# Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system

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ENVR Division of Environment and Sustainability
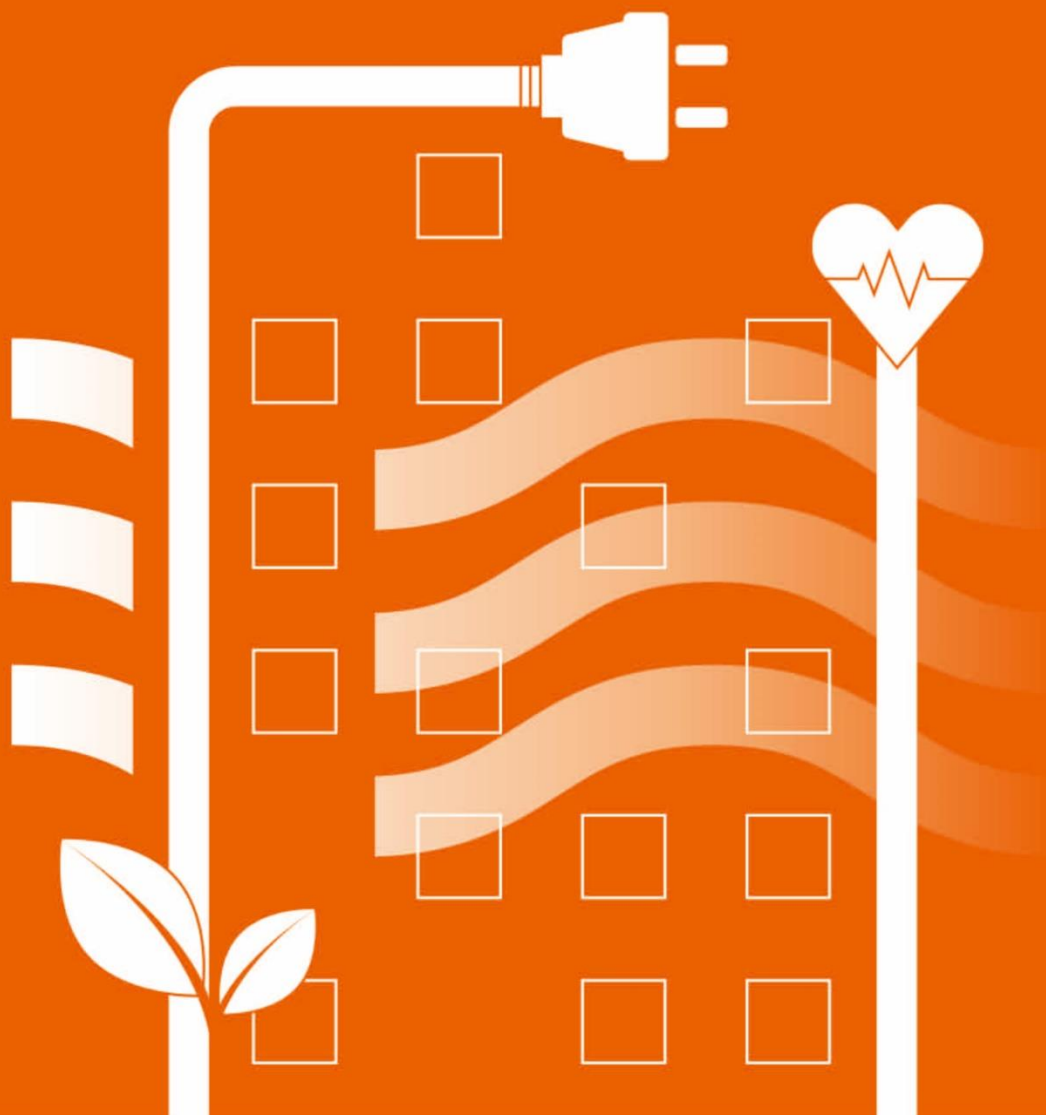
About Institute for the Environment

Institute for the Environment (IENV) is an interdisciplinary research institute of HKUST that promotes and conducts research aimed at improving the environment of Hong Kong, the Pearl River Delta, and beyond. We have a solid track record in conducting air quality related studies in Hong Kong and the region. Our research findings have been adopted in many different ways in the policy making process both locally and regionally.

IENV collaborates with a variety of stakeholders, including academic, industrial and environmental non-governmental partners. We are stretching our collaborative efforts and building cross-border synergies with mainland institutions for a greener and healthier Greater Bay Area.

We envision that IENV would be world class institute that can help bridge the gap between science, policy and best practices for improvement of environment and sustainability issues; and support science-based policy making and the shifting of practices towards sustainability.

Our team strives to achieve our visions through (1) High-quality scientific studies and collaborating with top-tier researchers; (2) Strategic research and demonstration projects; (3) Multi-stakeholder engagement and facilitating evidence-based decision-making process; and generating (4) Academic and non-academic publications.

Preface & Acknowledgement

Buildings are the major culprit on energy consumption hence greenhouse gas (GHG) emission in a city, yet they also provide shelters in protecting inhabitants from outdoor heat stress and air pollutions.

In Hong Kong, the Buildings Energy Efficiency Ordinance (BEEO) enacted on 21 September 2012 regulates energy efficiency standards of key building services installations including air conditioning installation, electrical installation, lighting installation as well as lift and escalator installation. Requirements on these building services installations are rather scattered measures, and have no integration with Indoor Air Quality (IAQ) considerations.

The current study based on a real-case renovation project in Hong Kong has demonstrated how a concerted Heat, Ventilation and Air Conditioning (HVAC) system is able to generate co-benefits on energy efficiency, indoor air quality, as well as occupants' health, thermal comfort and productivity. All these benefits would be translated further to the building's operation cost-saving, improved environmental health and public health.

Executive Summary

Retrofit on existing buildings for better energy performance is widely desired due to large share of building energy consumption. Meanwhile, the importance of thermal comfort and air pollution exposure has attracted increasing attention for occupant health, productivity and sustainable development. Heat, Ventilation and Air-Conditioning (HVAC) systems are responsible for a substantial proportion of energy use in buildings and are closely related to indoor environment quality. Unfortunately, there is some stigma around energy saving measures, as many people believe it will make their lives less comfortable.

This study examined the energy consumption and indoor environment in a commercial office building with a retrofitted HVAC system. The retrofitting measures included a sensor-based building management system, dehumidification of outdoor air, and a two-stage particle filtration system. Energy data were collected before and after the retrofit. Field measurements were conducted in both winter and summer to evaluate the thermal comfort and indoor exposure to air pollutants in the retrofitted area. An experiment was designed to assess the benefits of upgraded filters on exposure to ambient particles during summer. By combining all of these measures, the retrofitted HVAC system was able to reduce energy use by 50% while maintaining generally acceptable indoor thermal comfort. Most of the time, the indoor particle levels complied with the World Health Organization's guidelines. The upgraded filtration system with a pleated filter reduced outdoor PM ingress by 30% to 60% more than the aluminum filter used before the retrofit. Co-benefit assessment provides insights into sustainability in building development during a retrofit by holistically examining energy use and the environment.

Findings of the current HVAC system retrofitting study has very wide implications on buildings' energy efficiency and indoor air quality, as well as occupants' health, thermal comfort and productivity. Such high performance building operation, if implemented to more buildings in Hong Kong, could even serve as a mega-purification system in our city and improve the ambient air quality which will generate bigger health impact to the wider community.

