An investigation of thermal environment of an existing UFAD system in a high-rise office building in the tropics

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Abstract

The current case study was conducted to identify the causes of environmental health issues in the office space associated with the existing Underfloor Air Distribution (UFAD) system in a high-rise office building in the tropics. The causes of the indoor environmental quality degradation are the key to resolve the environmental health issues. Thus, the parameters such as the indoor air temperature, relative humidity (RH), relative air velocity, carbon monoxide (CO), carbon dioxide (CO₂), formaldehyde, total volatile organic compound (TVOC) and particulate matter (PM₁₀) were evaluated in five office spaces. The results showed that the diffusers were not effective in creating air mixing at the occupied space. The RH has exceeded the threshold limit of 70%. The CO₂ concentration has exceeded 1000 ppm, and the formaldehyde has exceeded 0.1 ppm. These indicate the poor design and maintenance of the building that lead to the degradation of indoor environmental quality. Long exposure to the poor indoor environmental quality will cause permanent health damages. The Indoor Air Quality (IAQ) management plan must be established and implemented in the ongoing basis to ensure the health of the occupants are safeguarded. As part of the plan, the practice to conduct an IAQ assessment once every 3 years is recommended to ensure the health and well-being of the occupants are safeguarded.

Keywords Underfloor air distribution (UFAD) · Indoor air quality (IAQ) · Thermal comfort · Ventilation · Environmental health · Tropics

Nomenclature

AHU	Air Handling Unit
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
GBI	Green Building Index
HVAC	Heating, Ventilating, and Air Conditioning
IAQ	Indoor Air Quality
LEED	Leadership in Energy and Environmental Design
PAHU	Precool Air Handling Unit
PM ₁₀	Particulate Matter of 10 Micrometers or less
RH	Relative Humidity
SBS	Sick Building Syndrome

TVOC	Total Volatile Organic Compounds
UFAD	Underfloor Air Distribution

Introduction

The indoor environmental quality of a building is influenced by thermal environment, Indoor Air Quality (IAQ), lighting and visual environment, and acoustic setting. Thermal environment and IAQ issues are usually associated with newly-constructed and refurbished buildings [1]. Thus, thermal environment and IAQ assessments are commonly used as a performance-based approach to measure the quality of indoor air in association with the performance of the building and the Heating, Ventilating, and Air Conditioning (HVAC) system. The indoor air temperature, relative humidity (RH), air velocity, carbon monoxide (CO), carbon dioxide (CO₂), formaldehyde, total volatile organic compounds (TVOC) and particulate matter (PM₁₀) are the key parameters in these assessments.

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Formaldehyde emission from the new products has been proven to significantly elevate the indoor concentration of formaldehyde and can last for several months [2]. However, they are less likely to persist if the building's indoor air quality and HVAC system are well-tested and commissioned according to specific guidelines provided for green buildings, such as Leadership in Energy and Environmental Design (LEED) in the US and Green Building Index (GBI) in Malaysia.

Mold has been considered as one of the most significant factors attributing to sick building syndrome (SBS) symptoms [3]. Mold requires moisture for initial infestation and growth. Long exposure to the relative humidity of above 70% has been widely recognized as a benchmark for mold to infest and grow [4].

The study of the occurrence of SBS with varying ventilation rates found that doubling the ventilation rates from minimum ventilation rates of 10 l/(s.person) could reduce the SBS symptoms by 24%. Reducing the ventilation rate by half of the minimum ventilation rates could increase the occurrence of SBS symptoms by 23% [5].

In view of the vertical airflow pattern of the UFAD system with the potential improvement on thermal comfort, ventilation and IAQ, various studies have been conducted by various researchers on the thermal comfort and IAQ. The studies on thermal comfort of an office building served by an UFAD system using physical measurement, subjective assessment and computational fluid dynamic (CFD) analysis shown that thermal comfort was improved by more than 90% when the supply air temperature increased from 18 to 21 °C and the velocity reduced from 1.5 to 1 m/s [6]. Similarly, increased the supply air temperature of the UFAD system and the personalized ventilation (PV) was integrated at the facial level in the study. The results suggested that the UFAD system with a higher supply air temperature decreased feet overcooling and improved the acceptability of local thermal sensation. The thermal sensation of the whole body was improved with the introduction of PV at the facial level. The cool and clean outdoor air supply of PV also improved the perceived air quality [7]. The studies on the influence of supply air flow rate and its corresponding momentum and buoyancy fluxes on the vertical temperature profile in the indoor environment shown that the supply airflow rate has a significant effect on the vertical temperature profiles of the indoor thermal environment. Stratification height increased to a higher total airflow rate [8].

