 hours), and the third meeting from 17:30 pm to 18:00 pm (0.5 hours). The total *DM* of three meetings can be calculated at 5.5 hours (= 3 hours+ 2 hours+ 0.5 hours).

- *Effective utilization ratio of the HVAC system (EURH)*: It can be calculated by referring the *ODH* and *DM* (refer to Equation (2)). The less the *EURH* would be, the more energy would be wasted (i.e. larger potential of the energy efficiency improvement of the HVAC system). If the *EURH* would be at 100%, the HVAC system would be regarded to be operated only at meetings, indicating that it would be most effectively operated without any waste. Based on two values (i.e. *ODH* and *DM*), the *EURH* can be calculated at 61.11% (= 5.5 hours / 9.0 hours) (refer to the shaded area in Table 8).
- *Accumulated effective utilization ratio of the HVAC system (AEURH)*: It can be calculated from a macro perspective (refer to Equation (3)). By accumulating the values of the *ODH* and *DM*, the accumulated operation duration of the HVAC system *(AODH)* and the accumulated duration of meeting *(ADM)* can be obtained, with which the *AEURH* can be calculated at 40.29% (= 213.25 hours / 529.25 hours) (refer to Table 8). As a result, it can be said to have the large potential of the energy efficiency improvement of the HVAC system in the large meeting room (i.e. 59.71%).

The more detailed results on the effective utilization of the HVAC system in the small and large meeting rooms can be found in Tables 7-8.

$$EURH = \frac{DM}{ODH} \quad (2)$$

$$AEURH = \frac{ADM}{AODH} \quad (3)$$

where, *EURH* is the effective utilization ratio of the HVAC system (%); *ODH* is the operation duration of the HVAC system (hour); *DM* is the duration of meeting (hour); *AEURH* is the accumulated effective utilization ratio of the HVAC system (%); *AODH* is the accumulated operation duration of the HVAC system (hour); and *ADM* is the accumulated duration of meeting (hour).

2.4. Intervention phase: basic and advanced control strategies

2.4.1. Basic control strategy for estimating the set-point temperature of the HVAC system

The real-time estimation of the set-point temperature of the HVAC system can be realized by applying a series of process how the HVAC system could maintain the indoor temperature within a certain range considering the set-point temperature and dead band. As explained in Section 2.3.1, the function "cpt.mean()" in the "changepoint" R package was used to estimate the set-point temperature of the HVAC system. On one hand, in case of reaching a lower set-point temperature, the indoor temperature would first decrease to the minimum limit of the corresponding set-point temperature (T_{min}), and then fluctuate within a certain range between "T_{min}" and "T_{min} plus dead band". Thus, the basic concept for the real-time estimation of the lower set-point temperature of the HVAC system is to identify "T_{min}" and a certain temperature that lies between "T_{min}" and "T_{min} plus dead band" so that the mean temperature could be calculated. On the other hand, in case of reaching a higher set-point temperature, the indoor temperature would first increase to the maximum limit of the corresponding set-point temperature (T_{max}), and then fluctuate within a certain range between "T_{max}" and "T_{max} minus dead band". Thus, the basic concept for the real-time estimation of the higher set-point temperature of the HVAC system is to identify "T_{max}" and a certain temperature that lies between "T_{max}" and "T_{max} minus dead band" so that the mean temperature could be calculated.

In this regard, a real-time control strategy for the estimation of the set-point temperature of the HVAC system can be developed, which can be used for: (i) detecting the potential failures in the HVAC system and (ii) providing feedbacks on the adjustment of the set-point temperature within the preferred range (i.e. Class 2, 24–25.5 °C) if necessary.

2.4.2. Advanced control strategy for improving the effective utilization of the HVAC system

There would be significant energy-saving potential if the concept of the occupancy-based control strategy could be implemented to the HVAC system in meeting rooms. There are four types of the occupancy-based controls (i.e. reactive control to occupancy in real time, control to occupants' preference, control to occupants' behaviors, and predictive control based on the future occupancy) [66]. For the meeting rooms with irregular occupancy schedule, it would be so hard to pre-set the operation schedule of the HVAC system. Thus, the predictive control would not be applicable for the HVAC system in meeting rooms. In addition, based on the results of the advanced analysis (for the effective utilization of the HVAC system in meeting rooms, refer to Section 2.3.2), the meeting attendees would seldom turn off the HVAC system after meeting, indicating that it would be unreliable to turn on/off the HVAC system manually.

In this regard, the real-time occupancy-based control strategy for the HVAC system in meeting rooms would be a promising way. According to the Equations (2)-(3), the *AEURH* and *EURH* are in proportion to the *ADM* and *DM*; but in inversely proportion to the *AODH* and *ODH*. Since the *ADM* and *DM* would be hard to predict and control, the *AODH* and *ODH* were selected as target parameters that should be carefully controlled. In other words, the HVAC system should be properly operated only in the meeting periods and be turned off when no occupants would be there. In this way, the *AEURH* and *EURH* could be optimized to the value of 100% (i.e. complete effective utilization of the HVAC system in meeting rooms).

In short, the proposed occupancy-based control strategy would be a reactive control strategy, which responds to the absence of occupants in real time in accordance with the variation of the CO_2 concentration. Further, it could consider the occupants' preference and behaviors, since it would be promised for the HVAC system to be operated during meetings.

3. RESULTS AND DISCUSSION

This study conducted the three-phase cyclic process (i.e. monitoring-diagnostic-intervention) to analyze the potential of the energy efficiency improvement of the HVAC system in meeting rooms by deploying the real-time indoor environmental indicators (i.e. temperature and CO_2 concentration). The detailed analyses were conducted and the relevant control strategies were developed in two ways: (i) basic approach: the set-point temperature of the HVAC system and (ii) advanced approach: the effective utilization of the HVAC system.

3.1. Basic analysis and control for the set-point temperature of the HVAC system

3.1.1. Basic analysis for the set-point temperature of the HVAC system in meeting rooms

Fig. 4 shows the distribution of the indoor temperature in two meeting rooms in accordance with four classes set by the regulation standards in Hong Kong [39-40]. As explained in Table 4, four classes have different characteristics in terms of energy saving and thermal comfort, with which the distribution of the indoor temperature can be analysed in detail as follows.

- *Class 1 (higher than 25.5 °C):* The proportions were determined at 30.46% for the small meeting room and 33.50% for the large meeting room, in which thermal comfort should be taken care of if the rooms would be occupied. Otherwise, it is needed to adopt an automatic control strategy to turn of the HVAC system in a more timely manner when the rooms would not be occupied.

- *Class 2 (24–25.5 °C):* The smallest proportions were determined at 17.08% for the small meeting room and 6.87% for the large meeting room, indicating that it would be possible to simultaneously achieve both of energy saving and thermal comfort.
- *Class 3 (20–24 °C):* The largest proportions were determined at 47.10% for the small meeting room and 41.34% for the large meeting room, in which there would be huge potential for energy saving if the indoor temperature could be adjusted within the range of Class 2 (i.e. 24-25.5 °C), especially to the upper limit of Class 2 (i.e. 25.5 °C). In addition, in this class, thermal comfort would still be satisfied.
- *Class 4 (lower than 20 °C):* The proportions were determined at 5.36% for the small meeting room and 18.29% for the large meeting room, indicating that the set-point temperature would be set at too low, especially with the large meeting room overcooled. This class should be entirely avoided because of uncomfortable cold feeling, energy waste, and potential dew condensation.

Based on these analyses, it can be concluded that the indoor temperature should be properly controlled within the prescribed range so that both of energy saving and thermal comfort could be achieved. To do so, it is necessary to firstly understand the current status of the set-point temperature of the HVAC system. As explained in Section 2.3.1, this study adopted the CPA, as an alternative way to estimate the set-point temperature of the HVAC system, so as to distinguish the different set-point temperatures in two meeting rooms.Tables 5-6 shows the estimated set-point temperature of the HVAC system within the range of 19.5-27.5 °C for the small meeting room and 17.5-29.0 °C for the large meeting room. Fig. 5 shows the frequency of the estimated set-point temperature of the HVAC system in two meeting rooms. The median value of the set-point temperature (refer to the black-colored dot line in Fig. 5) was calculated to clearly evaluate the skewness of the distribution. They were determined at 22.0 °C and 21.0 °C (which belonged to Class 3; 20–24 °C) for the small and large meeting rooms, respectively. It indicated that occupants tended to designate the lower set-point temperatures for cooler indoor environment and they would neglect the energy-saving aspect in two rooms.

Therefore, it is required to achieve the energy savings by deploying a real-time automatic control process, which could estimate the set-point temperature of the HVAC system and adjust it to Class 2 (24–25.5 °C, especially to the upper limit of 25.5 °C) in a timely manner.

