INVESTIGATING THE FACTORS AFFECTING INDOOR AIR QUALITY OF OFFICE BUILDINGS IN COLOMBO CITY – A CASE STUDY

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DECLARATION

"I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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(Dr. Inoka Manthilake)

ABSTRACT

The wellbeing, comfort, and satisfaction of office occupants are all influenced by the indoor air quality (IAQ). As such, it is important to maintain good IAQ in offices. However, several studies say that Sri Lankans have a limited understanding of IAQ. As a result, the aim of this research is to identify the factors that influence IAQ. Through this study, it is also expected to gain a better understanding of indoor air pollutants, recognize issues related to low IAQ, and determine ways to improve IAQ based on in situ levels of indoor air pollutants.

Following a walk through inspection, in situ measurements of IAQ were carried out in selected office spaces in Colombo, Sri Lanka, based on the findings of the literature review. Temperature (T), Relative Humidity (RH), Particulate Matters ($PM_{2.5}$ and PM_{10}), Carbon Monoxide (CO), Carbon Dioxide (CO_2) and Total Volatile Organic Compound (TVOC) were selected as the IAQ parameters. In addition, an experiment was conducted in a real office environment to measure TVOC concentrations in the presence of air fresheners and incense smoke.

Due to inadequate ventilation, the worst case of IAQ was found in office spaces which have no proper ventilation system. As a result, mechanical ventilation is appropriate to improve the IAQ of office spaces when natural ventilation is not possible. The key factors affecting IAQ in the selected office buildings of this study were identified as the location of the building, occupancy related activities, office equipment, and ventilation and air-conditioning system.

To improve and maintain good IAQ levels in a country, it is essential to have IAQ guidelines. However, it has been found that IAQ guidelines are not available in Sri Lanka. Conducting research on IAQ is essential for developing the country's IAQ guidelines.

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LIST OF ABBREVIATIONS

AHU	Air Handling Unit
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
Avg	Average
BRI	Building Related Illness
CO	Carbon monoxide
CO_2	Carbon dioxide
CRT	Cathode ray-tube
ETS	Environmental Tobacco Smoke
h	Hour
HKSAR	Hong Kong Special Administrative Region
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
LEED	Leadership in Energy and Environmental Design
MERV	Minimum Efficiency Reporting Value
Min	Minutes
N/A	Not applicable
NBRO	National Building Research Organization, Sri Lanka
PM	Particulate Matter
ppm	Parts per million
PABX	Private Automatic Branch Exchange
RH	Relative Humidity
SBS	Sick Building Syndrome
T	Temperature
TV	Television
TVOC	Total Volatile Organic Compound
USA	United State of America
VOCs	Volatile Organic Compounds
WHO	World Health Organization

LIST OF APPENDICES

CHAPTER 01: INTRODUCTION

The aim of this chapter is proving background information of the research. It also presents the problem formulation, aim, objectives, methodology and conceptual framework.

1.1 Background

Although people can survive for two weeks without food and for two days without water, an average person can only survive for few minutes without air [1]. The daily consumption of air by an average person is approximately 15 kg, which is a higher value comparative to the daily consumption of 1 kg food and 2 kg water approximately [2, 3]. Hence, the study on air is very important. Attention on the Indoor Air Quality (IAQ) was initiated due to the complaints of occupants about unspecific symptoms such as burning eyes, headache or fatigue, irritation or dryness of mucous membranes [4]. “Acceptable IAQ” is defined by ASHRAE Standard 62.1 as “air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction” [5].

Health, satisfaction and comfort of office workers are essential factors for better productivity [6]. Maintaining IAQ is a key element for achieving these factors of office workers [7] . Knowledge and concern on IAQ of the office environment in Sri Lanka are insufficient [8]. Hence, the IAQ of office buildings in Colombo Sri Lanka is investigated through this research.

1.1.1 Indoor air pollutants

Prior to study on IAQ, it is vital to know the indoor air pollutants and their sources. The WHO guidelines 2010 shows that carbon monoxide, nitrogen dioxide, benzene, formaldehyde, naphthalene, polycyclic aromatic hydrocarbons radon, trichloroethylene and tetrachloroethylene as commonly available indoor air pollutants [9]. Air contaminants are classified into two as particles (approximately above 3nm) and gases according to the state of matter [10]. Particles are further classified as solid particles, liquid particles and complex particles [11]. Solid particles are dust, fumes and bioaerosols. Liquid particles are mists and fogs. Smoke, smog and environmental tobacco smoke (ETS) are classified as complex particles. Gaseous contaminants are categorized into two, namely, organic and inorganic. Organic contaminants are further classified according to their volatility and all of them are called as Volatile Organic Compounds (VOCs) [12]. Carbon dioxide (CO_2), oxides of nitrogen (NO_X), carbon monoxide (CO), sulphur dioxide (SO_2), ammonia (NH_3) and ozone (O_3) are classified as inorganic gases, which have adverse effects on human health and comfort [10]. Classification of air contaminants according to the state of matter is shown in Figure 1 .