Tropical countries like Malaysia experience a relatively high outdoor air temperature and humidity, which can attribute to a different set of indoor environmental issues compared to cold climate countries [9]. Malaysia has two monsoonal winds. The South-West monsoon, which is referred as the dry season from May to September, and the North-East monsoon, which is referred as the rainy season from mid-November to March. The annual rainfall is 2500 mm, and RH is about 80% throughout the year [10]. The changes in

outdoor climate conditions should be considered in the design, operation and maintenance of HVAC systems.

Despite these extensive studies conducted on thermal comfort and IAQ, there is limited research work to examine the indoor environmental quality issues on an existing UFAD system in the tropics. This study is conducted to identify the common causes of the indoor environmental quality issues in a high-rise office building constructed with the UFAD system in the tropics. The findings from this study are expected to provide vital guidance in the future UFAD system design in the tropics.

Case study

In this case study, a 10-year-old skyscraper office tower in Malaysia was subjected to thermal environment and IAQ assessments. The 55-stories office tower has a height of 310 m and a total floor area of 148,800m². The building was designed with UFAD system and is served by a chilled water system supplied by a district cooling plant. Outdoor air is introduced at every floor through a pre-cooled air handling unit (PAHU) located in the lift lobby area. Figure 1 above shows the schematic diagram of the UFAD system.

Each floor is divided into North (N) and South (S) offices. The assessments were conducted at five office spaces, which are 33 N, 33S 34N, 34S and 35S. The interior of the office has an open-plan design with low partition walls. A few small rooms are partitioned out as meeting rooms at the inner section and the periphery of the office space. Note that five AHUs are installed throughout the office area to cater for approximately 830 m² floor area of each office space.

Research methodology

The assessment methodology was guided by the typical thermal environment and IAQ assessment methodology used in the tropical region [11–13]. However, the current study focuses only on objective measurements. Subjective measurements such as the questionnaire and its statistical analysis were not conducted due to the restrictions requested by the occupants and the building's owner. The assessment procedures have been divided into four stages, namely, preliminary, sampling, evaluation and recommendation.

Preliminary stage

The assessment procedure was started with a walk-through survey and an inspection of the HVAC plant room where the incoming and the outgoing district chilled water and the heat exchanger system were located. The walk was led by the building operation and maintenance team. A comprehensive

Fig. 1 The schematic diagram of UFAD system in the office space

discussion with the team and a detailed review of the HVAC as-built drawings were crucial to understand the routine operation and maintenance of the HVAC system. A walk-through and inspection of the office area was led by the office tenant. Feedbacks from the occupants were arbitrarily collected during the walk-through to grasp an understanding of the environmental health issues occurred. The location of the fresh air inlet, PAHU, AHU, the air distribution and the possible sources of indoor air pollutants in the office were located and inspected for the planning of assessments of sampling points [11].

Sampling stage

The thermal environment data (indoor air temperature, RH and air velocity) and IAQ data (CO , CO_2 , formaldehyde, TVOC and PM_{10}) were collected to identify the causes of environmental health issues. Five office spaces were examined in the current study, and eight sampling locations were selected at each office space as the red dot shown on the floor plan in Fig. 2 above [14]. Points 1 to 5 are located in the open-office area, Point 6 is located in the pantry area, and Points 7 to 8 are located in the partitioned meeting rooms. The height of the sampling points was fixed at 110 mm above the floor level, a height which is suitable for both sedentary and standing activities [15].

The indoor thermal environment is closely related to the outdoor climate conditions, while the CO_2 concentration is influenced by the occupancy's activity. These parameters fluctuate throughout the day. Hence, they were measured at four different time zones throughout the office hours to observe the profile changes, and thus to identify the effectiveness of the

HVAC system. The time zones divided are: 1 (9 am – 11 am), 2 (11 am – 1 pm), 3 (1 pm – 3 pm) and 4 (3 pm – 5 pm). Note that the data were taken based on the average of a half-hour of surrogated measurement at an interval of 5-min for a duration of a half-hour at each time zone [12].