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1. Introduction

Buildings are a major source of energy consumption, both globally and locally. In 2015, existing buildings accounted for approximately 30% of global final energy use and 28% of energy- related greenhouse gases (GHG) emissions [1]. The European Union (EU) has identified the existing building stock as the "single biggest potential sector for energy savings" [2]. Energy consumption in the building sector is even higher in cities with large blocks of commercial buildings. For example, in 2015, buildings in Hong Kong accounted for 64% of the city's total final energy use, of which commercial buildings alone accounted for 43% of the final energy use [3]. Consequently, retrofitting existing buildings has been widely viewed as a helpful method of tackling the energy crisis and climate change [4–9].

One of the core functions of any commercial office building is to provide a place for people to work. People spend on average 40 hours per week in their working environment [10]. The Universal Declaration on Human Rights proclaims that everyone has the right to just and favorable conditions at work. Furthermore, thermal comfort and air pollution exposure are two key factors that affect health and productivity in the working environment [11–18]. For example, indoor temperature has been found to be associated with cognitive ability and work performance in offices [13,16,19]. Exposure to air pollutants—such as particulate matter (PM) and nitrogen dioxide (NO_2)—is associated with a wide range of adverse health effects—such as cardiopulmonary mortality, respiratory mortality, chronic bronchitis, asthma attacks, inflammation and respiratory symptoms [20–24]. Reduced thermal comfort or poor indoor air quality imposes a health risk and adversely affects working performance, which leads to a substantial economic cost related to medical expenses and absence from work [18,25–29].

Heating, ventilation and air conditioning (HVAC) systems are responsible for a substantial proportion of energy consumption in modern buildings [30,31]. In tropical climates, the energy consumed by an HVAC system may exceed 50% of the total energy consumption of a building [31]. Therefore, the energy retrofitting of HVAC systems is of primary importance because it can reduce energy use [31,32]. Meanwhile, HVAC systems play an important role in thermal comfort and indoor air quality [16,18,19,33]. Different designs and operating principles of HVAC systems will lead to different levels of indoor temperature and humidity, which are important indicators of thermal comfort [34,35]. Changes in ventilation and filtration can also lead to variations in the air pollutant concentration, which affects indoor exposure to these pollutants [36].

Retrofitting HVAC systems can affect the energy use, thermal comfort and air pollution exposure, either individually or collectively [35–38]. This impact can either be positive or negative. For example, increasing cooling equipment efficiency may save energy, however, it may increase indoor humidity levels [36]. In hot and humid climate zones, this will have a substantial impact on thermal comfort and increase the potential for biological growth [35]. In another example, while increasing the ventilation might help to dilute indoor-generated pollution, it may increase the ingress of outdoor air pollutants, such as PM [36,37]. The World Health Organization (WHO) has reported that 92% of the world's population lives in areas with an ambient PM exceeding the WHO's limits, which is associated with 4.2 million annual premature deaths worldwide [39]. Both numeric modeling and field measurements have shown that a substantial proportion of outdoor PM can enter indoors and become a dominant source of PM in buildings with a mechanically ventilated structure, such as offices [40,41].

A sustainable building retrofit needs to take into account of any factors that may affect energy performance and the indoor environment. The region studied in this investigation, Hong Kong, is located in a sub-tropical zone with a hot and humid climate. Most of Hong Kong's commercial buildings are located in busy traffic areas with relatively high outdoor air pollution levels [42]. Assessing the energy benefits and environmental performance of retrofitted HVAC in the context of such an unfavorable climate and outdoor air environment can provide many insights into this

problem. It will also provide many incentives to achieve high-performance buildings conducive to sustainable energy and environment development in Hong Kong and elsewhere.

Therefore, this study evaluates the energy consumption, thermal comfort and exposure to air pollutants of a retrofitted commercial office in urban Hong Kong. In particular, the study aims to:

1. assess the energy benefit of the retrofitted HVAC system;
2. evaluate the thermal comfort and indoor air quality in the retrofitted office; and
3. assess how the ingress of outdoor particles changes with outdoor concentration and the use of particle filters.

2. Methodology

2.1 The study building

The selected building was built in 1975 and is located in an urban area of Hong Kong. The building is adjacent to a major road that has an annual average daily traffic of around 30,000 vehicles [43]. The nearest government-operated air quality monitoring station (AQMS) is located 2.1 km from the selected building, at the roadside junction of two major traffic roads that have an annual average daily traffic around 30,000 and 16,000 vehicles, respectively [43]. The selected building has sixteen floors, including a parking lot on the ground floor, restaurant and shopping areas on the first floor (1/F) and the second floor (2/F), and offices from the third floor (3/F) to the sixteenth floor (16/F). The ventilation and air conditioning systems of the office area and other areas are separate.

2.2 Retrofitted Heat, Ventilation & Air Conditioning (HVAC) system

The pre-existing HVAC system in the selected building consists of a chiller plant, fan coil units (FCUs), a primary air handling unit (PAHU) and fans. Air conditioning is mainly provided by a chilled water system. Chilled water is supplied by two water-cooled chiller plants that are located on the roof-deck area. The chilled water is pumped to end terminals (e.g. FCUs and PAHUs) through the chilled water piping network. Pre-treated fresh air from a central PAHU mounted on the roof is injected to the general office areas by a fresh air duct layout, which is distributed evenly at all floors along east and west wings of the building, as shown in Figure 1.

The retrofit HVAC project was conducted in 2012 on the roof and office area from 3/F to 8/F. The retrofit had the following major components:

(1) adding a split PAHU on 5/F for enhanced ventilation,
(2) adding additional cooling coils to dehumidify the fresh air to reduce moisture;
(3) upgrading a two-stage filtration system for the central PAHU on the roof,
(4) operating a positive indoor pressure system, and
(5) upgrading an intelligent building management system (BMS) to monitor and control ventilation and air conditioning, which will save energy. Lighting is also considered in the retrofit to save energy, but is not within the scope of this study.

The central PAHU has a ventilation capacity of 7,591 m^3/h at the east wing and 7,814 m^3/h at the west wing. A new PAHU (split PAHU) was added on 5/F to increase the ventilation capacity. Approximately half of the office area (show area) on 5/F was supplied with fresh air that was handled by the split PAHU, and the other half of the office area was supplied with fresh air handled by the central PAHU. These two areas were connected by two doors, which were usually left open during office hours.

Special dehumidification system was designed to reduce indoor humidity and maintain desirable thermal comfort

Dehumidification is a key feature of the retrofitted HVAC systems for thermal comfort. The cooling coil of the original HVAC system was designed primarily to reduce temperature which was not efficient for humidity control.

To deal with the humidity problem associated with the hot and humid climate in Hong Kong, an additional cooling coil is added in the PAHU. The added cooling coil (for dehumidification purpose) is specially designed in geometry regarding the number of rows, number of tubes in a row, number of fins, and coil dimension to increase the contact area with fresh air.