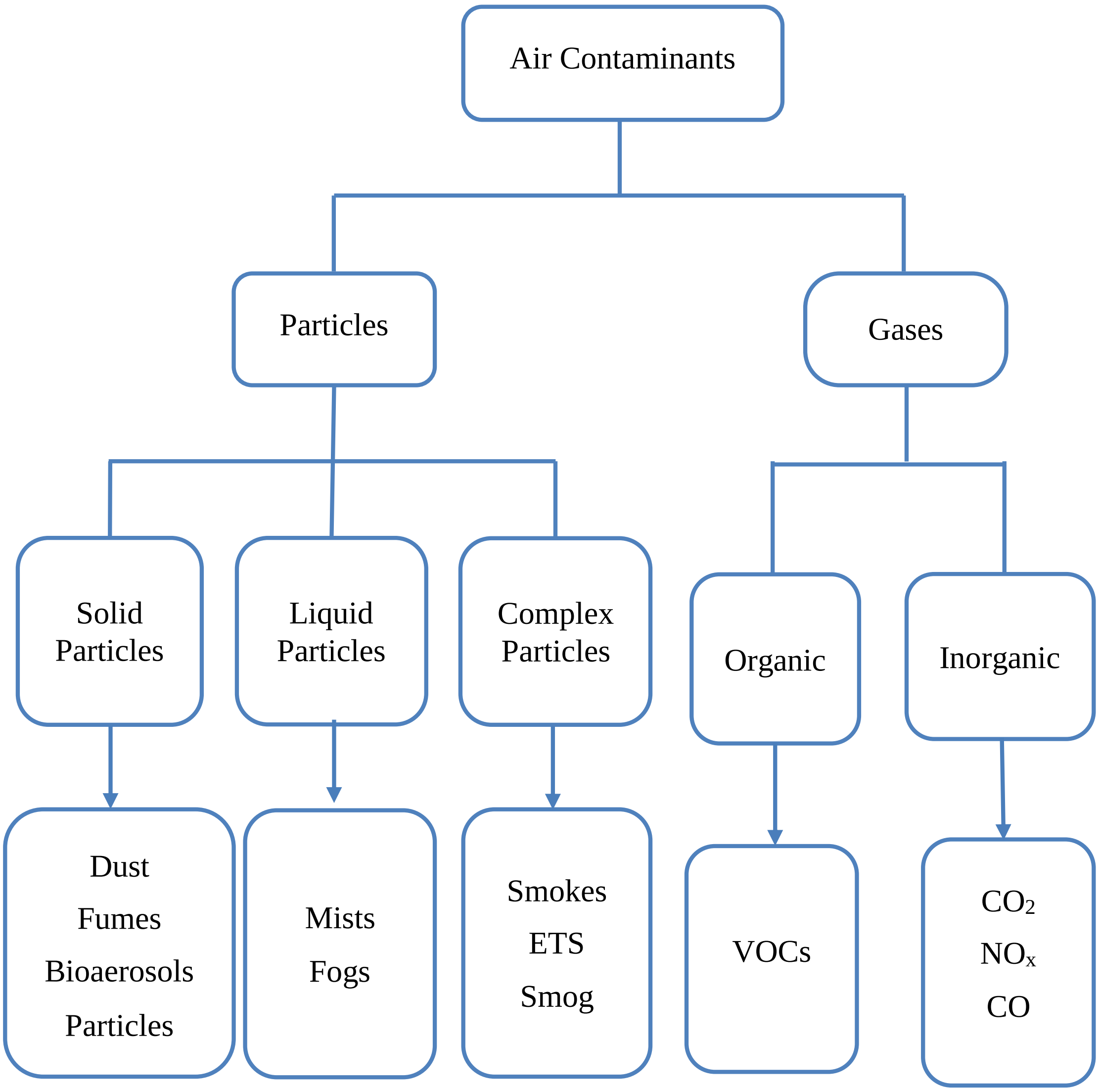

Figure 1:Classification of air contaminants according to the state of matter

1.1.2 Working environment

According to the Labour Force Survey conducted in 2017 by Department of Census and Statistics Sri Lanka, the employment shares of the Industry sector has been increased by 4.5 percentage points from 2011 to 2017 in Sri Lanka. During this period, employment shares of the Services sector has been increased by 2.6 percentage points [13]. Majority of employees in Industry and Services sector work inside an office. Hence, they spend 8 to 10 hours' indoor environment. Percentages of employment in Industry and Services sectors in Colombo district are 30.6% and 66.9%, respectively [13]. Hence, it can be derived that the majority of people in Colombo spend a higher percentage of their time indoors.

Split type air conditioners are popular in offices of Sri Lanka due to the ease of maintenance. These air conditioners do not have the ability to change the indoor air. The spaces that use this type of air conditioner rely on infiltration i.e, the air through cracks and other openings between the widows and door frames. If occupants do not move frequently, the air change rate will be extremely limited. Therefore, the quality of the conditioned air in an office space cannot be predicted. In one hand, if there is more fresh air in the space, it creates a waste of energy. On the other hand, if there is insufficient fresh air in the space, it leads to poor IAQ.

According to the shop and office employees act Sri Lanka, regular hours of working in a shop or office is 45 hours per week [14]. This amount would be higher with over time working hours. An average a person works for 30 years starting from the age of 20 to 55 years. Office personnel spend approximately 70,200 hours of the lifetime within the office indoors. Total hours for 30 years are 262,800. Hence, an office worker lives nearly 27% of his/her productive life time in an enclosed space. The population between the ages of 20 and 55 is the most important contributor to the country's economy. As a result, it's important to safeguard their health.

1.2 Problem formulation

An organization can have benefits such as improved staff morale, reduced staff turnover, reduced absenteeism, increased productivity and reduced health care through the workforce health promotion [15]. In accordance with the study by Nandasena et al. it is shown that both ambient and indoor pollution is a major public health problem in Sri Lanka [16]. Respiratory symptoms, low birth weight and lung cancers are identified as health issues due to exposure to ambient or indoor air pollution. It is found that both air quality level and air pollution are neglected public health problems in Sri Lanka. Hence, the study on the IAQ of office buildings in Sri Lanka is a matter of significance for a better future.

Most valuable asset of an organization is its employees. Employee satisfaction is an essential factor for developing an organization. A positive correlation between IAQ and lack of performance is observed [7]. Office performance reduces by 6%-9% due to poor air quality. Workers' productivity can be increased by optimizing the IAQ. Buildings must be maintained on a regular basis in order to achieve proper IAQ. Increases in workers' productivity is highly cost-effective because workers' salaries are much higher than building energy and maintenance costs [17]. The lack of comprehensive guidelines and attention on IAQ has resulted in many IAQ issues in office environments in Sri Lanka [18, 19].