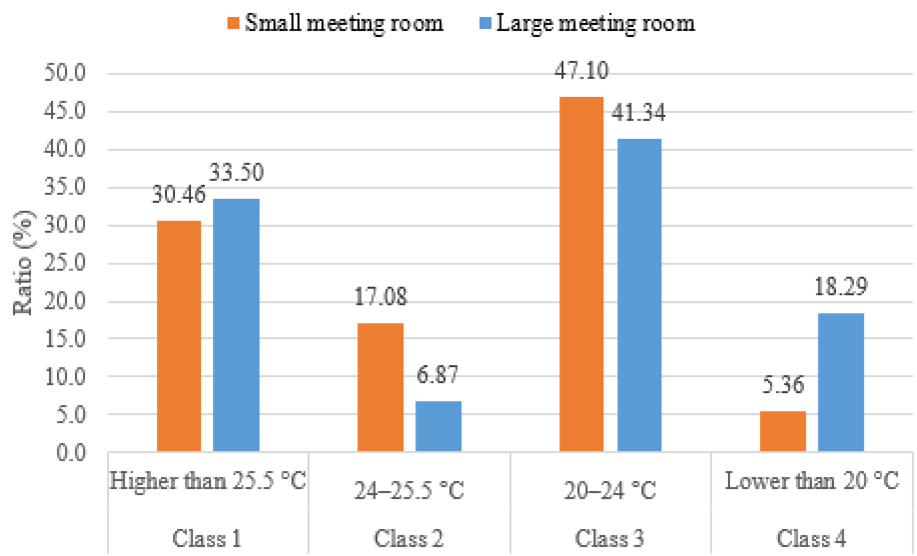

Fig. 4. Distribution of the indoor temperature by four classes in two meeting rooms

Table 5. "Basic analysis" for the set-point temperature of the HVAC system by the CPA in the small meeting room

Date	The time period	The mean indoor temperature	The estimated set-point temperature
Jul.31st	7:00-9:30	27.35	27.5
	9:45-12:00	24.71	24.5
	12:15-14:30	19.30	19.5
	14:45-22:45	21.23	21.0
Aug.1st	7:00-22:45	21.41	21.5
Aug.2nd	7:00-22:45	21.92	22.0
Aug.3rd	7:00-8:00	20.54	20.5
	8:15-22:45	22.24	22.0
Aug.4th	7:00-22:45	22.03	22.0
Aug.8th	7:00-22:45	21.74	21.5
Aug.9th	7:00-22:45	21.85	22.0
Aug.10th	7:00-22:45	21.83	22.0
Aug.11th	7:00-15:00	21.15	21.0
	15:15-22:45	24.61	24.5
Aug.28th	7:00-9:00	25.6	25.5
	9:15-22:45	23.77	24.0
Aug.29th	7:00-22:45	24.41	24.5
Aug.30th	7:00-22:45	25.28	25.5
Aug.31st	7:00-14:30	25.77	26.0
	15:45-17:30	23.31	23.5
	17:45-21:45	20.9	21.0
	22:00-22:45	22.88	23.0
Sep.1st	7:00-15:30	26.22	26.0
	15:45-18:15	22.07	22.0
	18:30-22:45	24.39	24.5
Sep.27th	7:00-10:00	26.18	26.0
	10:15-12:30	20.55	20.5
	12:45-22:45	24.54	24.5

Table 6. "Basic analysis" for the set-point temperature of the HVAC system by the CPA in the large meeting room

Date	The time period	The mean indoor temperature	The estimated set-point temperature
Jul.31st	7:00-8:30	28.80	29.0
	8:45-18:45	20.99	21.0
	19:00-22:45	26.26	26.5
Aug.1st	7:00-8:30	27.74	27.5
	8:45-10:45	20.08	20.0
	11:00-11:30	21.87	22.0
	11:45-22:45	19.96	20.0
Aug.2nd	7:00-9:30	18.75	19.0
	9:45-12:15	20.41	20.5
	12:30-22:45	25.92	26.0
Aug.3rd	7:00-9:30	26.89	27.0
	9:45-11:00	19.67	19.5
	11:15-11:45	21.63	21.5
	12:00-22:45	20.73	20.5
Aug.4th	7:00-9:15	20.47	20.5
	9:30-22:45	19.03	19.0
Aug.7th	7:00-10:15	18.66	18.5
	10:30-22:45	20.82	21.0
Aug.8th	7:00-22:45	20.71	20.5
Aug.9th	7:00-11:15	20.70	20.5
	11:30-13:15	22.44	22.5
	13:30-22:45	26.48	26.5
Aug.10th	7:00-8:30	27.19	27.0
	8:45-22:45	24.13	24.0
Aug.11th	7:00-21:15	23.26	23.5
	21:30-22:45	20.60	20.5
Aug.14th	7:00-14:00	20.32	20.5
	14:15-18:30	21.77	22.0
	18:45-22:45	25.79	26.0
Aug.15th	7:00-9:15	27.13	27.0
	9:30-22:45	20.00	20.0
Aug.16th	7:00-9:15	18.67	18.5
	9:30-11:00	21.20	21.0
	11:15-14:15	24.82	25.0
	14:30-22:45	20.81	21.0
Aug.17th	7:00-9:15	20.60	20.5
	9:30-10:30	18.64	18.5
	10:45-22:45	21.88	22.0
Aug.18th	7:00-14:15	21.03	21.0
	14:30-15:30	18.76	19.0
	15:45-22:45	22.79	23.0
Aug.21st	7:00-19:00	22.89	23.0
	19:15-22:45	20.99	21.0
Aug.22nd	7:00-9:45	20.53	20.5
	10:00-22:45	22.39	22.5
Aug.23rd	7:00-22:45	22.46	22.5
Aug.24th	7:00-22:45	22.29	22.5
Aug.25th	7:00-22:45	21.82	22.0
Aug.28th	7:00-10:30	18.63	18.5
	10:45-22:45	20.31	20.5
Aug.29th	7:00-7:45	19.90	20.0
	8:00-11:30	23.17	23.0
	11:45-22:45	25.21	25.0
Aug.30th	7:00-11:45	26.36	26.5
	12:00-17:30	22.15	22.0
	17:45-22:45	25.58	25.5

Table 6. "Basic analysis" for the set-point temperature of the HVAC system by the CPA in the large meeting room (continued)

Date	The time period	The mean indoor temperature	The estimated set-point temperature
Sep.1st	7:00-9:30	27.08	27.0
	9:45-10:45	23.16	23.0
	11:00-22:45	26.41	26.5
Sep.4th	7:00-8:45	27.08	27.0
	9:00-22:45	22.16	22.0
Sep.5th	7:00-22:45	22.16	22.0
Sep.6th	7:00-14:15	22.09	22.0
	14:30-22:45	19.39	19.5
Sep.7th	7:00-10:45	19.77	20.0
	11:00-17:15	22.54	22.5
	17:30-20:30	19.53	19.5
	20:45-22:45	23.79	24.0
Sep.8th	7:00-9:15	26.07	26.0
	9:30-16:00	20.78	21.0
	16:15-17:45	22.64	22.5
	18:00-22:45	25.20	25.0
Sep.11th	7:00-12:45	27.14	27.0
	13:00-13:45	19.58	19.5
	14:00-14:45	21.63	21.5
	15:00-22:45	26.35	26.5
Sep.12th	7:00-15:00	27.69	27.5
	15:15-18:45	19.01	19.0
	19:00-19:45	21.80	22.0
	20:00-22:45	25.58	25.5
Sep.13th	7:00-22:45	26.90	27.0
Sep.18th	7:00-9:00	24.48	24.5
	9:15-22:45	18.48	18.5
Sep.19th	7:00-13:00	17.65	17.5
	13:15-15:45	22.97	23.0
	16:00-22:45	25.66	25.5
Sep.20th	7:00-13:00	27.01	27.0
	13:15-16:45	19.29	19.5
	17:00-20:30	20.63	20.5
	20:45-22:45	18.83	19.0
Sep.21st	7:00-11:15	19.09	19.0
	11:30-16:00	25.04	25.0
	16:15-18:15	20.78	21.0
	18:30-22:45	25.14	25.0
Sep.22nd	7:00-9:30	26.54	26.5
	9:45-10:30	20.03	20.0
	10:45-15:45	25.17	25.0
	16:00-17:00	19.94	20.0
	17:15-18:15	21.22	21.0
	18:30-22:45	25.29	25.5
Sep.25th	7:00-9:00	27.34	27.5
	9:15-10:30	19.37	19.5
	10:45-18:00	21.08	21.0
	18:15-22:45	25.36	25.5
Sep.26th	7:00-9:00	27.00	27.0
	9:15-17:45	21.47	21.5
	18:00-22:45	25.43	25.5
Sep.27th	7:00-9:00	26.90	27.0
	9:15-18:00	20.05	20.0
	18:15-22:45	25.59	25.5
Sep.28th	7:00-10:15	27.40	27.5
	10:30-11:00	22.03	22.0
	11:15-16:15	25.97	26.0
	16:30-22:45	20.20	20.0