(1) Indoor sampling site

Indoor (Central) West
- Office area on 7/F
- Fresh air intake from roof
- Ventilation capacity ~3% larger than the PAHU's in East Wing

(2) Indoor sampling site

Indoor (Central) East
- Office area on 7/F
- Fresh air intake from roof

(3) Indoor sampling site

Indoor (Split)
- Office area on 5/F
- Fresh air intake from Split PAHU

(4) Outdoor sampling site

Outdoor (Roof)
- Point of outdoor air intake of central PAHU from roof

(5) Outdoor sampling site

Exhaust fan
- Mail toilet on 7/F

(6) Outdoor sampling site

Outdoor (5/F)
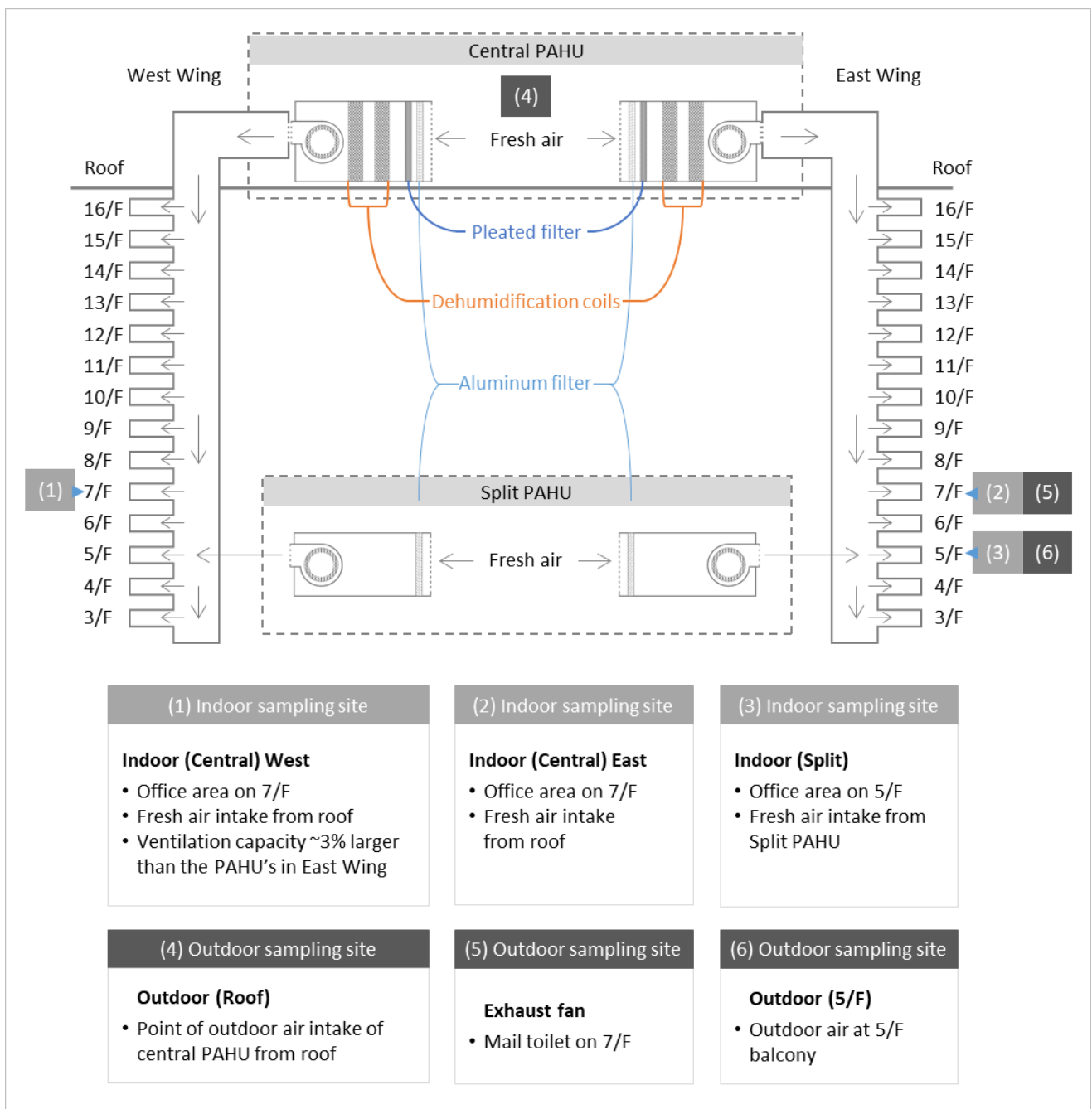- Outdoor air at 5/F balcony

Figure 1. HVAC system with the retrofitted upgrades; and the 6 air quality sampling sites. (Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

In the retrofitted HVAC system (Figure. 2), the filtered fresh air was forced through the cooling coil with sufficient contact time to remove the moisture before being injected indoors. Other alternatives of dehumidification were reviewed but not used in the retrofit for different reasons.

For example, dehumidification using desiccant wheels to absorb the water vapor in the fresh air is recommended in a study for a supermarket [44], however, it is not applicable in this case due to the limited space and lack of waste heat for regeneration.
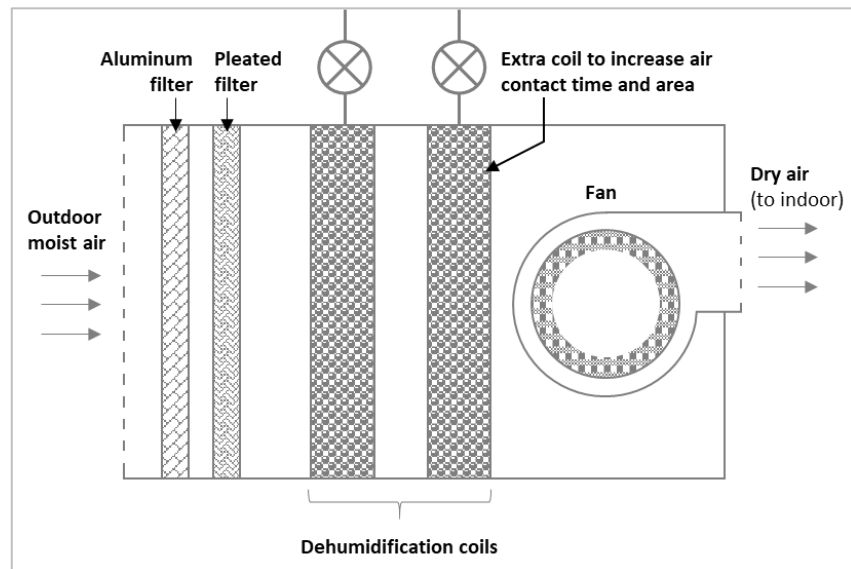
Figure 2. Cross-section diagram of the fresh air filtration and dehumidification in system in the retrofitted HVAC system. (Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

Upgraded filtration system to improve indoor air quality

The filtration system in the central PAHU on the roof was upgraded from a coarse particle filter of aluminum mesh (aluminum filter) to a two-stage filtration system that has both an aluminum filter and a pleated filter from AAF Varicel II, with a minimum efficiency reporting value (MERV) of 13. The aluminum filter is washable and reusable, while the pleated filter needs to be replaced every 3 to 6 months depending on the outdoor air pollution level. The cross section area of the retrofitted filtration system was increased to compensate the pressure drop caused by the added filter. Due to the limited space, only an aluminum filter was installed on the split PAHU on 5/F.

Smart sensors integrated to auto-adjust indoor meteorological parameters

The air conditioning adopted the pre-existing air-cooled chilled water system but was upgraded with a BMS that adjusted the opening of modulating water valve based on the temperature sensed by the temperature sensor (thermostat) installed in the office area. FCUs were used for heat exchange at each indoor terminal, which were controlled by a thermostat operated by a three speed switch. An occupancy sensor was used in the On/Off control of the FCU for all of the enclosed offices and meeting rooms.

2.3 Study design

Energy consumption, thermal comfort and air quality were evaluated in this study

The study design includes the following:

(1) data collection for the energy consumption of the HVAC system before and after retrofit,
(2) measurement of the parameters related to thermal comfort and indoor air quality under the retrofitted HVAC system, and
(3) an experiment to assess the impact of an upgraded pleated filter on the ingress of ambient particles.