Concentration of IAQ of offices is topical, since most of the office workers spent considerable amount of their time indoors. Due to emissions from inhabitants and their operations, as well as indoor products, IAQ is worse than outdoor air. Humans are not quickly affected by indoor air pollution. Its effect is slow and cannot be directly identified as there are many causes similar to the results of poor IAQ. As such, the study on IAQ is required to be performed carefully. As mentioned in many studies, poor IAQ is identified through complaints by occupants. However, there is doubt on the complaints of occupants, since some of these complaints depend on personal matters such as the sensitivity of the occupants.

1.3 Aim

To investigate the factors affecting the IAQ in office buildings.

1.4 Objectives

- To identify the indoor air pollutants
- To understand adverse effects of poor IAQ
- To explore the air quality of existing typical office buildings
- To propose methods of improving IAQ based on in situ level of indoor air pollutants.

1.5 Methodology

Phase I	Literature review on: • Indoor air pollutants. • IAQ and human health. • Factors affecting IAQ in office buildings. • Guidelines for IAQ.
Phase II	• Data collection survey on IAQ in office buildings. • Analysis of data to determine factors affecting IAQ.
Phase III	• Comparing the results with air quality standards for providing solutions to improve IAQ. • Prepare recommendations for establishing better IAQ in office buildings.

1.6 Conceptual framework

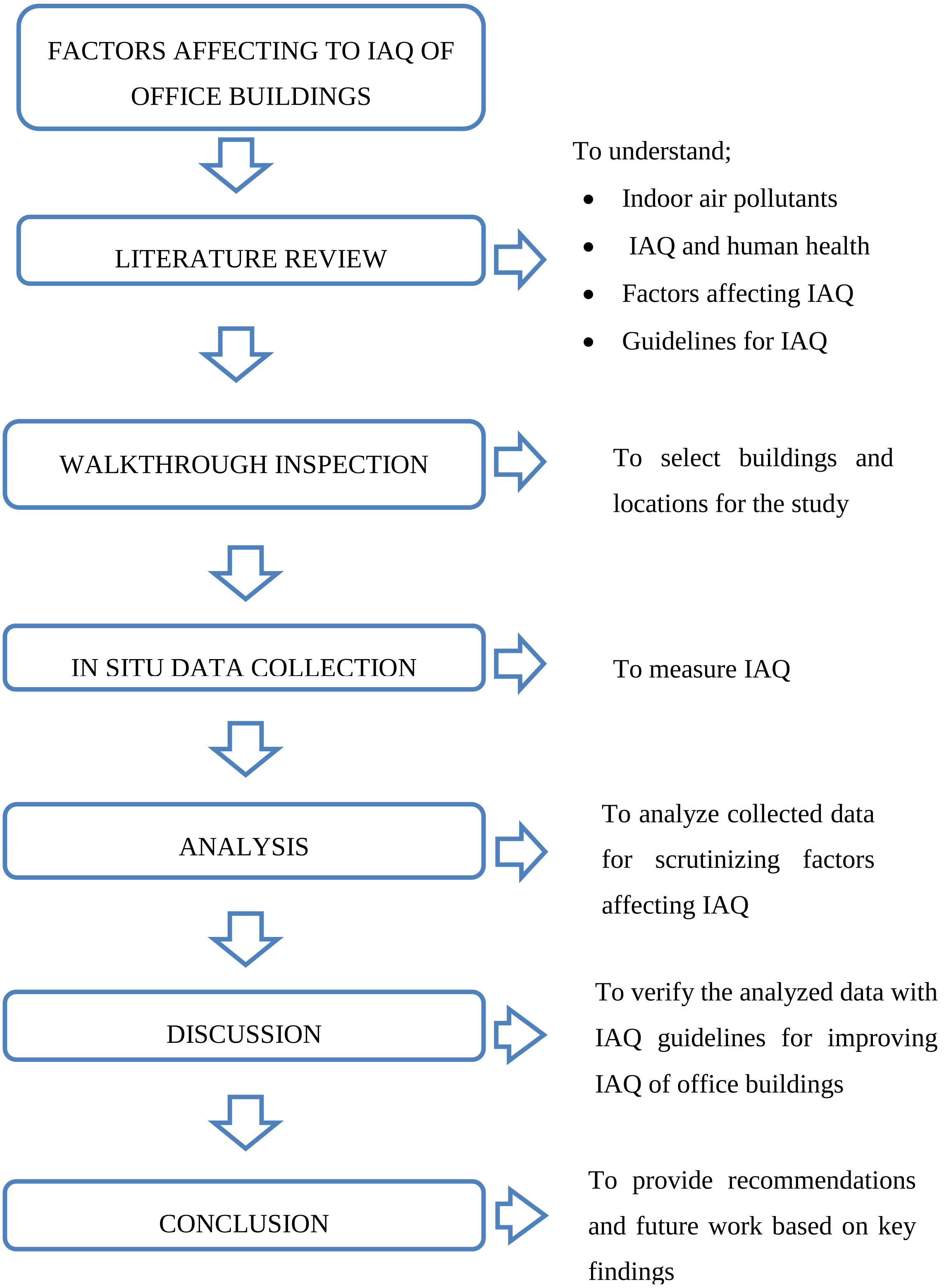

Figure 2: Conceptual framework of the study

CHAPTER 02: LITERATURE REVIEW

This chapter presents literature review on indoor air pollutants, living environment of people, IAQ & human health, factors affecting IAQ in office buildings and guidelines for IAQ. Further, the research gaps identified from the literature review are also presented.

2.1 Indoor air pollutants

Understanding of indoor air pollutants is very important for maintaining better IAQ levels inside offices. The causes for indoor air problems can be identified according to the type of pollutant, concentration, temperature, RH and time of exposure. Effects of poor IAQ on human health depend on the type of pollutant and exposure level.