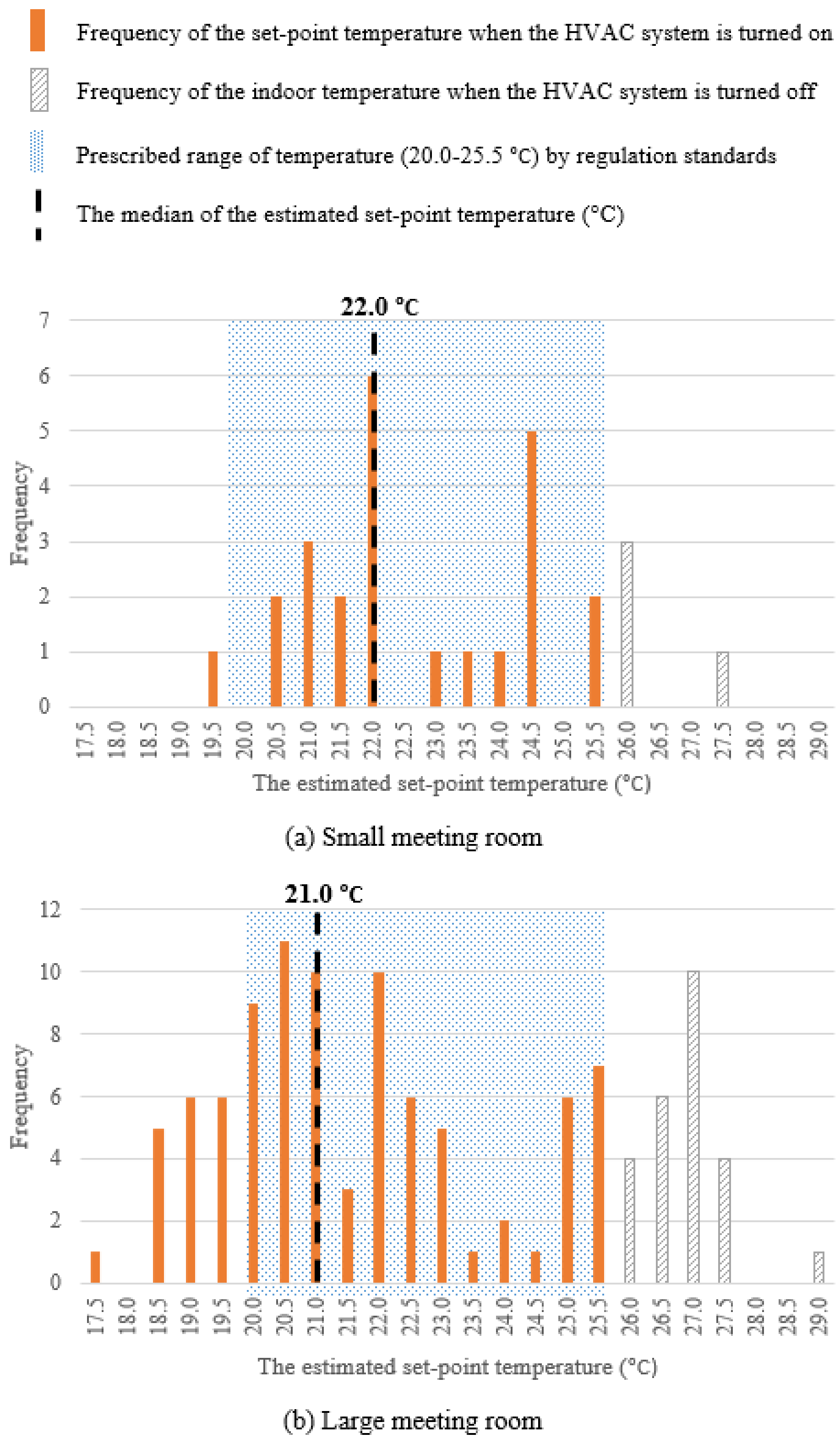

Fig. 5. Frequency of the estimated set-point temperature in two meeting rooms

3.1.2. Basic control strategy for estimating the set-point temperature of the HVAC system

Fig. 6 shows a logic-based event-driven flowchart for estimating the set-point temperature of the HVAC system in real time, which can be used for (i) anomaly detection of the HVAC system and (ii) suggestion of the adjustment of the set-point temperature to the preferred range (e.g. Class 2 of 24–25.5 °C). A basic control strategy was developed in five steps: (i) judgement of whether the set-point temperature decrease; (ii-1/ii-2) calculation of the mean value of the indoor temperature; (iii) estimation of the set-point temperature; (iv) anomaly detection of the HVAC system; and (v) suggestion of the adjustment of the set-point temperature.

- *(i) Judgement of whether the set-point temperature decreases:* If the data collected at the first sampling time ($T^{(1)}$) is lower than that collected at the initial sampling time ($T^{(0)}$), it indicates that the indoor temperature has decreased for the last 15 minutes. Accordingly, the set-point temperature of the HVAC system could be regarded to being decreased to a lower value, and the step (ii-1) will be followed to estimate the set-point temperature in real time. Otherwise, the set-point temperature of the HVAC system could be regarded to being increased to a higher value, and the step (ii-2) will be followed.
- *(ii-1/ii-2) Calculation of the mean value of the indoor temperature:* Depending on the judgement in step (i), the way how the set-point temperature is estimated could be determined. The step (ii-1) is used to explain the process in detail as an example. As explained in Section 2.4.1, the basic concept of step (ii-1) is to identify "T_{min}" and to calculate the mean value of temperatures that lie between "T_{min}" and "T_{min} plus dead band". First, $T^{(1)}$ is initially set as "T_{min}". As the sampling time increases, "T_{min}" will be replaced repeatedly by the temperatures lower than "T_{min}" (i.e. "T_{min} candidates"). As shown in Fig.2, the dead band of the HVAC system in this study was determined at 2 °C; and thus, the temperature between "T_{min}" and "T_{min} + 2 °C" will be considered to calculate the mean value ("T_m"). In the process, "*i*" is the cycle counter to count the sampling times; "*j*" is the

cycle counter to count the number of stabilized data between "T_{min}" and "T_{min} + 2 °C"; and "*k*" is the cycle counter to count the number of "T_{min} candidate". It should be noted that "T_{min}" could be determined in a cyclic process, in which the equality between i and k is used for evaluating whether to proceed to the next process. In other words, if the data collected in the current sampling time would be lower than "T_{min}" after the stabilization period of the indoor temperature (i.e. between "T_{min}" and "T_{min} + 2 °C"), it would replace "T_{min}" but not be treated as "T_{min} candidate". This is because the indoor temperature should decrease to "T_{min}" directly after establishing the set-point temperature; and then, it would fluctuate within the dead band. As for the step (ii-2), the basic concept is also to identify "T_{max}" and to calculate the mean value of temperatures that lie between "T_{max}" and "T_{max} minus dead band". And the following process are very equal to step (ii-1).

- *(iii) Estimation of the set-point temperature:* If the number of stabilized data ("*j*") is no less than 2, it indicates that the indoor temperature has been within the dead band (i.e., stabilized change) for at least 30 minutes. In this case, the mean value ("T_m"), rounded to the first decimal place with the value of 0 or 5, would be regarded as the estimated set-point temperature of the HVAC system ("T_{Es}").
- *(iv) Anomaly detection of the HVAC system:* The estimated set-point temperature ("T_{Es}") could be compared with the designated set-point temperature displayed on control panel ("T_s"). If the difference between "T_{Es}" and "T_s" would be within a certain level (e.g. 0.5 °C), the HVAC system could be considered to be operated in a normal condition. Otherwise, it could be assumed to have the equipment failures (e.g. bias of the measured data in a sensor, or signal errors) inside the HVAC system. In this case, it would be recommended to check and calibrate the working condition of the HVAC system to occupants for their reference.
- *(v) Suggestion of the adjustment of the set-point temperature:* If The estimated set-point temperature ("T_{Es}") would be below a certain range (e.g. Class 2 of 24–25.5 °C), it would

be recommended to adjust the set-point temperature within the range of 24–25.5 °C to occupants for their reference.

To further improve the real-time automatic control strategy for the estimation of the set-point temperature of the HVAC system, it is suggested to consider three aspects in the follow-up studies. First, the four classes were established based on two regulations set by the government in Hong Kong [39-40]. For more comprehensive classes, it is needed to consider the subjective perception of occupants and the adaptability to other districts in future studies. Second, it is required to determine the threshold level of the number of stabilized data ("*j*") in step (iii), and the threshold level of difference between "T_{Es}" and "T_s" in step (iv) by considering the project characteristics and the relevant properties in future studies. Third, an on-line CPA model could be used in developing a real-time control strategy for the estimation of the set-point temperature of the HVAC system in future studies.