Electricity uses before and after the retrofit were compared as changes in energy performance

Monthly data on electricity use from the fresh air system and air conditioning were collected from the management office for the period from January 2010 to July 2018. As the retrofit project of HVAC was conducted in 2012, the collected data allow us to evaluate the energy performance before and after the retrofit.

The air pollutants selected in this study are PM, CO and NO_2. PM is abundant in urban areas [45], while CO and NO_2 are indicators of vehicle emissions [46,47].

High performance pleated filter was removed for 1 week experimental comparison

The particle size dependent filtration efficiency of HVAC systems differs by filter type [41,48,49]. Generally, a pre-filter of aluminum mesh is useful to capture coarse particles, while a pleated filter is better able to capture fine particles [49–51]. The pleated filter installed in the central PAHU was taken out for one week during summer at the selected building for maintenance purpose. During the maintenance period, the HVAC system used aluminum filter, which was equivalent to the filtration operation before the retrofit. We measured the indoor and outdoor air quality during the maintenance period to access the impact of the aluminum filter on particle filtration. The benefits of the upgraded filtration system were assessed by comparing the ingress of outdoor particles with and without the pleated filter.

Using Government data as air quality background information

Corresponding air quality data recorded from the nearest AQMS during the sampling period were obtained from the government's website, which enabled comparison and correlation analysis of the outdoor pollution. Wind direction and wind speed were obtained from a back- ground meteorological station (Waglan Island) in Hong Kong to infer the regional flow of air pollution. The dominant wind direction is northeast in winter and south to southwest in summer. The average wind speed was 6-8 m/s in winter and 5-6 m/s in summer [52].

2.4 Field measurement & instruments

Meteorological parameters for thermal comfort and air pollution have been measured at different locations inside the building throughout a year

Simultaneous indoor and outdoor measurements were made for temperature, humidity, pressure and air pollutants during three periods, including:

(1) winter season under normal operation of retrofitted HVAC from 24th Nov to 4th Dec 2017, namely "Winter (normal)";
(2) summer season under normal operation of retrofitted HVAC from 21st to 29th May 2018, namely "Summer (normal)"; and

(3) a one-week filter experiment in summer from 30th May to 5th June 2018 by removing pleated filter installed on the central PAHU, namely "Summer (experiment)".

To assess the spatial variability in the selected meteorological parameters and air pollutants, multiple indoor locations were selected for sampling within the retrofitted areas. Outdoor measurements on roof of the selected building were made to represent the outdoor conditions. The integrated sensor system had the capability of storing local data and transmitting data to the server in lab on real time base.

2.5   Energy analysis

The data showing the energy consumption before and after the retrofit has been recorded and analyzed. A significant reduction in energy usage has been observed

The monthly energy consumption of the ventilation and air conditioning system in the study building was recorded and compared to the energy consumption from the electricity bill for validation. The energy consumption incorporated the data before and after the retrofit project (i.e. from 2010 to 2018). The period from Jan 2010 to May 2012 represents the duration before retrofitting of the HVAC system, meanwhile the period after May 2012 refers the duration that the retrofit project was completed. The energy consumption before and after the retrofit project were compared to evaluate the energy savings of the retrofit project.

2.6   Thermal comfort analysis

Thermal comfort is governed by six parameters, and measured from -3 (cold) to +3 (hot) with general comfort zone between values from -0.5 to +0.5

The thermal comfort was evaluated based on the thermal sensation scale defined in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 [53]. In this standard, the thermal sensation scale is categorized by seven points, from −3 to + 3, representing: cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (1), warm (2), and hot (3). Six thermal variables are recognized as primary factors in defining conditions for thermal comfort, including metabolic rate, clothing insulation, air velocity, air temperature, radiant temperature, and relative humidity [53] .

The values for PMV at the selected locations were calculated. Data for air temperature and relative humidity were obtained directly from the field measurement. Measurements conducted during office hours, i.e. 09:00-17:00, were used in the PMV estimation to evaluate the performance of the retrofitted HVAC system in terms of thermal comfort for human occupants. The metabolic rate was assumed to be 1.1, which was equivalent to typing at the office. The clothing insulation was assumed as 0.5 which is a typical value of office clothing in Hong Kong and the air velocity was 0.1 m/s with no local air speed control. The radiant temperature was assumed to be the same as the air temperature because the exposition and intensity of direct solar radiation to the rooms were low [54].
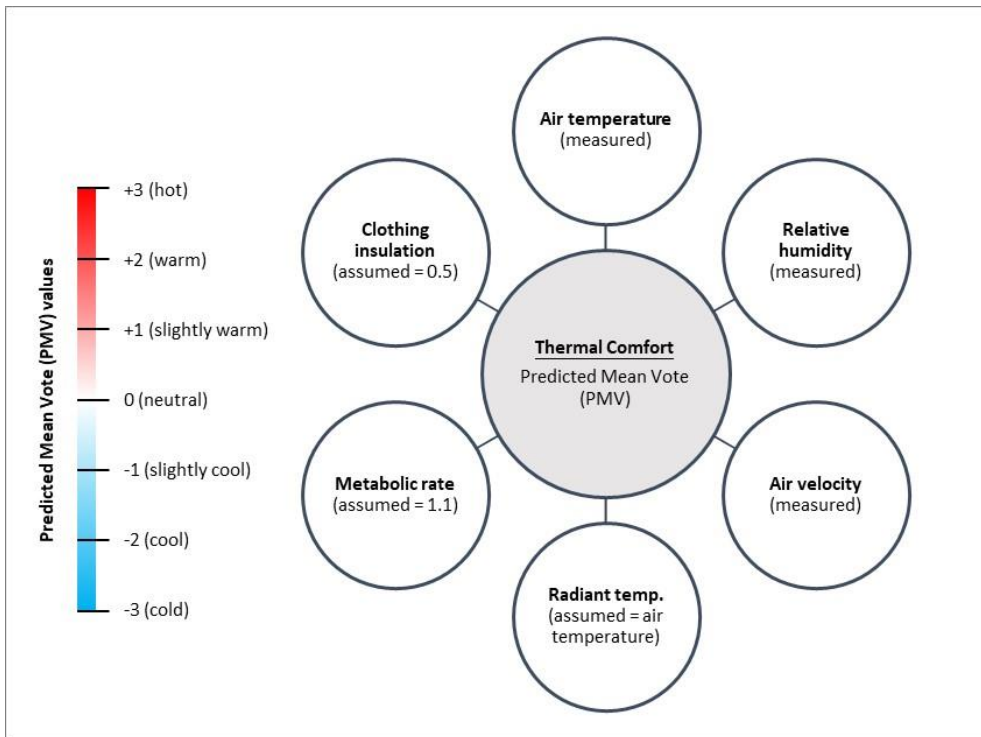
Figure 3. Six factors in defining conditions for thermal comfort, and the ASHRAE seven-point thermal sensation scale. (Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

The thermal comfort was evaluated for indoor (split), indoor (Central West) and indoor (Central East) in both winter (24th Nov to 4th Dec 2017) and summer (21st May to 5th June 2018). The PMV value was estimated for each of the sampling hour at selected locations and periods.

The ASHRAE seven-point thermal sensation scale together with the recommended range for general comfort, characterized by PMV values of -0.5 and 0.5, was used to evaluate the performance of the retrofitted HVAC system on thermal comfort.

2.7   Air quality analysis

Concentrations of measured air pollutants were quantified based on their mean and standard deviation by location and period, and were visualized with boxplots. The association between the indoor and outdoor $PM_{2.5}$ concentrations at the selected building and the AQMS was quantified using Spearman's correlation coefficient [55].