The Alnor air velocity meter and TSI VelociCalc air velocity meter were used to measure and record the thermal environment data. In addition, the Alnor CompuFlow indoor air quality meter, TSI DuskTrak II aerosol monitor, MiniRAE 2000 portable VOC monitor and PPM formaldemeter were used to measure the IAQ data. Note that all equipment used in the measurement were calibrated. Table 1 above provides a detail description of the equipment used for thermal environmental and indoor air quality assessments.

Evaluation stage

Data measured were compared to the local and international standards and regulations. The standards and regulations referred in the current study are the Industry Code of Practice on Indoor Air Quality 2010 [12], ASHRAE Standard 55–2013 [15], and the Malaysian Standard MS 1525:2014 [16]. Based on the measurements obtained, the causes of environmental health issues were discussed and determined.

Recommendation stage

In this final stage, remedial strategies were recommended to improve the indoor air quality, and to enhance the thermal comfort. A re-audit is recommended once the remedy has been performed to ensure the health and well-being of the occupants are safeguarded.

Fig. 2 Floor-plan showing the locations of the sampling points in the office space [14]

Bias uncertainty analysis

The bias uncertainty analysis is essential to be conducted to examine whether or not the errors present in the field work data collected (indicated in Tables 2, 3, 4, 5, and 6) are at a satisfactory level. The bias uncertainty (Δx) is the difference between measured and estimated result. The mathematical definition can be found in references [17, 18] and these mathematical expressions are repeated here for convenient reference as follows:

$$\Delta x = \frac{R}{2} \quad (1)$$

where, R is the difference between the maximum and minimum value of x :

$$R = x_{\max} - x_{\min} \quad (2)$$

For the comparison between both data, the uncertainty obtained can be converted into the percentage uncertainty [17]:

$$\text{Percentage Uncertainty (\%)} = \left(\frac{\Delta x}{\bar{X}} \times 100 \right) \quad (3)$$

where, $\bar{X}$ is the average reading of the maximum and minimum value of x .

The findings of the bias uncertainty analysis will be discussed later in Section “Bias Uncertainty”.

Results and discussion

The thermal environment and IAQ assessments of the five office spaces were conducted, not only to meet the standards and guidelines, more important to identify the cause of the indoor environmental health problem. The cause of the health problem is typical in indoor air quality of buildings in the tropics. The strategies to achieve a better IAQ will be discussed in the next section.

Thermal environment

The recommended indoor air temperature in MS 1525:2014 [16] and Industry Code of Practice on Indoor Air Quality 2010 [12] is range from 23 to 26 °C. Similarly to Singapore guidelines, which range from 22.5 to 25.5 °C [13]. The recommended RH range from 50 to 70%. The recommendation considers that the occupants in the tropics can tolerate a higher RH than those in the sub-tropics. However, a long exposure to RH above 70% will encourage mold growth, and subsequently causes indoor health hazard. Thus, all the standards, codes and guidelines do not allow the RH to exceed 70%.

Figure 3 above shows the indoor air temperature and the RH of the office space. Generally, most of the office spaces have relatively low indoor air temperatures below 23 °C. The low air temperature was found due to the failure of the chilled water valve actuators. The malfunctioning chilled water valve actuators allow the chilled water to continue cool the space even when the temperature set-point is achieved. The low indoor air temperature causes the RH to be relatively higher. Thus, over-cooling a space for a long period of time is can be harmful as it may cause mold to grow.

Table 1 Equipment used for thermal environmental and indoor air quality assessments

Equipment type / model	Manufacturer	Country of manufacturing	Parameters (range, accuracy)
Alnor Air Velocity Meter AVM440-A	TSI	USA	Indoor air temperature (−10 to 60 °C, ±0.3 °C, resolution 0.1 °C) Relative humidity (5 to 95%, ±3%) Air velocity (0 to 30 ms ^{−1} , ±3% or ±0.015 ms ^{−1} whichever is greater)
TSI VelociCalc Air Velocity Meter 8345	TSI	USA	Indoor air temperature (−17.8 to 93.3 °C, ±0.3 °C, resolution 0.1 °C) Air velocity (0 to 30 ms ^{−1} , ±3% or ±0.015 ms ^{−1} whichever is greater)
Alnor CompuFlow Indoor Air Quality Meter CF930	TSI	USA	CO ₂ concentration (0 to 5000 ppm, ±3% or ±50 ppm whichever is greater) CO concentration (0 to 500 ppm, ±3% or ±3 ppm whichever is greater)
TSI DuskTrak II Aerosol Monitor Model 8532	TSI	USA	Particulate, PM10 (0.001 to 150 mg/m ³ , ±0.1% or ±0.001 mg/m ³ whichever is greater)
MiniRAE 2000 Portable VOC Monitor PGM-7600	RAE System	USA	TVOC concentration (accuracy for 0 to 2000 ppm: ±2 ppm or ±10% of reading, accuracy for more than 2000 ppm: ±20% of reading)
PPM Formaldemeter Model htV-m	PPM Technology	UK	Formaldehyde concentration (0 to 10 ppm, ±2%)