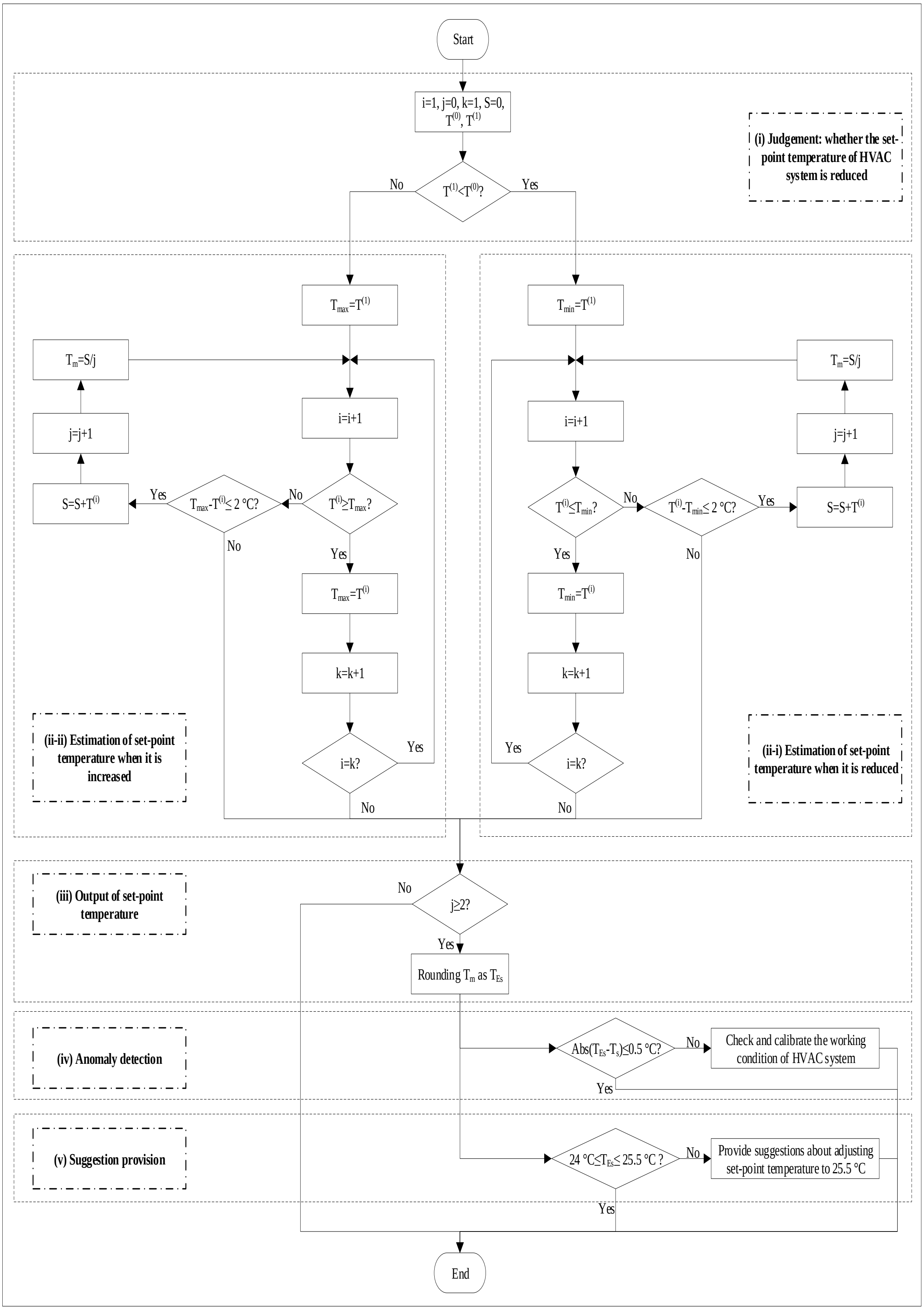

Fig. 6. A logic-based event-driven flowchart for estimating the set-point temperature of the HVAC system in real time

3.2. Advanced analysis and control for the effective utilization of the HVAC system

3.2.1. Advanced analysis for the effective utilization of the HVAC system in meeting rooms

As mentioned in Section 2.3.2, temperature and CO_2 concentration were used as proxy indicators to judge whether the HVAC system would be operated and whether the meeting room would be occupied by person, respectively. Accordingly, without referring to the historical information provided by office managers, it is possible to infer the operation duration of the HVAC system (ODH) and the duration of meeting (DM) in meeting rooms.

Tables 7-8 show the "advanced analysis" for the effective utilization of the HVAC system in two meeting rooms. Considering the HVAC system automatically operated by the BEMS (refer to Section 2.2), the shutdown periods (i.e. from 23:00 pm to 7:00 am in working days as well as the whole day in holidays) were not included in calculating the *ODH* (refer to the third column in Tables 7-8). For example, the HVAC system in the large meeting room would start to operate at 8:30 am on 1 August, and it would be kept operating despite no meeting until the automatic shutdown by the BEMS at 23:00 pm in the same day. Then, the HVAC system would be turned on automatically by the BEMS at 7:00 am in 2 August, and it would be kept despite no meeting until the manual turn-off at 14:15 pm in 2 August (refer to the shaded area of Table 8). As a result, the *ODH* of this example was determined at 21.75 hours, which was summed up by 14.5 hours (from 8:30 am to 23:00 pm) and 7.25 hours (from 7:00 am to 14:15 pm).

The results can be described in detail from the different perspectives as follows:

First, on the macro level, even if the *AEURH* would be determined at a very small value, it could be expected to have the large potential of the energy efficiency improvement of the HVAC system in two meeting rooms. In other words, the *ADM* and *AODH* were determined at 99.75 and 220.25 hours for the small meeting room and at 214.25 and 531.5 hours for the large meeting room. The large difference between the *ADM* and *AODH* in two meeting rooms indicates that the operation of the HVAC system would not be properly matched with the meeting schedule. In addition, the *AEURH* was determined at 45.29% for the small meeting room and at 40.29% for the large meeting room. For the small meeting room, it means that the amount of energy consumed by the HVAC system would be suitably used at a level of 45.29% to provide meeting attendees with a comfortable indoor temperature, while other 54.71% of the energy consumption in a cooling mode would be wasted in an unoccupied room. For the large meeting room, only 40.29% of the cooling energy supplied by the HVAC system would be meaningful, and 59.71% could be potentially saved.

Second, on the micro level, the results indicate that the two meeting rooms would be irregularly occupied. Also, the HVAC system would not be timely controlled before and after the meeting, which led to energy waste. The detailed results were explained as follows.

- *The meeting schedule:* Compared to other office rooms which were regularly occupied by staffs in a normal nine-to-five working mode, two meeting rooms would be irregularly occupied. Thus, it would be very difficult to define the meeting schedule and to set up the designated operation schedule of the HVAC system in advance.
- *The operation of the HVAC system in meeting rooms*: Since the preset of the designated operation schedule is impractical, the HVAC system in two meeting rooms is generally controlled in a manual mode. However, the operation duration of the HVAC system often significantly exceeded the meeting duration, indicating that a large amount of cooling energy had been wasted. As shown in Tables 7-8, the *DM* doesn't equal to the *ODH* (i.e. *EURH* were determined at 100%, refer to Equation (2)), meaning that the HVAC system would be operated only during the meeting time. By contrast, in almost all cases, the *DM* was evidently smaller than the *ODH*, of which ratio (i.e. *EURH*) was ranged between 16.00-58.62% for the small meeting room and 26.79-66.67% for the large meeting room. It means that the meeting attendees would forget turning off the HVAC system and make it continue to work for a long period. As a result, it could be mentioned that 41.38-84.00% and 33.33-

73.21% of energy consumption by the HVAC system would be wasted in the small and large meeting rooms despite no person in there.

In conclusion, considering the accumulated value (i.e. *AEURH*) or individual value (i.e. *EURH*) in two meeting rooms, there were the large potential of the energy efficiency improvement of the HVAC system. And the automatic control strategy for the real-time occupancy-based shutdown control of the HVAC system would be developed to solve this issue.

Table 7. "Advanced analysis" for the effective utilization of the HVAC system in the small meeting room

Manually controlled starting time of the HVAC system	Manually controlled downtime of the HVAC system	*ODH*[a] (h)	Meeting Time	*DM*[b] (h)	*EURH*[c] (%)
Jul.31st,9:15	Aug.4th,23:00[d]	77.75	Jul.31st,9:15-10:30	37.75	48.55
			Jul.31st,11:00-12:30		
			Jul.31st,12:45-13:30		
			Jul.31st,13:45-15:30		
			Jul.31st,16:30-17:30		
			Aug.1st,7:30-11:00		
			Aug.1st,11:15-13:30		
			Aug.1st,14:15-16:00		
			Aug.2nd,7:45-11:15		
			Aug.2nd,11:45-13:15		
			Aug.2nd,13:30-14:15		
			Aug.2nd,16:15-17:15		
			Aug.2nd,17:30-18:15		
			Aug.2nd,18:30-19:45		
			Aug.3rd,7:45-11:30		
			Aug.3rd,13:30-16:00		
			Aug.4th,7:30-11:45		
			Aug.4th,13:00-17:45		
Aug.8th,7:00	Aug.11th,23:00[d]	64	Aug.8th,8:00-12:15	31	48.44
			Aug.8th,14:00-15:45		
			Aug.8th,16:15-17:00		
			Aug.8th,21:15-22:45		
			Aug.9th,7:00-11:15		
			Aug.9th,13:45-18:00		
			Aug.10th,7:45-10:45		
			Aug.10th,11:00-11:45		
			Aug.10th,12:00-12:45		
			Aug.10th,14:00-17:45		
			Aug.10th,19:00-21:15		
			Aug.11th,8:00-10:45		
			Aug.11th,14:00-15:00		