To assess the benefits of upgraded filtration on indoor air quality, the ingress of ambient PM was quantified by location and period.

3. Key Findings

3.1 Energy consumption

Post-retrofit energy consumption reduced 69-72% in winter and 45-52% in summer.

Figure 4 shows the monthly energy consumption of the ventilation and air conditioning system before and after the retrofit project of the HVAC system. The energy consumption of the HVAC system decreased substantially after the retrofit.

Taking the lowest temperature month, January, as an example, the energy consumption before the retrofit was 71,000 and 78,000 kWh in 2010 and 2011, respectively. The energy consumption after retrofit was 22,000 kWh in both 2013 and 2014, which was 69% to 72% lower than those before the retrofit.

The energy consumption for July, the month with the highest temperature, was 150,000 and 170,000 kWh in 2010 and 2011, respectively. The energy consumption after retrofit was 82,000 and 83,000 kWh in 2013 and 2014, respectively, which were 45% to 52% lower than those before the retrofit. Similar decreasing patterns were also observed in other months.
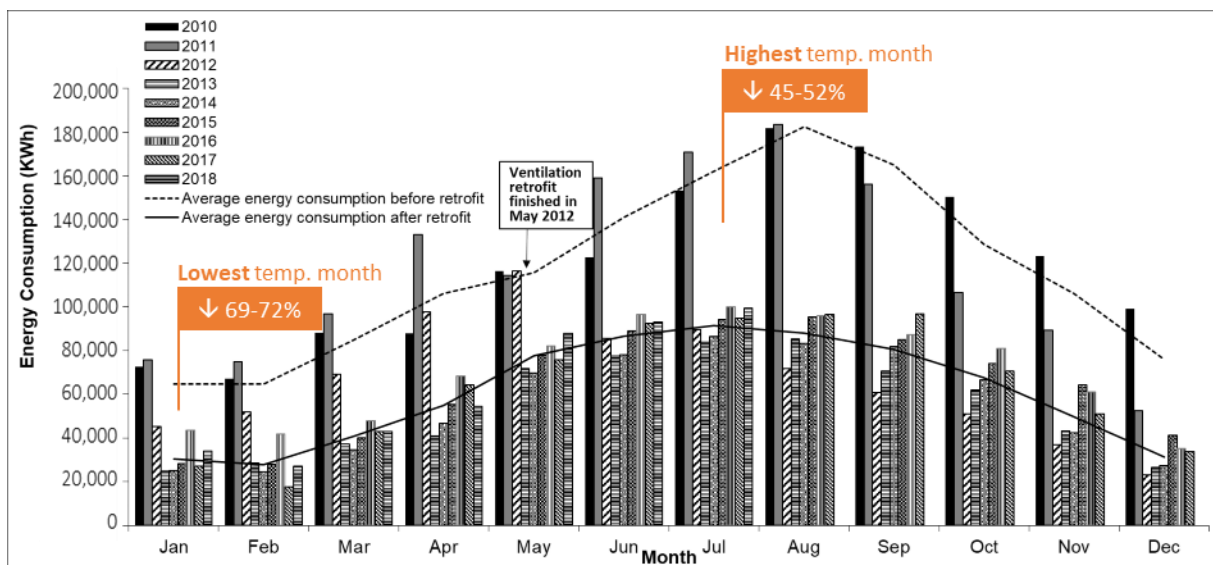
Figure 4. Monthly energy consumption of ventilation and air conditioning system before and after the retrofit project. Significant energy savings can be observed. (Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

The overall energy consumption of the HVAC system dropped by 51% after the retrofit.

Overall, the average energy consumption of the ventilation and air conditioning system after retrofitting the HVAC system over the period of Jun 2012 to July 2018 was 51% lower than the energy consumption before the retrofit project over the period of 2010 to May 2012, resulting in annual average energy saving of 670,000 kWh

Multiple energy saving measures have been taken, such as an innovated process for dehumidification, an

The reduction in the energy consumption is related to several retrofitting measures:

1. Firstly, adding dehumidification in the retrofitted PAHU helped to reduce the energy consumption. Nevertheless, for conventional

acceptable 'higher' indoor temperature, as well as a smart sensor-based building management system (BMS).

dehumidification process in buildings, the air is cooled at the dew point for dehumidification and then the air is reheated to the desired temperature for controlling room humidity. A large amount of energy is required to cool and then reheat the air. The dehumidification in the retrofitted PAU was able to effectively control humidity and thus avoid reaching dew point. Therefore, extra cooling and reheating processes were not necessary. Although the added coil for dehumidification also requires energy, it should be much lower than the energy needed in the cooling and reheating processes.

2. Moreover, under a lower humid condition, a relatively high indoor temperature is acceptable for the thermal comfort. For example, at relative humidity of 70%, the maximum allowable temperature at an indoor environment to achieve an acceptable thermal comfort is 27.5°C while that is 29.1°C at relative humidity of 40% [53], which may further reduce the amount of the chiller water needed for cooling.

3. Besides, the upgrade of the BMS system can adjust the modulating water valve based on the temperature sensed by the thermostat installed in the office area, which reduced the usage of chiller water thus reducing energy consumption. The energy saving from the upgraded BMS system was more profound when the set temperature was close to the outdoor temperature, such as January. The retrofitted HVAC system saved a substantial amount of the energy, however, it is unclear that which part of the retrofit project contributes the most, because the retrofit measures were conducted simultaneously and there were no separate data collected to evaluate the impact of each separate measure.

3.2 Thermal comfort

Figure 5 shows the distribution of PMV values falling among the thermal comfort categories at indoor (split), indoor (central west) and indoor (central east) in both winter and summer.

Office location		Sampling season	Thermal sensation scale (Equivalent PMV)		
			Comfortable (-0.5 to +0.5) ☺☺☺	Slightly warm (+0.5 to +1) ☺☺	Warm (>+1) ☺
Indoor (Split)	5/F; air intake from Split PAHU	Winter	100%		
		Summer	69%	31%	
Indoor (Central) East	7/F; air intake from Central PAHU on the rooftop	Winter	100%		
		Summer	8%	83%	8%
Indoor (Central) West		Winter	100%		
		Summer	89%	4%	6%

Figure 5. Distribution of the predicted mean vote (PMV) values recorded from the three sampling office locations in winter and summer. (Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

In winter, the retrofitted HVAC provided thermally comfortable environment

In winter, the indoor temperature ranged from 24°C to 25°C at all selected locations. The indoor relative humidity ranged from 38% to 65% at indoor (split) and ranged from 46% to 55% at indoor (central west) and indoor (central east). The PMV values for all sampling hours fell in the range between -0.5 to 0.5 at all three locations, which were very comfortable to occupants. This indicates that the retrofitted HVAC provided thermally comfortable environment in the winter.

In summer, the retrofitted HVAC provided thermally comfortable environment at Indoor (Central) West; while Indoor (Central) East is "slightly warm" …

In summer, the indoor temperature ranged from 24°C to 30°C and relative humidity ranged from 44% to 62% at all selected locations. There was more variety in thermal comfort in summer than in winter. The percentage of the sampling hours deemed very comfortable was 69% for indoor (split), 89% for indoor (central west), and 8% for indoor (central east).

There are substantial portions of the PMV values in summer that fell between 0.5 and 1, meaning it was bit warmer than optimal. The percentage of sampling hours with PMV values that fell in this range was 31% for indoor (split), 4% for indoor (central west), and 83% for indoor (central east). This means in summer; it was slightly warmer than optimal.