The phenomenon of the low indoor air temperature and the high RH can be seen mostly at points 6, 7 and 8 where the pantry area and meeting rooms are located. These places are not usually occupied. The heat load is less compared to the open-plan office. Data fluctuation can also be seen at different time zones in these areas where the movements of the occupants are random. Over-cooling was observed at certain time zones. Note that points 1 to 5 have a much more stable indoor air temperature and RH, except for 35S where the office space has not been fully occupied and more occupants' movement is observed due to the nature of work.

Figure 4 above shows the distribution of the humidity ratio at different time zones. The humidity ratio of the office space is in the range of 9.52–12.59 g_{water}/kg_{air} with most of the data falling between 10.0 and 11.5 g_{water}/kg_{air}. This moisture level is relevant to a relative humidity of 56.8–65.2% of the indoor air temperature of 23 °C, which has proven the effectiveness

of dehumidification of the AHU cooling coil. Hence, the RH can be maintained within the recommended range if the temperature does not decrease below the comfort level.

To put it into perspective, the indoor air temperature and RH are inversely related. Thus, the control of indoor air temperature and RH is rather important to ensure a reliable operation. The results indicate that failure in maintenance has led to serious health and safety concern.

Air velocity

The air velocity in the office space is presented in Table 2 above. It shows that the air movement is very low compared to the standards. In order to identify the reason of the low air movement, a further analysis on the HVAC design air change is recorded. Due to the limited resources available to identify

Table 2 The air velocity of the office spaces

Office space	Air velocity (m/s)			Bias uncertainty (%)
	Maximum	Minimum	Average	
Level 33 N	0.10	0.01	0.04	113
Level 33S	0.07	0.02	0.04	63
Level 34 N	0.11	0.01	0.04	125
Level 34S	0.11	0.03	0.06	67
Level 35S	0.08	0.04	0.05	40

Table 3 The Carbon Monoxide (CO) concentration in ppm of the office spaces

Office space	Carbon monoxide (ppm)			Bias uncertainty (%)
	Maximum	Minimum	Average	
Level 33 N	2.5	0.2	0.9	128
Level 33S	2.0	0.2	0.9	100
Level 34 N	1.5	0.2	0.6	108
Level 34S	2.3	0.2	0.8	131
Level 35S	2.0	0.2	0.8	113

Table 4 The Carbon Dioxide (CO₂) concentration in ppm of the office spaces

Office space	Carbon monoxide (ppm)			Bias uncertainty (%)
	Maximum	Minimum	Average	
Level 33 N	1352	818	1113	24
Level 33S	1130	720	948	22
Level 34 N	1256	772	1021	24
Level 34S	1128	764	1014	18
Level 35S	818	635	716	13

the system's design airflow rate, the design air change was measured through the total supply airflow of each diffuser and the total supply airflow of each AHU unit. The results shown identical data are obtained. The air change of about 20 ACH is recorded. This has proven that the design airflow rate is sufficient for the space. Thus, lower air velocity in the office space is due to the short circuit of supply and return air.

Air distribution from the floor diffusers is crucial for the performance of UFAD system. Air throw from the floor diffusers shall induces air mixing at the occupant's space to create the stratification effect at the height of 1.2–1.8 m above floor level [19]. It was observed that most of the floor grilles either broken or with missing diffuser blades. It is pertinent to mention that without the diffuser blades, the conditioned air will not spread out to the space and will not effectively create an air-mixing at the occupied space. A separate study will be conducted to study the effect of airflow pattern affected by the floor grille thickness and diffuser blades [20]. Based on the observation, we can identify that without the diffuser blades, conditioned air will eject upwards with a much higher velocity.