Table 7. "Advanced analysis" for the effective utilization of the HVAC system in the small meeting room (continued)

Starting time of the HVAC system (manually controlled)	Downtime of the HVAC system (manually controlled)	*ODH*[a] (h)	Meeting Time	*DM*[b] (h)	*EURH*[c] (%)
Aug.28th,8:00	Aug.30th,20:00	44	Aug.28th,8:00-11:30	18.5	42.05
			Aug.28th,13:45-15:00		
			Aug.28th,15:30-16:15		
			Aug.29th,8:00-11:15		
			Aug.29th,14:00-15:00		
			Aug.29th,15:15-17:45		
			Aug.30th,8:15-10:45		
			Aug.30th,11:30-12:30		
			Aug.30th,14:15-17:00		
Aug.31st,8:30	Aug.31st,23:00[d]	14.5	Aug.31st,8:30-12:30	8.5	58.62
			Aug.31st,13:45-15:15		
			Aug.31st,16:15-18:30		
			Aug.31st,20:00-20:45		
Sep.1st,15:30	Sep.1st,23:00[d]	7.5	Sep.1st,15:30-17:30	2	26.67
Sep.27th,10:00	Sep.27th,22:30	12.5	Sep.27th,10:00-10:45	2	16.00
			Sep.27th,11:00-12:15		
AODH[e] (h)		220.25	*ADM*[f] (h)	99.75	
AEURH[g] (%)					45.29

Notes: [a] *ODH* stands for the operation duration of the HVAC system; [b] *DM* stands for the duration of meeting; [c] *EURH* stands for the effective utilization ratio of the HVAC system; [d] Part of data were missed. It was not easy to infer when the HVAC system would be turned off manually; thus, 23:00 pm (which is automatic shutdown time) was listed here; [e] *AODH* stands for the accumulated operation duration of the HVAC system; [f] *ADM* stands for the accumulated duration of meeting; and [g] *AEURH* stands for the accumulated effective utilization ratio of the HVAC system.

Table 8. "Advanced analysis" for the effective utilization of the HVAC system in the large meeting room

Starting time of the HVAC system (manually controlled)	Downtime of the HVAC system (manually controlled)	*ODH*[a] (h)	Meeting Time	*DM*[b] (h)	*EURH*[c] (%)
Jul.31st,8:30	Jul.31st,19:45	11.25	Jul.31st,8:30-9:45	5.75	51.11
			Jul.31st,11:30-13:45		
			Jul.31st,14:15-16:30		
Aug.1st,8:30	Aug.2nd,14:15	21.75	Aug.1st,8:30-10:30	8.25	37.93
			Aug.1st,11:45-12:45		
			Aug.1st,14:15-16:45		
			Aug.2nd,7:15-10:30		
Aug.3rd,9:30	Aug.9th,14:15	72.75	Aug.3rd,9:30-11:15	22.5	30.93
			Aug.3rd,13:30-15:15		
			Aug.4th,7:45-10:45		
			Aug.7th,7:30-11:45		
			Aug.8th,7:45-12:00		
			Aug.8th,14:30-16:15		
			Aug.8th,16:30-17:15		
			Aug.9th,7:45-11:45		
			Aug.9th,12:15-13:15		
Aug.10th,8:45	Aug.14th,19:45	43	Aug.10th,8:45-12:30	20.75	48.26
			Aug.11th,7:30-10:30		
			Aug.11th,14:00-15:15		
			Aug.11th,16:30-18:00		
			Aug.11th,20:00-21:00		
			Aug.14th,7:15-13:15		
			Aug.14th,14:00-15:30		
			Aug.14th,16:00-17:45		
Aug.15th,9:15	Aug.29th,19:15	170	Aug.15th,9:15-10:45	66.5	39.12
			Aug.15th,13:45-15:00		
			Aug.15th,15:45-16:30		
			Aug.15th,18:15-20:30		
			Aug.16th,8:00-11:00		
			Aug.16th,14:00-15:15		
			Aug.17th,8:00-12:15		
			Aug.17th,14:15-15:00		
			Aug.17th,15:15-16:00		
			Aug.17th,17:45-18:45		
			Aug.18th,8:00-12:00		
			Aug.18th,13:30-17:00		
			Aug.21st,8:00-12:45		
			Aug.21st,14:00-16:45		
			Aug.21st,17:00-18:00		
			Aug.22nd,8:00-10:45		
			Aug.22nd,11:00-12:45		
			Aug.22nd,14:15-16:30		
			Aug.22nd,16:45-18:30		
			Aug.24th,8:45-11:15		
			Aug.24th,13:45-17:15		
			Aug.25th,9:00-13:00		
			Aug.25th,14:00-15:30		
			Aug.25th,16:00-17:15		
			Aug.25th,18:00-19:00		
			Aug.28th,8:00-11:30		
			Aug.28th,14:15-17:30		
			Aug.29th,7:30-9:30		
			Aug.29th,14:30-17:15		

Table 8. "Advanced analysis" for the effective utilization of the HVAC system in the large meeting room (continued)

Starting time of the HVAC system (manually controlled)	Downtime of the HVAC system (manually controlled)	*ODH*[a] (h)	Meeting Time	*DM*[b] (h)	*EURH*[c] (%)
Aug.30th,12:00	Aug.30th,19:15	7.25	Aug.30th,12:00-13:45	3.75	51.72
			Aug.30th,14:15-15:00		
			Aug.30th,16:30-17:45		
Sep.1st,9:30	Sep.1st,11:45	2.25	Sep.1st,9:30-10:45	1.25	55.56
Sep.4th,9:00	Sep.7th,23:00[d]	62	Sep.4th,9:00-10:15	22.75	36.69
			Sep.4th,12:30-13:45		
			Sep.4th,15:00-16:00		
			Sep.4th,16:45-17:45		
			Sep.5th,7:45-11:15		
			Sep.5th,11:30-12:15		
			Sep.5th,14:00-15:15		
			Sep.5th,16:45-17:30		
			Sep.6th,7:45-10:15		
			Sep.6th,11:00-12:00		
			Sep.6th,14:15-15:45		
			Sep.7th,8:00-10:45		
			Sep.7th,14:15-16:00		
			Sep.7th,17:00-19:30		
Sep.8th,9:15	Sep.8th,21:45	12.5	Sep.8th,9:15-12:00	6	48.00
			Sep.8th,14:15-17:30		
Sep.11th,12:45	Sep.11th,15:45	3	Sep.11th,12:45-14:00	1.25	41.67
Sep.12th,15:15	Sep.12th,21:15	6	Sep.12th,15:15-18:30	3.25	54.17
Sep.13th,9:45	Sep.13th,10:45	1	Sep.13th,9:45-10:45	1	100.00
Sep.18th,7:00	Sep.19th,19:00	28	Sep.18th,8:15-10:00	7.5	26.79
			Sep.18th,11:30-12:15		
			Sep.18th,15:30-16:45		
			Sep.19th,8:15-11:00		
			Sep.19th,11:15-12:15		
Sep.20th,11:00	Sep.21st,14:15	19.25	Sep.20th,11:00-12:00	8.5	44.16
			Sep.20th,14:45-16:15		
			Sep.20th,16:30-17:30		
			Sep.20th,18:00-20:00		
			Sep.21st,8:45-11:45		
Sep.21st,15:30	Sep.21st,21:00	5.5	Sep.21st,15:30-18:00	2.5	45.45
Sep.22nd,9:30	Sep.22nd,13:00	3.5	Sep.22nd,9:30-10:45	1.25	35.71
Sep.22nd,15:30	Sep.22nd,20:30	5	Sep.22nd,15:30-18:15	2.75	55.00
Sep.25th,9:00	Sep.25th,20:15	9	Sep.25th,9:00-12:00	5.5	61.11
			Sep.25th,14:00-16:00		
			Sep.25th,17:30-18:00		
Sep.26th,9:15	Sep.26th,20:00	10.75	Sep.26th,9:15-13:00	6.75	62.79
			Sep.26th,14:00-16:15		
			Sep.26th,17:00-17:45		
Sep.27th,9:15	Sep.27th,19:45	10.5	Sep.27th,9:15-12:30	5	47.62
			Sep.27th,14:00-15:45		
Sep.28th,10:00	Sep.28th,12:15	2.25	Sep.28th,10:00-11:30	1.5	66.67
Sep.28th,16:15	Sep.29th,23:00[d]	22.75	Sep.28th,16:30-17:45	9	39.56
			Sep.29th,8:00-11:00		
			Sep.29th,11:15-12:30		
			Sep.29th,12:45-13:45		
			Sep.29th,14:30-15:45		
			Sep.29th,16:30-17:45		
AODH[e] (h)		529.25	*ADM*[f] (h)	213.25	
AEURH[g] (%)					40.29

Notes: [a] *ODH* stands for the operation duration of the HVAC system; [b] *DM* stands for the duration of meeting; [c] *EURH* stands for the effective utilization ratio of the HVAC system; [d] Part of data were missed. It was not easy to infer when the HVAC system would be turned off manually; thus, 23:00 pm (which is automatic shutdown time) was listed here; [e] *AODH* stands for the accumulated operation duration of the HVAC system; [f] *ADM* stands for the accumulated duration of meeting; and [g] *AEURH* stands for the accumulated effective utilization ratio of the HVAC system.