In view of the general PMV values overestimation at higher temperatures, the retrofitted HVAC system provides thermal comforts both in winter and summer

Despite of the higher PMV values recorded from Indoor (Central) East, previous studies showed that the PMV values generally overestimate occupant response on the ASHRAE scale at high temperatures and predict discomfort at temperatures that subjects in field surveys find comfortable, especially in hot-humid climate areas [56,57].

Therefore, it is reasonable to believe that the retrofitted HVAC system is able to provide acceptable thermal comfort in summer, considering that the PMV values may have been overestimated.

3.3   Indoor air quality

Figure 6 summarizes the hourly air quality measurement at the selected building by period and location using boxplot, together with corresponding data at AQMS.

ABOUT PM:

PM levels met the WHO IAQ guidelines for most of the time; and the average indoor PM levels were substantially lower than those observed at outdoor.

The average indoor PM_{10} concentrations measured in both winter (normal) and summer (normal) were below the WHO indoor air guideline for annual PM_{10} of 20 μg/m^3 [58], maintaining an acceptable indoor PM quality for health.

The average indoor $PM_{2.5}$ concentrations were below the WHO annual $PM_{2.5}$ guidelines of 10 μg/m^3 [58] in both seasons, except indoor (split) in winter of 12 μg/m^3.

The average indoor PM_1 concentrations were below 5 μg/m^3 for most of the sampling time.

The indoor PM_{10}, $PM_{2.5}$ and PM_1 were substantially lower than outdoors during normal operation of the HVAC, indicating that the filtration system helped to remove the outdoor particles.

ABOUT PLEATED FILTER:

The pleated filter installed at the central PAHU was more efficient in capturing fine particles than the aluminum filter

The PM$_{2.5}$ concentrations at indoor (split) were approximately twice of the PM$_{2.5}$ concentrations measured at indoor (central east) and indoor (central west) in both winter and summer. This indicates that the pleated filter installed at the central PAHU (on the roof) was more efficient in capturing fine particles than the aluminum filter installed in the split PAHU (on the 5/F).

Indoor PM levels are expected to be contributed by both outdoor air and sources generated from indoor environment, though the PM$_{2.5}$ concentrations measured at "exhaust" were 70% lower than that measured at the "outdoor (roof)" where the outdoor air was drawn to the system. This indicates that the filtration system not only cleans up indoor air but also substantially helps to improve ambient air quality in a potential magnitude of up to 70%!
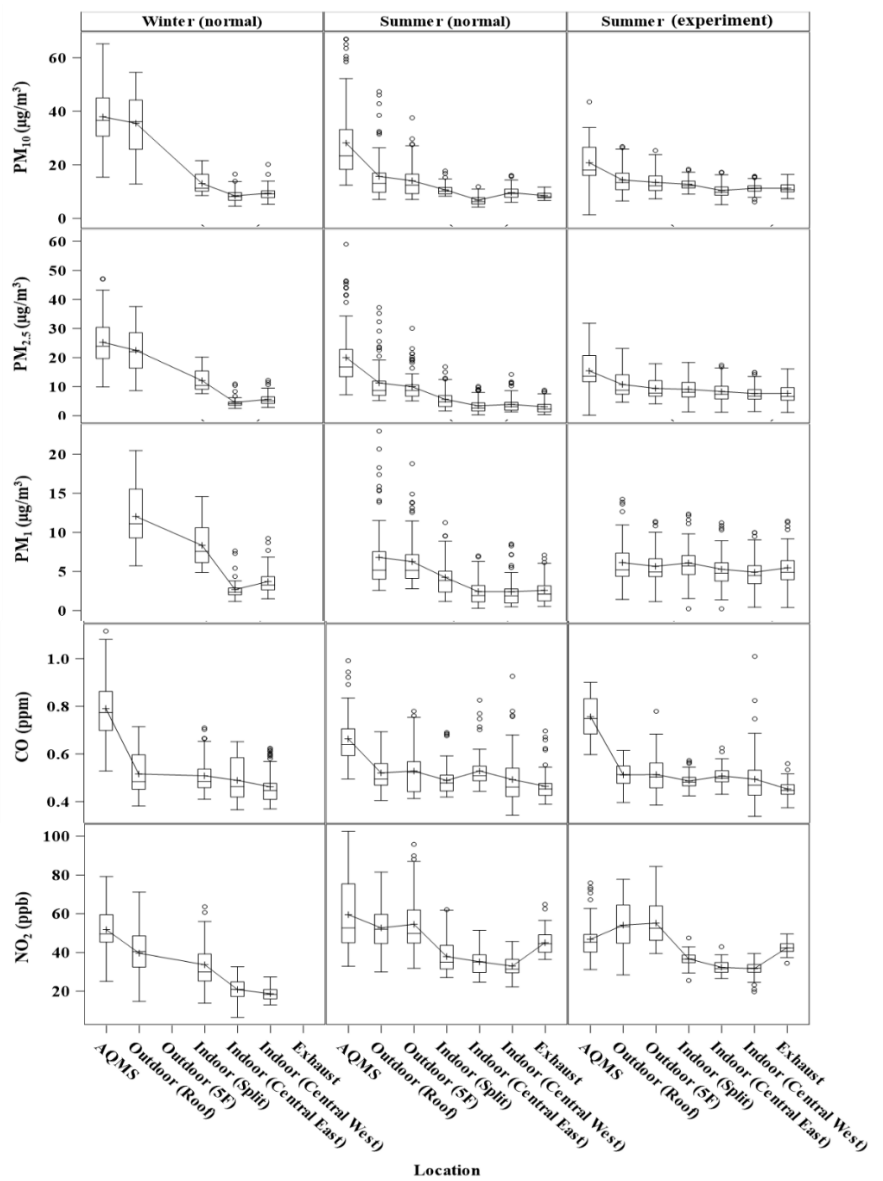

Figure 6. Air pollutant concentration measured at selected indoor and outdoor locations during HVAC operation compared with corresponding data from AQMS by period. When the outdoor air quality is worse, such as in winter, we can see that the air filter is working especially more efficiently. (Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

ABOUT NO$_2$:

The indoor NO$_2$ concentrations were 20-50% lower than those at the air intakes, possibly due to chemical loss from surface reactions inside the building, as well as the reactions in the filtering system and ventilation ducts

The average indoor NO$_2$ concentrations (20 ppb to 30 ppb in winter and 30 ppb to 40 ppb in summer) slightly exceeded the annual WHO indoor air quality guideline of 21 ppb for most of the sampling period [58].

Nevertheless, the indoor NO$_2$ concentrations were 20% to 50% lower than those at the air intakes. These results are consistent with studies conducted in the European cities, in which lower NO$_2$ concentrations were observed in indoor areas [59,60].

While the mechanisms for such reduction is uncertain, potential reasons include chemical loss from surface removal inside the building and also with the reactions in the filtering system and ventilation ducts [61,62].

ABOUT CO:

The indoor CO levels were also extremely low and below WHO IAQ guideline

The average indoor CO concentrations were below 1 ppm, well below the WHO indoor air guideline on CO for 24 hours (the largest time available interval in the guideline) of 7 mg/m^3 (6 ppm) [58]. There were no significant differences in CO concentration between locations or periods.

3.4 Association between indoor and outdoor air pollution

PM concentrations were very similar from air intake points on the 5/F and rooftop

Correlations between hourly concentrations of selected air pollutants at various indoor and outdoor locations were studied.

The particulate matter concentrations observed at 5/F outdoor sampling site and rooftop were found highly correlated to one another. This would mean that initial PM concentration at air intakes of the two PAHU systems were similar.

PM levels around the study building were mostly affected by regional pollution in winter than that in summer.