As diffuser blades also play a significant role in creating an air stratification, in which ASHRAE 62.1 [21] has rated a higher air ventilation effectiveness of 1.2 for the UFAD system, and the terminal velocity of 0.25 m/s is achieved at 1.4 m or less above the floor level. Without the diffuser blades, conditioned air will eject upwards with a much higher velocity. The upper stratified zone will not be formed when the supply air jet exceeded the heat plumes within the space. As a result,

Table 5 The Formaldehyde concentration in ppm of the office spaces

Office space	Formaldehyde (ppm)			Bias uncertainty (%)
	Maximum	Minimum	Average	
Level 33 N	0.30	0.21	0.26	17
Level 33S	0.29	0.23	0.27	11
Level 34 N	0.37	0.32	0.34	7
Level 34S	0.18	0.13	0.15	17
Level 35S	0.28	0.24	0.25	8

Table 6 The PM₁₀ concentration in mg/m³ of the office spaces

Office space	PM ₁₀ (ppm)			Bias uncertainty (%)
	Maximum	Minimum	Average	
Level 33 N	0.427	0.131	0.143	103
Level 33S	0.198	0.118	0.128	31
Level 34 N	0.308	0.108	0.116	86
Level 34S	0.293	0.057	0.120	98
Level 35S	0.280	0.119	0.126	64

the ventilation effectiveness is reduced. The low air movement will cause human discomfort and feeling stuffy. Note that occupants in the tropics are used to a damped environment and sweating. A higher air velocity acting on the human body will improve thermal comfort [7].

Indoor air quality

The IAQ parameters in association with occupants' health are CO, CO₂, formaldehyde, TVOC and PM₁₀. The interior office spaces were newly renovated. Hence, an IAQ assessment is important, especially on the formaldehyde, TVOC and PM₁₀, which are closely related to materials and adhesives used in furniture. The IAQ results are shown in Tables 3, 4, 5, and 6 above.

TVOC was not detected in the office space. However, formaldehyde was detected and exceeded the threshold limit of 0.1 ppm [12]. It is evident that less than 1 month before the study was conducted, new wooden tables and partitions were moved in to the offices, which could be the cause of the high formaldehyde level. Formaldehyde, which is used widely in many wood products, is carcinogenic to humans as reported by IARC [22]. The short-term effects are skin, eye, nose, and throat irritations. A prolonged exposure could be cancerous. The cancer effects associated with formaldehyde are nasopharynx cancer, leukemia and nasal sinuses cancer [23, 24]. Thus, the formaldehyde level at 0.2–0.75 ppm is the threshold limit in many countries [25, 26]. However, the formaldehyde emission rate decreases through time. A higher ventilation rate and temperature enhance the formaldehyde emission rate [27]. Smoke spill fans, which are available at the office spaces, are suggested to flush out the indoor air to be replaced with the outdoor air during off-hours. The HVAC system should be off during the air flushing as a higher temperature can effectively enhance the formaldehyde emission and remove it from the office spaces.

The average PM₁₀ in the office spaces was in the range of 0.116–0.143 mg/m³, which is below the threshold limit of 0.15 mg/m³. The peak PM₁₀ has exceeded the threshold limit at 0.198–0.427 mg/m³ were recorded for a short interval of

Fig. 3 Indoor air temperature and relative humidity of the office spaces: **a** office space 33 N, **b** office space 33S, **c** office space 34 N, **d** office space 34S, **e** office space 35S

time is acceptable because the movement of occupants will incur the air turbulences that cause a higher PM_{10} measured.

The CO and CO_2 levels are the parameters used to measure the air pollutants that have been created from human activity. The measured average CO levels are all below 0.9 ppm, which

is far below 10 ppm threshold limit. This is expected as the office spaces do not have any potential activities and sources that emit CO such as smoking.

The CO_2 concentration gradually increased from the morning to evening in the same office space. Office spaces in 33 N,

Fig. 4 The distribution of the humidity ratio at different time zones

34 N and 34S had CO_2 concentration that exceeded the threshold limit of 1000 ppm for most of the time, while 33S exceeded the threshold limit of 1000 ppm at time zone 3. The CO_2 concentration in 35S was within the safe margin between 676 and 749 ppm as the office was not fully occupied. It is pertinent to mention that outdoor CO_2 concentration can vary between 350 and 400 ppm [28]. Hence, exceeding the limit of 1000 ppm shows a major CO_2 concentration increase compared to the levels normally measured outdoors. It indicates that the fresh air supply is insufficient. The concentration of the indoor pollutants depends on the fresh air ventilation. When inspected, it was found that the fresh air supply unit and the PAHU were not operating during the evening although the occupancy rate remains the same. A separate test was performed to measure the duct fresh air flowrate using the traverse method, and it has determined that the sufficiency of the designed fresh air supply was meeting the requirement of ASHRAE Standard 62.1–2013 [21]. Hence, the CO_2 sensor is encouraged to be used for the PAHU control to avoid human maneuver in switching off the fresh air supply, as well as providing the optimum control of the fresh air supply to reduce power wastage.