3.2.2. *Advanced control strategy for improving the effective utilization of the HVAC system*

Fig. 7 shows a logic-based event-driven flowchart for the automatic on/off control of the HVAC system in real time so that the effective utilization of the HVAC system could be improved. The main concept is to timely turn off the HVAC system after the meeting, which could be identified by considering the variation of the CO_2 concentration as a proxy indicator. An advanced control strategy was developed in five steps: (i) data collection; (ii) judgment of whether the CO_2 concentration decreases; (iii) judgment of whether the indoor temperature decreases or keeps at a low level; (iv) judgment of whether the HVAC system keeps operating after the meeting; and (v) Automatic on/off control of the HVAC system.

- *(i) Data collection*: The advanced control strategy was developed with the collected data in 1-minute interval on the CO_2 concentration ("$CO_2^{(i)}$") and indoor temperature ("$T^{(i)}$") in accordance with the environmental sensor's specification on the data collection interval (refer to Table 3). In this process, "i" is the cycle counter to count the sampling times.
- *(ii) Judgment of whether the CO_2 concentration decreases*: If the CO_2 concentration collected at the "$(i)^{th}$" sampling time would be lower than that collected at the "$(i-1)^{th}$" sampling time, it means that the CO_2 concentration would have decreased for 1 minute, and then step (iii) will be conducted. Otherwise, the process will be restarted for the first step.
- *(iii) Judgment of whether the indoor temperature decreases or keeps at a low level*: When the indoor temperature collected at the "$(i)^{th}$" sampling time would be lower than that collected at the "$(i-1)^{th}$" sampling time, it means that the indoor temperature would have decreased for 1 minute. When the indoor temperature collected at the "$(i)^{th}$" sampling time would be lower than 25.5 °C (which is an example for a low level as the upper limit of Class 2), it means that the indoor temperature would be kept at a low level. If either of the aforementioned two conditions would happen, step (iv) will be conducted. Otherwise, the process will be restarted for the first step.

- *(iv) Judgment of whether the HVAC system keeps operating after the meeting*: This step could be conducted only when the demands in steps (ii) and (iii) could be satisfied. If the cycle counter "*i*" equals to a certain value (e.g. 15), it means that the CO_2 concentration would have decreased for 15 minutes and the indoor temperature would have decreased or been kept at a low level for 15 minutes. Thus, it can be judged that the HVAC system would be kept operating when the meeting would have ended; then, step (v) will be conducted. Otherwise, the process will be restarted for the first step.
- *(v) Automatic on/off control of the HVAC system*: This step would be conducted only when the demand in step (iv) could be satisfied, meaning that occupants would forget to turn off the HVAC system when they leave the meeting room. Thus, the HVAC system should be turned off automatically.

To further improve the accuracy of the Automatic on/off control of the HVAC system, it is suggested to consider some aspects in the follow-up studies. To be specific, it is required to determine the threshold level of the low temperature level (in step (iii)) and the cycle counter value (*i* in step (iv)) by carefully considering the project characteristics and the relevant properties in future studies and by calibrating the control strategy with the ground truth.

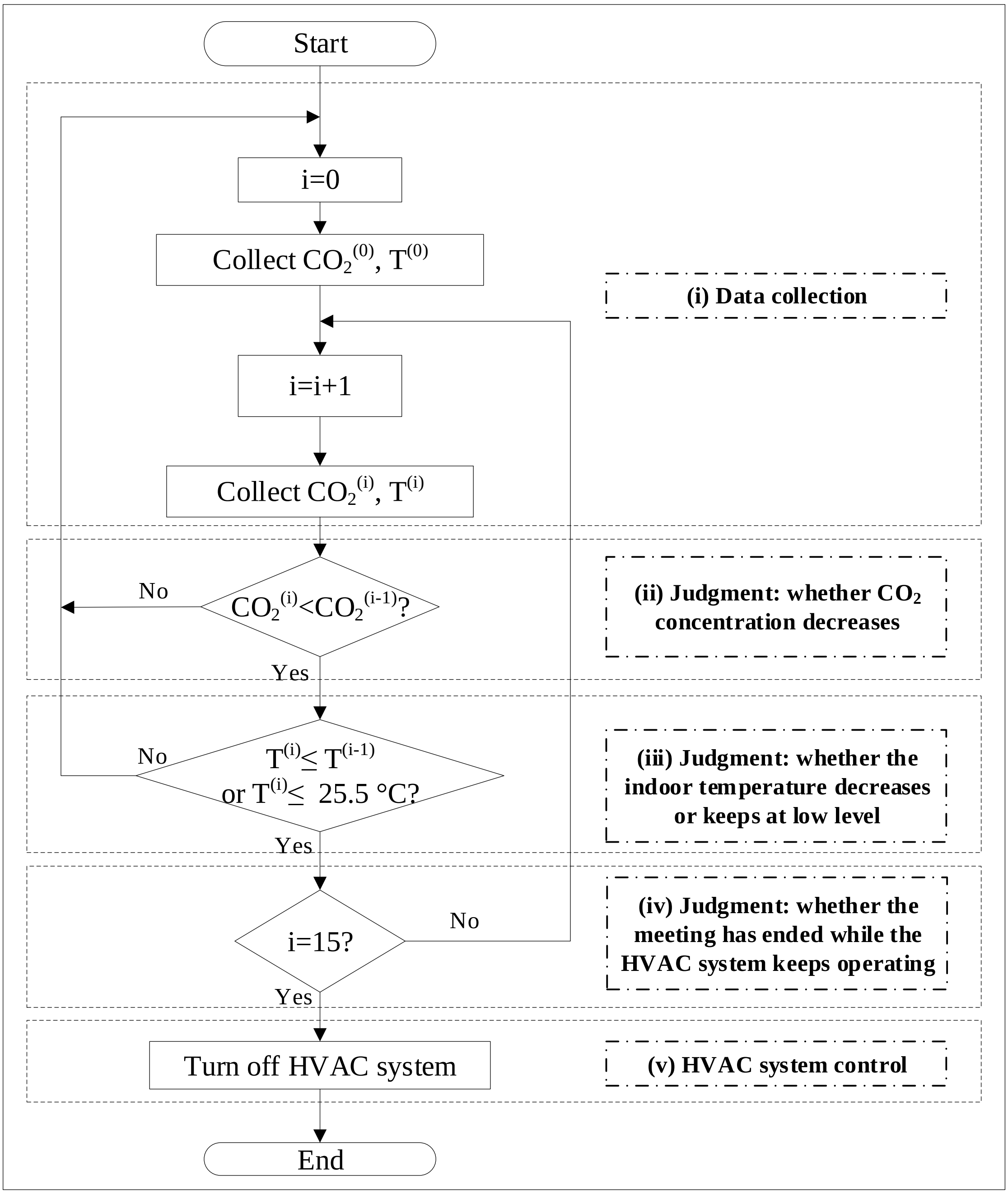

Fig. 7. A logic-based event-driven flowchart for the automatic on/off control of the HVAC system in real time

3.3. Discussion

The main findings of this study (i.e. current status with potential problems and the corresponding developed control strategies) can be summarized in two perspectives: (i) basic analysis and basic control for the set-point temperature of the HVAC system; and (ii) advanced analysis and basic control for the effective utilization of the HVAC system.

- *Basic analysis and basic control for the set-point temperature of the HVAC system:* The set-point temperature of the HVAC system was generally designated with low value. The real-time temperature in four temperature classes (for small/large meeting rooms) were distributed as Class 1 (30.46%/33.50%), Class 2 (17.08%/6.87%), Class 3 (47.10%/41.34%) and Class 4 (5.36%/18.29%). The set-point temperature of the HVAC system, estimated by mean value of real-time temperature, ranged in 19.5-27.5 °C (with the median of 22.0 °C) for small meeting room and 17.5-29.0 °C (with the median of 21.0 °C) for large meeting room. They skewed towards low temperature rather than recommended range of 24–25.5 °C (i.e. Class 2), where energy-saving potential existed. To overcome this challenge, based on the real-time temperature data, a logic-based event-driven control strategy for the real-time estimation for set-point temperature of the HVAC system was developed, so as to detect possible equipment failure in the HVAC system as well as provide suggestions for occupants about adjusting set-point temperature of the HVAC system to Class 2 if necessary.
- *Advanced analysis and basic control for the effective utilization of the HVAC system*: The HVAC system were not efficiently operated in two meeting room, in that unnecessary cooling was provided for empty room. The effective utilization condition of the HVAC system both in accumulated scale (*AEURH*) and individual scale (*EURH*) were low: the *AEURH* were 45.29% and 40.31% for small and large meeting room respectively; and the *EURH* ranged between 16.00-58.62% and 26.79-100.00% for small and large meeting room respectively. There were difference between *AEURH* as well as *EURH* and 100%,

where energy-saving potential existed. To overcome this challenge, based on the real-time data of temperature and CO_2 concentration, a logic-based event-driven control strategy for the real-time shutdown of the HVAC system was developed to improve the effective utilization of the HVAC system in real time. If a room is identified as being unoccupied (judge by variation of CO_2 concentration) while the HVAC system keeps operating (judge by variation of temperature), the HVAC system will be turned off automatically by actuating the control strategy.