2.1.1 Carbon dioxide (CO_2)

Carbon dioxide or carbonic acid gas is an odourless, colourless gas. Although it is not normally considered toxic gas, it is asphyxiant in limited spaces. The main source of CO_2 in the indoor environment is human metabolism. As such, concentration of CO_2 in indoor is higher than the outdoor air CO_2 concentration [20, 4]. A higher CO_2 concentration suggests the presence of other indoor air contaminants, and the upper limit of CO_2 for better ventilation is set at 1000 ppm [21].

Exposure to CO_2 levels ranging from 1,000 to 4,000 ppm for periods of 1 to 6 hours have an effect on the mind and cause inflammation in the human body [22, 23]. Kidney calcification, bone demineralization, physiological stress, and behavioral changes affect human health after exposure to CO_2 levels ranging from 700 to 3000 ppm for periods of 13 to 19 days [24, 23]. A study was conducted to discover the association between increased level of CO_2 and decision making. Participants were exposed to 600 ppm, 1,000 ppm and 2,500 ppm levels of CO_2 in an office type chamber and tested for decision-making performance for 3 hours. Moderate reduction of decision-making performance was observed at 600 ppm and 1000 ppm. At 2500 ppm, a large reduction in decision-making performance was observed [25].

According to a study conducted to determine the CO_2 levels in bedrooms, a lower concentration of CO_2 was observed in naturally ventilated bedrooms than air-conditioned ones. 1600 ppm of CO_2 level was observed in bedrooms utilizing air conditioners without fresh air intake [26]. CO_2 level was reduced from about 1200 to about 1000 ppm after opening the air vent of window type air conditioners. CO_2 levels at the bedrooms with portable air conditioners were floated around 750–800 ppm. 550 ppm to 600 ppm of CO_2 levels were reported inside naturally ventilated bedrooms [26].

2.1.2 Carbon monoxide (CO)

Carbon monoxide (CO) is an odourless, colourless, tasteless and toxic gas. It is a product of imperfect combustion of hydrocarbons. This gas can enter office environment by road traffic near the building, vehicle emission of parking garages and tobacco smoke [10].

CO goes in to the human body through inhalation and it is soluble in human blood. As a result of reaction between dissolved CO in the blood and haemoglobin, carboxyhaemoglobin is formed in the blood. This carboxyhaemoglobin reduces the availability of haemoglobin for carrying oxygen and causes arterial hypoxaemia. Further, carboxyhaemoglobin reduces the discharge of oxygen into tissues from blood. It is highlighted that the formation of carboxyhaemoglobin depends on the concentration of carbon monoxide in the inhaled air and duration of exposure to carbon monoxide [9]. Guidelines for the indoor exposure of CO are shown in Table 1.

According to the ASHRAE standard concentration of interest for CO is 9 ppm for the average time of 8 hours in nonindustrial environments. Indoor sources for CO are recognized as parking garages, combustion appliances, etc. It is reported that CO is hazardous for people who have health problems such as heart diseases and damaged lungs [5].

Monitoring of CO in an office building near busy roads was conducted in Central London. Spatial variation of CO was evaluated in this study. It is found that most of the CO comes inside from outside. Horizontal and vertical concentration of CO reduces all over the building away from the roads. The concentration of CO inside and outside of the building is highly variable and depends on the meteorological conditions [27].

Table 1: WHO guidelines for indoor CO exposure

Average time	**Concentration (mg/m^3)**
15 minutes	100
1 hours	35
8 hours	10
24 hours	7

Source: [9]

2.1.3 Particulate matter (PM)

Particulate Matter is categorized according to the size of the solid and liquid particles suspended in ambient air. It is denoted by PM_X and x is the size range of the aerodynamic diameter $\leq$ x µm [28]. The particle size fractions used in ISO/DIS 16890 –1 standard are shown in Table 2.

Table 2: The particle size fractions denoted by ISO/DIS 16890-1 standard

Fraction	**Size range**
PM_{10}	$\leq$ 10 µm
$PM_{2.5}$	$\leq$ 2.5 µm
PM_1	$\leq$ 1 µm

Source: [28]

Attention on the size of the particles is essential, since the deposition of PM on human respiratory system depends on the size of the particles. The deposition efficiency of smaller particles on the pulmonary and trachea region is higher than the nasal region of human respiratory system. It is pointed out that 99.9% of particles in normal air are below 1 µm [10]. Particles below 0.1 µm do not have exact settling velocity and they act as gas molecules. Particles between 0.1 and 1 µm have predictable settling velocities and it is negligible. Although, the settling time of the particles greater than 10 µm such as skin flakes is five seconds. Particles below 0.1 µm such as viruses take approximately ten days for settling. The settling time of particles 1 to 5 µm such as bacteria is ten hours [10].

Particles are further categorized as Inhalable, Thoracic and Respirable particles according to their ingress into various compartment of the respiratory system. Particles enter the respiratory tract and head airways during breathing are called Inhalable Particles. Thoracic particles are the particles, which can enter the gas exchange region of the lung through lower respiratory tract. The particles which are capable of entering the alveolar regions are called Respirable Particles [29]. The cleaning processes such as vacuuming and sweeping produce indoor particles. Human movements, cooking, animal and plants are also sources of indoor air particles. Chemical compositions of the particles depend on its origin and sources. It is understood that particles generated by combustion processes consist of carbon and organic compounds. Toxic compounds are deposited on the human respiratory system through the particles. The cause for this deposition is the absorption of harmful materials such as polycyclic aromatic hydrocarbons into the particles [30].

Although, numerous health effects on humans due to exposure to the Particulate Matter, it affects respiratory and cardiovascular systems mainly. Vulnerability to the pollution depends on the health condition and the age of the victims. According to WHO, PM_{10} is called Coarse Particles and main sources are construction activities and road dust. $PM_{2.5}$ is called Fine Particles and it is generated through the combustion of wood and biomass fuels [31].Considering the lung cancer mortality and other health effects, WHO has specified guidelines for particulate matter as shown in Table 3.