Bias uncertainty

In Table 2, the error of air velocity indicated that uncertainty was present in these collected data. The major objective of the

current work is to examine the thermal comfort and air contaminant levels using the objective measurement technique in an office space, and so highly precise data are not essential. Nonetheless, a full set of realistic estimated field data to represent the comfort and contaminant level is needed in the current work. Therefore, an error analysis must be conducted to examine whether or not the errors happen in the field work data were at an acceptable level.

The bias uncertainty of the average air velocity is in the range of 40–125% (Table 2). This can be explained that the error is considerably significant at low air flow rate caused by the reduced sensitiveness at air velocities below 0.5 m/s [29].

The bias uncertainty for Carbon Monoxide (CO) concentration is in the range of 100–131%. These results suggested that non-uniform CO distributions were present during the field work testing (Table 3). This can be traced to the fact that uneven air distribution was present for all zones examined. It is observed that the bias uncertainty for all zones is quite consistent.

It can be seen that the bias uncertainty for Carbon Dioxide (CO_2) concentration is in the range of 13–24%. These results suggested that non-uniform CO_2 distributions were present during the field work running (Table 4) at a much smaller percentage error in comparison to the error of CO concentration just mentioned above. This is attributed to the fact that the error is significantly lower when the sensitiveness of the CO_2 sensor is higher in the range of concentration of 350–1000 ppm.

The bias uncertainties for Formaldehyde and PM10 concentrations are in the ranges of 7–17% and 31–103 respectively. These results suggested that non-uniform Formaldehyde and PM10 distributions were present during the field work testing (Tables 5 and 6). Again, this can be traced to the fact that uneven air distributions were present for all zones examined.

Conclusions

The study to identify the causes of the environmental health issues in open-office installed with an UFAD system has been successfully carried out. The findings of the current work can serve as an important guide to ventilation design that must be considered when using UFAD systems in the tropics. The significant findings and strategies recommended are as follows:

1. The high air velocity at each individual diffuser causes the air to flow into the office space vertically upwards without spreading into the space to create an air-mixing at the occupied zone. This was shown with a relatively low air velocity in the office space while having sufficient air change. The diffuser blades at each floor grille should be streamlined to follow the airflow pattern in the office space and to reduce the air stagnation. A separate study is conducted to study the airflow pattern of the existing floor diffuser.
2. Malfunctioning chilled water valve actuators cause the indoor air temperature to be over-cooled. It has contributed to a high indoor RH above 70%, which can be detected in most unoccupied areas, where the heat load is much less. The control failure has proven to be the causes of IAQ problems. It promotes the infestation and the growth of mold in the offices, especially locations such as carpet and return air grille. Note that mold growth is seen as a major indoor hazard that affects the health and well-being of occupants. The replacement of chilled water valve actuators becomes critical. Regular maintenance of HVAC system is also important to avoid future IAQ issues.
3. CO₂ sensors and controls are recommended to be used to avoid human maneuver in switching off the fresh air supply. Besides, it will provide an optimum control of fresh air supply to reduce power wastage. Providing a constant fresh air supply can be energy consuming.
4. It is suggested that smoke spill fans, which are available within the office spaces should be operated to replace indoor air with the outdoor air during the off-hours. The air flushing procedure is recommended to perform during warm and dry weather climates to avoid introduction of humid outdoor air. Relative humidity should be observed during and after the procedure. HVAC systems should be

turned off during the air flushing as a higher temperature can effectively enhance the formaldehyde emission and remove it from the office space.

5. The IAQ management plan should be established and implemented. As part of the plan, the practice to conduct an IAQ assessment once every 3 years is recommended to ensure the health and well-being of the occupants are safeguarded.
6. The maintenance team has a crucial role to ensure the indoor air quality is maintained up to the required standard. A scheduled checking and maintenance work should be in place, so that HVAC systems can function based on the intended design.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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