4. CONCLUSIONS

The three-phase cyclic process (i.e. monitoring-diagnostic-intervention process) was conducted into the study of energy efficiency improvement in meeting rooms, and a novel approach for optimal operation of the HVAC system in real time was proposed. The pilot of this study were two meeting rooms, which are representatives of rooms with irregular occupancy, of "A" office located in Hong Kong. The real-time indoor environmental indicators (i.e. temperature and CO_2 concentration) were collected from 31 July to 30 September in 2017. Two issues concerning energy efficiency improvement were focused: (i) set-point temperature of the HVAC system; and (ii) effective utilization of the HVAC system.

- *(i) Set-point temperature of the HVAC system:* The mean value of real-time temperature was estimated as the set-point temperature of the HVAC system. The CPA model which identifies changes in mean was applied to distinguish set-point temperatures of the HVAC system in "basic analysis". The current status of set-point temperature showed skewness towards low temperature rather than recommended range of 24–25.5 °C. In "basic control", the concept, which identified T_{min} (T_{max}) and calculated the mean temperature within T_{min} (T_{max} minus dead band) and T_{min} plus dead band (T_{max}), was applied to the real-time estimation of set-point temperature. Based on this, it was able to detect the potential equipment failure in the HVAC system, and provide feedbacks about adjusting the set-point temperature to the recommended temperature range.

- *(ii) Effective utilization of the HVAC system*: The real-time data of temperature and CO_2 concentration were used to indicate on/off condition of the HVAC system and schedule of meeting respectively in "advanced analysis" and "basic control". The "advanced analysis" shows that the HVAC system were not efficiently operated in two meeting rooms, specifically occupants generally forgot to turn off the HVAC system and unnecessary cooling was provided for empty room. The "basic control" strategy was developed to turn off the HVAC system in real time if a room is identified as being unoccupied, which is judged by CO_2 concentration variation.

As mentioned before, the future work could focus on advanced control (refer to the black-colored dash lines in Fig. 1). At the current stage, only the shutdown of the HVAC system was controlled in basic control strategy, and it is expected to be most efficient if HVAC system can be turned off as occupants leave the room. However, the time for starting up of the HVAC system, which is another operational parameter, was not included in this study. If HVAC system is turned on as occupants enters the room (i.e. the current situation), energy can be saved but thermal comfort possibly cannot be satisfied. Thus HVAC system should operate prior to occupants' arriving, and the time for starting up of the HVAC system should be optimized to consume less energy but promise thermal comfort. The on-going topic, advanced control strategy for optimal on/off control of the HVAC system, is expected to gain benefits in energy-saving, cost-saving and thermal comfort.

This study is a beneficial attempt for energy efficiency improvement in irregularly occupied offices (i.e. meeting rooms) by utilizing real-time data. For the real-time estimation for the set-point temperature of the HVAC system, it can calibrate the function of temperature monitoring and adjustment for HVAC system, which is a potential way to detect and remove the accidental failure of the HVAC system. It can also provide feedbacks about adjusting the set-point temperature to the preferred temperature range without bothering occupants to know the extra field knowledge about HVAC system and related regulations. For the real-time improvement for the effective utilization of the HVAC system, the occupancy in a room is detected non-intrusively by variation of CO_2 concentration rather than intrusive monitoring sensors. Furthermore, the real-time occupancy-based shutdown control of the HVAC system is especially applicable in the rooms with unpredicted and irregular occupancy, where the traditional centralized control strategy with fixed operation schedule and the manual control by occupants are not appropriate any more.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP; Ministry of Science, ICT & Future Planning) (NRF-2018R1C1B4A02022690).

NOMENCLATURE

ADM	accumulated duration of meeting
AEURH	accumulated effective utilization ratio of the HVAC system
AODH	accumulated operation duration of the HVAC system
BEMS	building energy management system
CPA	change point analysis
DM	duration of meeting
EURH	effective utilization ratio of the HVAC system
HVAC system	heating, ventilating and air-conditioning system
IEQ	indoor environmental quality
ODH	Operation duration of the HVAC system
VOCs	volatile organic compounds

REFERENCE

[1] National Development and Reform Commission, Comprehensive Work Plan for Conserving Energy and Reducing Emissions for The Thirteenth Five-year Plan (National Development and Reform Commission), 2016. http://www.ndrc.gov.cn/zcfb/zcfbqt/201701/W020170105634585914832.pdf. 2017).

[2] M. Ouf, M. Issa, P. Merkel, Analysis of real-time electricity consumption in Canadian school buildings, Energy and Buildings 128 (2016) 530-539.

[3] The Electrical & Mechanical Services Department of the Government of the Hong Kong Special Administrative Region, Hong Kong Energy End-use Data 2017, 2017.

[4] M.S. Gul, S. Patidar, Understanding the energy consumption and occupancy of a multi-purpose academic building, Energy and Buildings 87 (2015) 155-165.

[5] S. Katipamula, R.M. Underhill, J.K. Goddard, D.J. Taasevigen, M. Piette, J. Granderson, R.E. Brown, S.M. Lanzisera, T. Kuruganti, Small-and medium-sized commercial building monitoring and controls needs: A scoping study, Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2012.

[6] Energy Information Administration, How many smart meters are installed in the United States, and who has them?, 2016. https://www.eia.gov/tools/faqs/faq.php?id=108&t=1. 2018).

[7] C. Miller, Z. Nagy, A. Schlueter, A review of unsupervised statistical learning and visual analytics techniques applied to performance analysis of non-residential buildings, Renewable and Sustainable Energy Reviews 81 (2018) 1365-1377.

[8] J.-S. Chou, N.-T. Ngo, Time series analytics using sliding window metaheuristic optimization-based machine learning system for identifying building energy consumption patterns, Applied Energy 177 (2016) 751-770.

[9] X. Luo, T. Hong, Y. Chen, M.A. Piette, Electric load shape benchmarking for small- and medium-sized commercial buildings, Applied Energy 204 (2017) 715-725.

[10] J. An, D. Yan, T. Hong, Clustering and statistical analyses of air-conditioning intensity and use patterns in residential buildings, Energy and Buildings 174 (2018) 214-227.

[11] Z. Ma, R. Yan, N. Nord, A variation focused cluster analysis strategy to identify typical daily heating load profiles of higher education buildings, Energy 134 (2017) 90-102.

[12] A. Ozawa, R. Furusato, Y. Yoshida, Determining the relationship between a household's lifestyle and its electricity consumption in Japan by analyzing measured electric load profiles, Energy and Buildings 119 (2016) 200-210.

[13] J. Yang, C. Ning, C. Deb, F. Zhang, D. Cheong, S.E. Lee, C. Sekhar, K.W. Tham, k-Shape clustering algorithm for building energy usage patterns analysis and forecasting model accuracy improvement, Energy and Buildings 146 (2017) 27-37.

[14] J.-S. Chou, A.S. Telaga, Real-time detection of anomalous power consumption, Renewable and Sustainable Energy Reviews 33 (2014) 400-411.

[15] J.-S. Chou, A.S. Telaga, W.K. Chong, G.E. Gibson, Early-warning application for real-time detection of energy consumption anomalies in buildings, Journal of Cleaner Production 149 (2017) 711-722.

[16] M. Horrigan, W.J.N. Turner, J. O'Donnell, A statistically-based fault detection approach for environmental and energy management in buildings, Energy and Buildings 158 (2018) 1499-1509.

[17] Y. Li, M. Liu, J. Lau, B. Zhang, Experimental study on electrical signatures of common faults for packaged DX rooftop units, Energy and Buildings 77 (2014) 401-415.

[18] C. Fan, F. Xiao, S. Wang, Development of prediction models for next-day building energy consumption and peak power demand using data mining techniques, Applied Energy 127 (2014) 1-10.

[19] A. Afram, F. Janabi-Sharifi, A.S. Fung, K. Raahemifar, Artificial neural network (ANN) based model predictive control (MPC) and optimization of the HVAC systems: A state of the art review and case study of a residential HVAC system, Energy and Buildings 141 (2017) 96-113.

[20] A. Ghofrani, M.A. Jafari, Distributed air conditioning control in commercial buildings based on a physical-statistical approach, Energy and Buildings 148 (2017) 106-118.