Table 3: WHO guidelines for particulate matter

Averaging time	Concentration of PM_{10} (µg/m^3)	Concentration of $PM_{2.5}$ (µg/m^3)
24 hour	50	25
Annual	20	10

Source: [31]

Parking garage, cooking and outdoor air are identified as indoor sources of $PM_{2.5}$. ASHRAE standard for $PM_{2.5}$ is 15 µg/m^3. Considering respiratory morbidity and aggravating of asthma, ASHRAE standard for the annual exposure of PM_{10} is 50 µg/m^3. Nose and throat irritation to premature death is identified as adverse health effects due to exposure to PM_{10} [5].

2.1.4 Volatile organic compounds (VOCs)

Volatile organic compounds are the chemicals containing carbon and they contribute to photochemical reactions in ambient air. VOCs are organic chemicals, which have extraordinary vapour pressure at room temperature. Normally, boiling points of VOCs are in the range of 50 to 250 ^{0}C and vapour pressure is higher than 0.01 Pa or 0.1 Pa [10, 12]. WHO categorization of VOCs according to the volatility is shown in Table 4. Commonly available VOCs in indoor air identified in previous studies are shown in Table 5.

Table 4: Classification of indoor organic pollutants

Description	Contraction	Boiling Point Range, ^{0}C
Very volatile (gaseous) organic compounds	VVOC	0 to 50–100
Volatile organic compounds	VOC	50–100 to 240–260
Semi volatile organic compounds	SVOC	240–260 to 380–400

Source: [10, 12]

Table 5: Commonly available indoor volatile organic compounds

Benzene	Toluene
Chloroform	Styrene
Trichloroethylene	Ethyl acetate
formaldehyde	Dichloromethane
Isopropanol	Tetrachloroethylene
Butane	Ethanol
Naphthalene	Acetone

Source: [10]

The building materials containing volatile organic compounds emit them to the indoor air through evaporation or sublimation. Even inorganic or metallic surfaces can respond as a source of VOCs, as they emit VOCs accumulated on the surfaces due to the sink effect. Emission rate and the source strength are major factors affecting to the concentration of VOCs in indoor air. The duration of VOC emissions displays the strength of source. Materials such as mothballs have a constant emission rate until it is finished. However, materials such as paint coatings emit VOCs for a short period, which would be few minutes, hours or days after the application. It is shown that factors such as temperature, humidity, volatility of the constituents, the age of the materials influence the emission rate of VOCs [12]. In addition to building materials, cleaning products, adhesives, cosmetics, pesticides, clothing and carpets have been identified as sources of VOCs. A large number of VOCs emit indoor air through environmental tobacco smoke [4].

Benzene is a colourless, highly flammable, volatile organic compound. It has a pungent odour. WHO does not recommend a safe exposure level for benzene, since it is genotoxic carcinogen for human beings. The indoor concentrations of benzene are generally higher than that of the ambient air. In addition to the outdoor air, emissions from furniture and consumer products and smoking are the main indoor sources of benzene. WHO has assessed that excess lifetime risk due to the concentration of 1 $\mu g/m^3$ of benzene in indoor air is 6×10^{-6} [9]. Aplastic anemia and acute myelogenous leukemia are major health effects due to the exposure of benzene [32].

Formaldehyde is a colourless gas with pungent odour. Formaldehyde is added to the indoor environment through combustion processes such as cooking, smoking and incense burning. Indoor materials such as furniture, plywood, fiberboard and adhesive contribute to enhancing the indoor concentration of formaldehyde. Individuals recognize formaldehyde below the concentration of 0.1 mg/m^3 due to its pungent odour. It is found that 4 hours' exposure to 0.38 mg/m^3 of formaldehyde cause sensory irritation of human eyes. Redness in the conjunctiva of the eye and increase in blinking frequency occurs at 0.6 mg/m^3 [32].

a. Total volatile organic compound (TVOC)

Several studies have used the concept of total volatile organic compounds considering the difficulty of measuring individual VOCs separately. Total volatile organic compound is used to measure the exposure level and an indicator of IAQ. Thus, it is used to measure the likelihood of health and comfort. Concentrations of TVOCs in non-industrial indoor air are less than 1 mg/m^3 and in some places it goes beyond 25 mg/m^3 [33]. Higher concentration greater than 25 mg/m^3 of TVOCs is a major cause for various human health effects. The increase in sensory effects such as sensory irritation, dryness of eyes and nose occurs due to the increase in TVOCs over 1 mg/m^3. However, it is not confirmed that sensory irritation caused by total mass concentration of TVOCs at low exposure limits in non-industrial environment. Due to the lack of human exposure studies and inconsistency of the results of epidemiological studies, exact guidance for the exposure limit of TVOCs has not been decided in order to have better human health and comfort [33] . It is recommended to set targets for individual VOCs rather than setting targets for TVOCs concentration [5].

2.2 Living environment of people

A National Human Activity Pattern (NHAP) Survey was conducted in United State in order to determine human activity patterns in United State of America from 1992 to 1994 by the University of Maryland's Survey Research Centre. It is observed that respondents of this survey spend an average of 87% of their time indoors. These indoor locations were indicated mainly as residence, office or factory, bar or restaurant or some other indoor location [34].

After exploring time use surveys worldwide, it is understood that people spend more time working other than sleeping per average day. Time spent for working is higher in developing countries [35]. In Asia/Pacific countries people work one quarter of the day approximately [36]. According to the time use survey conducted in Sri Lanka in 2017, mean population spend 8 hours and 6 minutes for sleep & related activities and 3 hours and 12 minutes for work-related activities [37]. It has been reported that time spent for all other activities are less than work-related activities other than sleep-related activities. Hence, the working environment is a concerning factor for human health in a developing country like Sri Lanka.