In winter, correlations between PM concentration measured at outdoor locations and the nearby AQMS were significantly high, indicating the persistent influences by northeast monsoon that brings in pollutants from the Asian continents.

In summer, the correlations in PM concentrations between AQMS and outdoor (roof) were still high but lower than those observed in winter, indicating that outdoor PM concentrations in summer were less affected by regional pollution (but instead more affected by local/district sources).

Indoor PM levels were found mainly influenced by outdoor PM pollution; whereas indoor PM$_{10}$ would have been affected by indoor sources

Indoor PM concentrations were found significantly correlated with outdoor values in both winter and summer, but the magnitude of correlations varied by particle size.

The link between outdoor and indoor values for PM$_{2.5}$ and PM$_1$ were very high (Spearman's correlation coefficients > 0.8) for any pair of indoor and outdoor locations for all three periods, indicating that the indoor exposure level to fine particulate matter was dominated by outdoor pollution.

However, the correlations for larger PM (i.e. PM$_{10}$) were lower than those of the smaller PM$_{2.5}$ and PM$_1$, which might be due to the fact that larger PM$_{10}$ could be generated during indoor activities, such as cleaning and construction, which may affect the contribution from

indoor sources and thus the correlations with outdoor PM_{10}.

Significant moderate to high correlations were observed between indoor and outdoor CO concentrations in both Winter (normal) and Summer (normal). The correlations between indoor and outdoor NO_2 concentrations were generally low, which might be associated with loss in chemical reactions between NO_2 and building materials.

It should be noted that there were no obvious indoor sources for CO and NO_2 because no combustion or smoking is allowed in the indoor office area. Therefore, the CO and NO_2 observed inside the building should be mainly ventilated from outdoor.

3.5   Impact of pleated filter on outdoor PM ingress

Figure 7 summarized the outdoor ingress values of PM_{10}, $PM_{2.5}$ and PM_1 at different sampling locations under both normal situations and experimental operations with the pleated filter being removed.

Outdoor ingress of various pollutants	Normal HVAC operation						Pleated filter removed		
	Winter (normal)			Summer (normal)			Summer (experiment)		
	Indoor (Central East) [a]	Indoor (Central West) [a]	Indoor (Split) [b]	Indoor (Central East) [a]	Indoor (Central West) [a]	Indoor (Split) [b]	Indoor (Central East) [a]	Indoor (Central West) [a]	Indoor (Split) [b]
PM_{10}	10%	10%	30%	20%	20%	30%	50%	40%	40%
$PM_{2.5}$	20%	20%	60%	30%	40%	60%	70%	60%	90%
PM_1	40%	40%	70%	40%	40%	70%	90%	80%	90%

Figure 7. Outdoor PM ingress values based on hourly PM concentrations between outdoor and various indoor locations during HVAC operation in different experimental period.

(a) Air intake from PAHU (with pleated filter) on the roof;
(b) Air intake mainly from PAHU on 5/F (without pleated filter)

(This table is developed based on information from the original article. Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

Filtering efficiency: $PM_{10} > PM_{2.5} > PM_1$

A consistent pattern is shown under all conditions that outdoor ingress rates of larger PM are smaller than those of smaller PM. This is because higher filtering efficiency occurs for larger particulate matters (PM_{10} in particular) than smaller particles.

Filtering efficiency for PM_{10} and $PM_{2.5}$: Winter > Summer

Differences in the outdoor ingress observed between winter and summer indicates that the performance of the pleated filters varies by seasons. Previous numerical studies indicated that the performance of the pleated filter was affected by the particle loading [63,64].

In this study, higher outdoor PM_{10} and $PM_{2.5}$ concentrations were observed in winter, which may lead to more PM loading on the pleated filter and thus increased the filtering efficiency.

The retrofitted HVAC system with two-stage filtration system is very effective in filtering PM

Under normal HVAC operation, outdoor ingresses of PM_{10}, $PM_{2.5}$ and PM_1 at Indoor (Split) on 5/F where the fresh air supply is mainly from Split PAHU (with aluminum only) were 30%, 60% and 70% in both winter and summer – higher than corresponding ingress values for those at Indoor (Central) from a magnitude between 10-40%.

This indicates that the retrofitted HVAC system with two-stage filtration system (particularly with the application of pleated filter) is effective in filtering PM and preventing outdoor PM from getting into the indoor environment.

Removing the pleated filter for experimental purpose doubled the outdoor PM ingress in summer

During the experiment period when the pleated filter had been removed, the outdoor ingress during summer (experiment) was twice as high as that during summer (normal), indicating that the indoor exposure to ambient PM_{10} would be doubled in a HVAC with an aluminum filter compared with the retrofitted HVAC with a two-stage filtration system that includes both an aluminum filter and a pleated filter.

For $PM_{2.5}$, the indoor concentration in summer (experiment) increased by 50% to 100% more than those under normal operations with pleated filters. This shows the benefits of upgrading the filtration system with a pleated filter in an HVAC retrofit to protect building occupants from exposure to outdoor fine particles.

Same case also happened on PM_1. The outdoor ingress was about 40% in both winter and summer when using the pleated filter, and was up to 80-90% when the pleated filter was removed in the experiment period. This further confirmed the importance of using pleated filter in filtering PM including ultra-small particles like PM_1, even though the filtering efficiency was not as high as those for larger PM particles.

3.6   Investment cost and payback period analysis

The net annual savings are 0.72 million HKD with payback period of 3.3 years

The initial investment cost for the retrofit measures mentioned in this study was approximately $2.4 million HKD (approx. 0.31 million U.S. dollars), which included the added split PAHU, specially designed cooling coils for dehumidification, the two-stage filtration system, pressurized indoor system for generating indoor positive pressure, and the upgraded BMS system for monitoring and controlling the ventilation and air conditioning.

The annual operation of the pleated filter (assume replacing every 3 months) is approximately $0.06 million HKD for the selected building of 16-stories. The retrofit measures led to an annual average energy saving of 670,000 kWh. Based on the electrical tariff policy, the annual energy saving is equivalent to $0.78 million HKD in capital.

While the net annual savings are $0.72 million HKD after deducting the operation cost of the pleated filter, the payback period is around 3.3 years using a simple calculation of the ratio between investment cost (i.e. $2.4 million HKD) and the net annual savings ($0.72 million HKD/year).

4. Discussions & Policy Recommendations

This study demonstrated a feasible building retrofit design for generating co-benefits on energy saving, thermal comfort and IAQ

Air conditioning contributed to the largest single energy end-use category (about 30% of energy consumption) in commercial buildings in Hong Kong [3]. A high-performance HVAC system thus plays an important role on saving energy use, reducing GHG emissions and mitigating climate change.

Nevertheless, improving energy efficiency is generally not popular for building occupants, as it has been easily misinterpreted as energy saving hence sacrificing people's thermal comfort.

This study demonstrated a successful case of building retrofit which has generated synergistic co-benefits on the energy efficiency-thermal comforts-IAQ nexus.