[21] R. Kuroha, Y. Fujimoto, W. Hirohashi, Y. Amano, S.-i. Tanabe, Y. Hayashi, Operation planning method for home air-conditioners considering characteristics of installation environment, Energy and Buildings 177 (2018) 351-362.

[22] A. Ghahramani, K. Zhang, K. Dutta, Z. Yang, B. Becerik-Gerber, Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings, Applied Energy 165 (2016) 930-942.

[23] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings, Building and Environment 88 (2015) 89-96.

[24] T. Labeodan, C. De Bakker, A. Rosemann, W. Zeiler, On the application of wireless sensors and actuators network in existing buildings for occupancy detection and occupancy-driven lighting control, Energy and Buildings 127 (2016) 75-83.

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

[26] L. Wang, S. Greenberg, J. Fiegel, A. Rubalcava, S. Earni, X. Pang, R. Yin, S. Woodworth, J. Hernandez-Maldonado, Monitoring-based HVAC commissioning of an existing office building for energy efficiency, Applied Energy 102 (2013) 1382-1390.

[27] N. Yamtraipat, J. Khedari, J. Hirunlabh, J. Kunchornrat, Assessment of Thailand indoor set-point impact on energy consumption and environment, Energy Policy 34(7) (2006) 765-770.

[28] A. Ghahramani, F. Jazizadeh, B. Becerik-Gerber, A knowledge based approach for selecting energy-aware and comfort-driven HVAC temperature set points, Energy and Buildings 85 (2014) 536-548.

[29] W. Kim, S. Katipamula, R. Lutes, Improving HVAC operational efficiency in small- and medium-size commercial buildings, Building and Environment 120 (2017) 64-76.

[30] J.W. Moon, S.-H. Han, Thermostat strategies impact on energy consumption in residential buildings, Energy and Buildings 43(2-3) (2011) 338-346.

[31] D. Manjarres, A. Mera, E. Perea, A. Lejarazu, S. Gil-Lopez, An energy-efficient predictive control for HVAC systems applied to tertiary buildings based on regression techniques, Energy and Buildings 152 (2017) 409-417.

[32] J.W. Moon, S.K. Jung, Development of a thermal control algorithm using artificial neural network models for improved thermal comfort and energy efficiency in accommodation buildings, Applied Thermal Engineering 103 (2016) 1135-1144.

[33] Z. Yang, B. Becerik-Gerber, The coupled effects of personalized occupancy profile based HVAC schedules and room reassignment on building energy use, Energy and Buildings 78 (2014) 113-122.

[34] S. Nagarathinam, H. Doddi, A. Vasan, V. Sarangan, P. Venkata Ramakrishna, A. Sivasubramaniam, Energy efficient thermal comfort in open-plan office buildings, Energy and Buildings 139 (2017) 476-486.

[35] L. Nikdel, K. Janoyan, S.D. Bird, S.E. Powers, Multiple perspectives of the value of occupancy-based HVAC control systems, Building and Environment 129 (2018) 15-25.

[36] T. Hong, C. Koo, J. Kim, M. Lee, K. Jeong, A review on sustainable construction management strategies for monitoring, diagnosing, and retrofitting the building's dynamic energy performance: Focused on the operation and maintenance phase, Applied Energy 155 (2015) 671-707.

[37] W. Li, C. Koo, S.H. Cha, T. Hong, J. Oh, A novel real-time method for HVAC system operation to improve indoor environmental quality in meeting rooms, Building and Environment 144 (2018) 365-385.

[38] A. De Mauro, M. Greco, M. Grimaldi, A formal definition of Big Data based on its essential features, Library Review 65(3) (2016) 122-135.

[39] 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.

[40] Environment Bureau in Hong Kong (2017), Energy Saving Charter 2017. http://www.energysaving.gov.hk/esc2017/en/home/index.html. 2017).

[41] Z. Du, B. Fan, J. Chi, X. Jin, Sensor fault detection and its efficiency analysis in air handling unit using the combined neural networks, Energy and Buildings 72 (2014) 157-166.

[42] J. Schein, S.T. Bushby, N.S. Castro, J.M. House, A rule-based fault detection method for air handling units, Energy and Buildings 38(12) (2006) 1485-1492.

[43] E.H. Borgstein, R. Lamberts, J.L.M. Hensen, Mapping failures in energy and environmental performance of buildings, Energy and Buildings 158 (2018) 476-485.

[44] V. Guralnik, J. Srivastava, Event detection from time series data, Proceedings of the fifth ACM SIGKDD international conference on Knowledge discovery and data mining, ACM, 1999, pp. 33-42.

[45] A. Szczurek, M. Maciejewska, Detection of occupancy events from indoor air monitoring data, Mathematics and Computers in Sciences and in Industry (MCSI), 2016 Third International Conference on, IEEE, 2016, pp. 229-234.

[46] P.F. Pereira, N.M.M. Ramos, Detection of occupant actions in buildings through change point analysis of in-situ measurements, Energy and Buildings 173 (2018) 365-377.

[47] A. Zeileis, A. Shah, I. Patnaik, Testing, monitoring, and dating structural changes in exchange rate regimes, Computational Statistics & Data Analysis 54(6) (2010) 1696-1706.

[48] R. Killick, I. Eckley, changepoint: An R package for changepoint analysis, Journal of statistical software 58(3) (2014) 1-19.

[49] R. Killick, I. Eckley, Changepoint: analysis of changepoint models, Lancaster University, Lancaster, UK. URL http://CRAN. R-project. org/pacakge= changepoint (2010).

[50] R. Killick, P. Fearnhead, I.A. Eckley, Optimal detection of changepoints with a linear computational cost, Journal of the American Statistical Association 107(500) (2012) 1590-1598.

[51] R. Killick, K. Haynes, I. Eckley, P. Fearnhead, J. Lee, Package 'changepoint', R package version 0.4.-2011.-http://cran. rproject. org/web/packages/changepoint/index. html (2016).

[52] D. Calì, P. Matthes, K. Huchtemann, R. Streblow, D. Müller, CO 2 based occupancy detection algorithm: Experimental analysis and validation for office and residential buildings, Building and Environment 86 (2015) 39-49.

[53] Z.T. Ai, C.M. Mak, D.J. Cui, P. Xue, Ventilation of air-conditioned residential buildings: A case study in Hong Kong, Energy and Buildings 127 (2016) 116-127.

[54] M.S. Zuraimi, A. Pantazaras, K.A. Chaturvedi, J.J. Yang, K.W. Tham, S.E. Lee, Predicting occupancy counts using physical and statistical Co 2 -based modeling methodologies, Building and Environment 123 (2017) 517-528.

[55] J. Yang, M. Santamouris, S.E. Lee, Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings, Energy and Buildings 121 (2016) 344-349.

[56] A. Szczurek, M. Maciejewska, A. Wyłomańska, R. Zimroz, G. Żak, A. Dolega, Detection of occupancy profile based on carbon dioxide concentration pattern matching, Measurement 93 (2016) 265-271.

[57] Z. Chen, C. Jiang, L. Xie, Building occupancy estimation and detection: A review, Energy and Buildings 169 (2018) 260-270.

[58] L.M. Candanedo, V. Feldheim, Accurate occupancy detection of an office room from light, temperature, humidity and CO 2 measurements using statistical learning models, Energy and Buildings 112 (2016) 28-39.

[59] M. Luoma, S.A. Batterman, Characterization of particulate emissions from occupant activities in offices, Indoor air 11(1) (2001) 35-48.

[60] C. Rösch, T. Kohajda, S. Röder, M.v. Bergen, U. Schlink, Relationship between sources and patterns of VOCs in indoor air, Atmospheric Pollution Research 5(1) (2014) 129-137.

[61] A. Szczurek, A. Dolega, M. Maciejewska, Profile of occupant activity impact on indoor air — method of its determination, Energy and Buildings 158 (2018) 1564-1575.

[62] M. Guo, X. Pei, F. Mo, J. Liu, X. Shen, Formaldehyde concentration and its influencing factors in residential homes after decoration at Hangzhou, China, Journal of Environmental Sciences 25(5) (2013) 908-915.

[63] H. Hori, S. Ishimatsu, Y. Fueta, T. Ishidao, Evaluation of a real-time method for monitoring volatile organic compounds in indoor air in a Japanese university, Environ Health Prev Med 18(4) (2013) 285-92.

[64] A. Caron, B. Hanoune, N. Redon, P. Coddeville, Gas sensor networks: relevant tools for real-time indoor air quality indicators in low energy buildings, Proceedings of the Healthy Buildings Europe 2015 Conference, 2015.

[65] C.-C. Jung, P.-C. Wu, C.-H. Tseng, H.-J. Su, Indoor air quality varies with ventilation types and working areas in hospitals, Building and Environment 85 (2015) 190-195.

[66] S. Naylor, M. Gillott, T. Lau, A review of occupant-centric building control strategies to reduce building energy use, Renewable and Sustainable Energy Reviews 96 (2018) 1-10.