2.3 IAQ and human health

According to a report published by the Commission of the European Communities, there are several effects on human respiratory system due to exposure to indoor air pollution. Acute and chronic changes in pulmonary function can occur due to exposure to indoor air pollution [38] . In terms of health effects, indoor air pollutants affect the respiratory and cardiovascular systems directly. The intensity of the pollutant and period of exposure determine the severity of the effect on human health [39]. Indoor air pollution is more dangerous, since the pollutants are emitted too close to the occupants. After analysing global mortality, it is revealed that the total deaths due to indoor air pollution are higher than the outdoor air pollution [40]. Concerning factor for the deaths due to the indoor air pollution is suspended particulate matter. Suspended particulate matter affects lungs heavily in indoor air as they are insignificant and can penetrate deeply into the lungs. Air contaminants, individual sensitivity, exposure limit and duration of exposure are factors affecting to the human health due to poor indoor air quality. Although 100,000 numbers of poisonous pollutants are available, the exposure limit is curtailed to less than 400 substances. Numerous diseases from eye irritation to lung cancers are identified due to indoor air pollutants [41].

The issues due to the IAQ are described in three categories such as Building Related Illness (BRI), Sick Building Syndrome (SBS) and performance and efficiency of office workers.

2.3.1 Building related illness (BRI)

Sick Building Syndrome (SBS) and Building Related Illness (BRI) are two terms found in past literature regarding the health issues of buildings. In BRI, symptoms can be identified and causes for the illness can be clinically recognized. Complains from the occupants are the illness such as fever, cough and chest tightness. The occupants who suffered from BRI need a long period for recovery [42]. Allergic and immunologic disease, infections and exposure to chemicals are the three main categories that cause BRI. Building Related Illness is associated with distinct illnesses such as asthma, Legionnaire's disease, pneumonitis, but no causes are obvious to SBS [43]. Building related diseases are less common and can cause significant medical illnesses. Subjective nature, reversibility and high prevalence are factors to be distinguished BRI from SBS [44].

2.3.2 Sick building syndrome (SBS)

According to the past literature prevalence of the SBS symptoms among the occupant of office buildings is common. Hence, it is expected to focus on SBS in this study. SBS is defined as “a generic term used to describe common symptoms which, for no obvious reason, are associated with particular buildings” [45]. There is no exact definition for SBS in past literature. Symptoms are common to a particular building and victims recover from the symptoms within few hours after leaving the building. It is found that indoor environmental factors such as air contaminants and ventilation affect SBS. Individual risk factors affecting SBS are identified as gender and job stress. Due to the dependability of these factors, it cannot give a broad view for SBS [46].

A study was conducted to investigate the relationship between SBS symptoms and psychosocial, environmental and personal factors. Primary school students in Iran were selected for the study. It is observed that 43% of students were having SBS symptoms [47]. The prevalence of SBS symptoms among female students is higher than male students. Hence, gender is identified as a significant personal factor affecting to the SBS. Headache is identified as the most common SBS symptoms. In addition to headache, confusion, fatigue and nausea are identified as common symptoms. The size of the classroom, lights, ventilation and age of the building are identified as significant factors affecting SBS among primary school students. A survey was conducted to determine the prevalence of SBS among office workers and the factors influencing them in the United State of America (USA). 4,373 of office workers at 47 offices in USA were used in this survey. Different types of ventilation systems were available at selected buildings. According to the results of this study, it has been reported that SBS was common in air-conditioned buildings [48]. Features of the ventilation system are directly affected the prevalence of SBS symptoms in office buildings. Although, some differences in symptoms are observed between naturally and mechanically ventilated buildings, they are identified as reliable healthiest workplaces. Further, air-conditioned buildings ventilated by all air systems are identified as healthier buildings than water-based systems. Air conditioned buildings, which have operable widows indicate as healthy as naturally ventilated buildings [48].

Semi-structured interviews were conducted to study the influence of SBS on office workers using three buildings in the urban area in Sri Lanka. Further, previous literature from 1990 to 2010 was reviewed in this study and it is revealed that building-related factors including poor IAQ are common factors associated with SBS. Subsequently, indoor climate is identified as a significant factor affecting SBS. It is observed that the measurement of IAQ is a hard task in Sri Lanka considering the cost. Hence, the occupants have become victims of SBS especially in the industry. Further, SBS has not been identified as an issue of the buildings in Sri Lanka due to the lack of knowledge or it has been identified as BRI. The likelihood of prevalence of SBS in Sri Lanka is high [49].

2.3.3 Effect on performance

According to the research conducted to study the influence of perceived IAQ on productivity loss, it is proved that there is a positive linear correlation connected with productivity loss and perceived air quality [50].Thinking and typing tasks were tested to measure the productivity with perceived air quality. It is revealed that the loss of productivity in thinking is worse than productivity loss in typing. Five to nine percent loss of productivity was observed with the minimum acceptable outdoor air flow rate of 0.5 to 1.5 liters per second.

The presence of computers (with Cathode Ray Tube monitors) declines the IAQ by influencing the performance of office type work [51]. Although 10 liters per second fresh air was supplied, 40% of dissatisfaction in perceived IAQ was observed with the presence of computers. Proofreading has not been affected considerably. But, time spent for text processing was increased by 9%.

An experimental study was conducted to determine the influence of ventilation rate for the performance of office work and perceived air quality. Performance was checked under exposure of VOCs which were emitted from new finishing materials for a period of eight hours. It was observed that the working performance increases 2.5 to 5% with an increase in ventilation from 5 to 20 liters per second per person [52].

SBS symptoms, perceived air quality and productivity were tested in an existing office building. The level of indoor air pollution of the office was changed by introducing or removing a source of pollutant, which was 20 years old used carpet. It is found that air quality dissatisfaction is about 7% higher than after introducing the pollution source. Bad IAQ was associated with increased headaches and lower rates of concentration during text typing and calculation tasks [53].