Dehumidification system is the driver for multiple benefits

In this study, the use of the dehumidification device with specially designed geometry is the major smart innovation leading to the multiple benefits on saving energy, improving thermal comfort and IAQ.
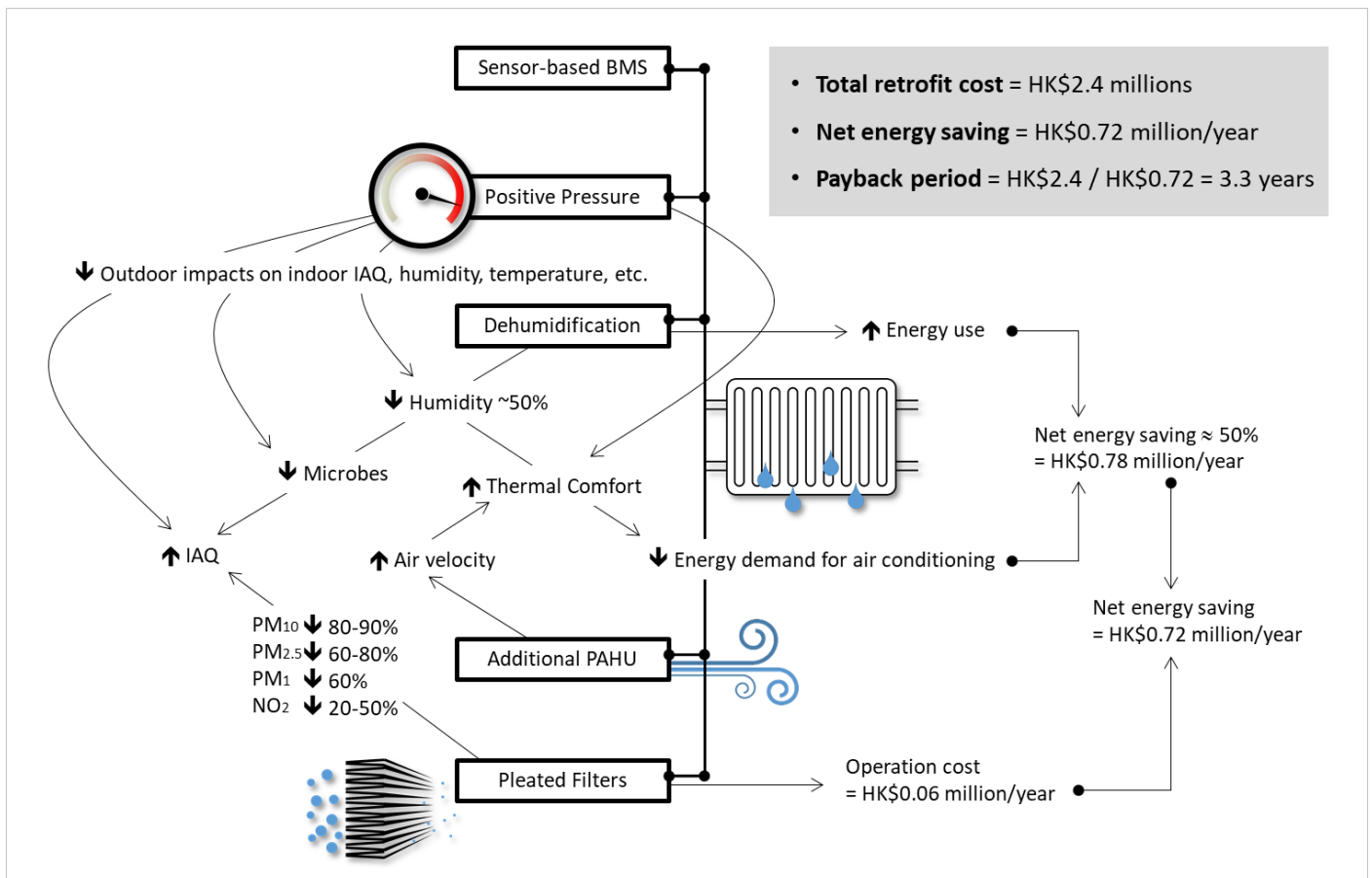
Figure 8. Schematics diagram showing the major retrofit components and key outcomes in this study design. (This figure is developed based on information from the original article. Please cite this figure as: W.W. Che, C.Y. Tso and L. Sun et al., Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system, Energy Build. 201 (2019) 202-215)

Net energy saving of 50%	Even though the process to remove moisture from air intake has resulted in increased energy consumption, the corresponding lowered indoor relative humidity has created a margin that favored considerable energy saving (from cooling indoor temperature particularly in summer under the context of hot and humid climate in Hong Kong).
	As a result, the net energy saving (among increased energy use in dehumidification and reduced energy use in cooling indoor air temperature) was noted 50% compared to the pre-retrofitted HVAC system, while at the same time maintaining generally acceptable indoor thermal comfort.
Considerable amount of GHG reduction	While air conditioning and ventilation systems were the leading cause of electricity usage in both the residential sector and commercial sector with approximately 35% each [3], and most of that electricity comes from coal-based power generation, decreasing the energy usage of air conditioning becomes a huge opportunity to decrease our carbon footprint and to help mitigating climate change.
Inhibited microbial growth hence improving IAQ	The lowed indoor relative humidity (around 50% in average) also inhibited growth of bio-aerosols, such as bacteria, viruses or fungi which might cause sickness to building occupants.
Enhanced air filtering system improved IAQ extensively	The retrofitted HVAC with two-stage filtration system of both aluminum filter and pleated filter was able to filter out 80-90% of outdoor PM_{10}, 60-80% of outdoor $PM_{2.5}$ and 60% of outdoor PM_1.
Positive pressure reduced negative impacts from outdoor environment	The application of a positive pressure also plays an important role in protecting the indoor environment from being affected by the outdoor temperature, humidity, pollutants and/or bio-aerosols for most of the time in Hong Kong.
Better thermal comfort and IAQ lead to improved health, productivity and wellness	Hong Kong has more than 9,000 high-rise buildings, a portion of which could be retrofitted with smarter HVAC systems. Coupled with high-efficiency air purifier filters and smart sensor-based BMS, upgraded ventilation systems not only save electricity cost and protect occupants' health but also increase productivity and wellness.
	For example, Fisk and Rosenfeld estimated that in the U.S., the financial benefits on health and productivity resulting from an improved indoor environment in an office with upgraded high efficiency filters may exceed the costs of filtration by as much as a factor of 20. [65].
Better IAQ also helps improve outdoor air quality	In this study, the fine particles level was found to have been reduced by 70% in the "exhaust" location, which flowed through the system and was then expelled to the outside. This remarkable finding suggested that the current retrofit system is capable to also improve the outdoor air quality when the indoor air is cleaned before being discharged to the outdoor environment!
Decision-makers should shape policies for high-	In view of the results from this study as well as the great potentials for buildings on improving both environmental and human health,

performance buildings

policy-makers in Hong Kong should prioritize high building performance in Hong Kong:

Baseline study for existing buildings

- Hong Kong should run a baseline study and identify existing building types and potentials/priority for HVAC retrofits.

Regulating IAQ and building energy efficiency standards

- While the existing Code of Practices for both new buildings and existing buildings do not mandate installations to improve indoor air quality or any integrated systems for higher energy saving objectives, policy-makers could consider to progressively tighten requirements for new buildings and develop timeline for building retrofits.

- Hong Kong should also plan the roadmap for formulating its IAQ Objectives in the long run.

- Concerted efforts from cross bureau collaboration – e.g. between Buildings Department (BD), Electrical and Mechanical Services Department (EMSD), and Environmental Protection Department (EPD) – are needed for the above objectives.

High-performance buildings is our smart city future to drive sustainability and wellbeing

- The Office of Government Chief Information Officer (OGCIO) released the "Smart City Blueprint for Hong Kong" in December 2017, with the mission to cover 6 objectives areas – including "Smart Mobility", "Smart Living", "Smart Environment", "Smart People", "Smart Government" and "Smart Economy".

- While "high-performance buildings" plays a key role unlock many smart city potentials, the Government should factor this into its smart city strategic development roadmap.

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