2.4 Factors affecting IAQ in office buildings

According to the past literature, there are so many factors influencing indoor air pollution in office buildings. The impact of these factors seems to be varied in different buildings. Hence, understanding of these factors is vital to take necessary measures to improve indoor air quality. Thermodynamic factors and building-related factors are the two primary categories of these factors.

2.4.1 Thermal factors

Temperature, humidity and ventilation are discussed under the thermal factors.

a. Temperature

Temperature, humidity and ventilation are the main physical factors affecting indoor air pollution. Increased room temperature enables the spread of air contaminants and the release of air contaminants from construction materials and furniture [54]. The existence of dust and suspended bacteria is increased with the humidity level less than 20%. Indoor spaces with humidity greater than 60% and high temperature indicated the presence of germs and mold when the required level of ventilation is not available [54].

b. Humidity

The effect of temperature and humidity on chemical and sensory emission from building materials were tested using a climate chamber. The building materials used for this test are carpet, sealant, floor varnish, polyvinyl chloride flooring and wall paint. Humidity in the range of 30%-70% affects floor varnish and wall paint significantly. Temperature in the range from 18 ^{0}C - 28 ^{0}C does not show a significant effect on chemical or sensory emission [55].

c. Ventilation

Ventilation is an essential factor related to the IAQ. In Sri Lanka, a study was performed to measure CO_2 levels with various ventilation patterns. The lower level of CO_2 was recorded with good ventilation rates. Void to wall ratio and good window-operating schedule were identified as related factors for good ventilation. Further, it was found that the decrease in CO_2 level with an increase in wind speed. This study has concluded that better ventilation and recharge of fresh air can maintain CO_2 level around 500 ppm with acceptable level of comfort and no complaints on SBS symptoms

[56]. In addition to CO_2, concentration of particulate matter, formaldehyde, carbon monoxide and nitrogen dioxide reduces with the increased rates of ventilation in an office building [57]. A slight increase in perception of odour was observed with a decrease in ventilation rates.

A study was conducted to determine the possible effects of ventilation rates and air filters on indoor concentration of $PM_{2.5}$ and ozone in Los Angeles and Beijing. It was observed that two filter system (outdoor air filter and AHU filter) more resilient to the outdoor $PM_{2.5}$ level than single filter system (AHU filter only). 28% reduction in $PM_{2.5}$ level was observed during the usage of two filter system when ventilation rate increased from 8.5 to 34 L/s per person. In the case of ozone, indoor concentration was increased by 141% due to the increase in ventilation rate from 8.5 to 34 L/s per person. Although 73% reduction in indoor concentration of ozone was observed with the use of AHU filter, addition of outdoor air filter has reduced only 2% of indoor concentration. Hence, two filter system has marginally affected the indoor ozone level.

Further, MERV rating of the filters has a positive effect on the reduction of indoor $PM_{2.5}$ level. The increase in MERV rating from 8 to 16 has contributed to reducing the indoor concentration of $PM_{2.5}$ level over 91.3% [58].

According to a study conducted in Quebec using 17 schools and office buildings, reason for indoor particulate matter is identified as the infiltration of outdoor air. In mechanically ventilated building, the efficiency of the HVAC system filters directly affects the indoor concentration of dust. Further, human activities are also related to the indoor concentration of dust [59]. It is found that indoor NO_2 concentration increases due to the infiltration from outdoor air [60]. It is shown that indoor concentration of NO_2 is higher in schools than that of in offices. Since the schools are ventilated naturally, infiltration of outdoor NO_2 is at higher level than offices. Since most of the offices are ventilated mechanically, a smaller quantity of NO_2 enters the offices through filters [60].

2.4.2 Building related factors

Equipment, activities, location and occupancy are discussed under the building related factors.

a. Equipment

It is reported that VOCs emission rate of cathode ray tube monitors is higher than the thin film transistor monitors [61]. VOCs emission rate of notebook computers is low. It is found that several SVOCs are emitted by computes. For example, the plastic covers of the video display units emit triphenylphosphate flame retardants and printed boards at 60 ^{0}C emit polybrominated diphenyl ether. Although the office equipment is not strong indoor air pollutant sources compared to the other sources, personal exposure for indoor air pollution is higher due to the close proximity and the duration of the usage of office equipment [61]. Effects on IAQ were investigated during laser-printing processes in an office environment. It was observed that VOCs emission rate is higher during a laser printer is working. Ozone and $PM_{2.5}$ concentrations are shown in low levels during the idling process of the printers [62]. Higher levels of VOCs are reported in nonsmokers' office due to the use of photocopy machines and tile adhesives [63] .

b. Activities

Building renovation and maintenance work are matters to be considered for generating dust. It is observed that repainting increases indoor VOCs concentration 3 to 4 times than normal concentration [59]. The places where much paper work is handled in offices are observed with high concentrations of dust. Building and air inlet locations are significant factors to be considered for infiltrating pollutants into buildings. The IAQ of buildings, which have air inlets faced to main streets is poor. Infiltration through elevators from parking garages is identified as a main factor affecting to indoor CO concentration [59].

c. Location

The location of the building is a significant factor related to the indoor concentration of indoor NO_2, because concentration in schools in urban areas is higher than schools near the oil and gas industry areas. Prevailing traffic of the area affects the indoor concentration of NO_2. It is found that the concentration in the morning and evening is high due to the traffic condition of the road at these times [60].

d. Occupancy

Occupancy is a key factor affecting indoor air pollution of office buildings. The primary indoor source for carbon dioxide is human respiration [10]. Each exhale of an average adult holds 35,000 ppm to 50,000 ppm of carbon dioxide [58].

Use of various products inside the buildings directly enhance the level of pollutants. Cleaning agents and air fresheners play a major role in this [64]. In addition to the emission of direct harmful chemicals, cleaning agents and air fresheners react with the available contaminants in air to generate secondary hazardous chemicals. The formation of formaldehyde as a result of reaction between terpenes in air fresheners and ozone in indoor air is an example for the of secondary pollutant [64]. It is further revealed that operational practices of a building such as spraying of air fresheners influence the indoor environment. TVOC and CO levels in indoor air increases after spraying air fresheners [65].

According to a study conducted using three different type of indoor environments, it is found that the concentration of particulate matter increases due to the high occupancy [63]. A positive correlation between occupancy and carbon dioxide, temperature, and airborne bacteria was revealed according to the results of a research conducted using air conditioned public offices [61].

2.5 Available guidelines for IAQ

It is expected to compare the measured indoor air pollutant levels with IAQ with prevailing IAQ guidelines. WHO, ASHRAE, Hong Kong IAQ and LEED guidelines are used for the comparison since, Sri Lanka does not have IAQ guidelines. Further, many researchers use WHO, ASHRAE and LEED IAQ guidelines worldwide. Since Hong Kong and Sri Lanka are in the same South Asian region, this study focused more on Hong Kong IAQ Objectives. Summary of all these guidelines are shown in Table 6.

2.5.1 ASHRAE IAQ guidelines

ASHRAE 62.1 is the IAQ standard introduced for the commercial and institutional buildings by American Society of Heating, Refrigerating and Air-Conditioning Engineers. This standard is most widely used for quantifying suitable conditions and proper HVAC system design [66]. The aim of ASHRAE 62.1 is to define minimum ventilation rates and other steps that will provide human occupants with sufficient IAQ while minimizing adverse health effects. This standard is applicable for improving the IAQ in new buildings and existing buildings. But, this is not applicable for residential dwellings, since their occupants are non-transient. Further this is not applicable for the spaces that contains smoking. Chemical, physical, and biological pollutants that can influence air quality are the basis for the ventilation requirement of the ASHRAE 62.1 standard.

CO levels do not exceed 9 ppm for an average of 8 hours, according to ASHRAE 62.1. The effects on people with coronary artery disease are used to calculate this CO level. CO_2 levels should not be higher than 700 ppm above outdoor levels, according to this guideline. ASHRAE annual standard for $PM_{2.5}$ and PM_{10} are 15μg/m^3 and 50 μg/m^3 respectively. The PM_{10} level was set to safeguard the general public from respiratory morbidity and asthma aggravation [67]. Recommended indoor air operative temperature ranges for thermal comfort are 20.0 - 23.5 °C and 22.5 - 26.0°C in winter and summer respectively, according to the ASRAE standard 55 [68]. It is further defined that if the RH is 30%, the comfortable temperature range in winter is 20-24 ^{0}C with warm clothing. If the RH is 60%, the comfortable temperature range in summer is 24.5-28 ^{0}C with light clothing. The upper limit of the RH has been defined as 60% by ASHRAE 55 [69]. ASHRAE has not stipulated a lower limit of RH for thermal comfort. However, a lower level of RH causes human health issues. As such, considering human health factors, a lower level of RH has been defined. Summer RH values of 40–60% and winter RH values of 30–60% were established by ASHRAE [68].

2.5.2 World health organization (WHO) IAQ guidelines

The World Health Organization (WHO) has established air quality guidelines to protect public health from the hazards of a wide range of chemicals contained in indoor air. The WHO expects to reduce the exposure to hazardous air pollutants to a minimum level by establishing air quality guidelines [9]. These guidelines are focused on a thorough examination and assessment of the scientific evidence on the toxic properties and health effects of indoor air pollutants. Since WHO guideline values cannot fully protect human health, the WHO proposed establishing IAQ goals by area, based on WHO guidelines. The evidence review of the WHO guidelines has included indoor sources, current indoor levels, and their connection to outdoor levels of the considered pollutants [31].

WHO has established four guidelines for CO considering exposure times, which are 15-min, 1-h, 8-h, and 24-h. The 15-min guideline is intended to prevent against short-term peak exposures like those caused by an unvented stove. The 1-h limit is intended to prevent overexposure to CO levels, such as from faulty appliances. The 15-min and 1-h guidelines for CO are 100 mg/m^3 and 35 mg/m^3 respectively. 15-min and 1-h exposures should not be occurred more than once a day according to WHO guidelines. The 8-h guideline of 10 mg/m^3 for CO is applicable to occupational exposures. Based on epidemiological studies, WHO established a 24-h CO guideline of 7 mg/m^3 [9]. Considering the study on cardiopulmonary and lung cancer mortality, WHO has established annual guideline for $PM_{2.5}$ and PM_{10} as 10 μg/m^3 and 20 μg/m^3 respectively. In order to reduce health risks based on short exposures, WHO 24-h guidelines for $PM_{2.5}$ and PM_{10} are 25 μg/m^3 and 50 μg/m^3, respectively [9].

2.5.3 Hong kong IAQ objectives

In order to use the IAQ Certification scheme for offices and public places, the government of the Hong Kong Special Administrative Region (HKSAR) IAQ management group has developed IAQ objectives. The IAQ Objectives assigned unique guideline values to twelve parameters that influence IAQ, including three physical and eight chemical parameters. For the ‘Excellent' and ‘Good' classes, values for each of the twelve parameters were defined as benchmarks. The maximum permissible values for each of the IAQ parameters are designated as ‘Good' class values. Unsatisfactory values are those that exceed the ‘Good' class values [70].

In an 8-h average, the HKSAR IAQ management group set CO concentration values of 2,000 μg/m3 for "Excellent" IAQ and 10,000 μg/m3 for "Good" IAQ. CO_2 concentrations of 800 ppm and 1,000 ppm over an 8-h period have been established as “Excellent” and ‘Good' IAQ, respectively. A guideline for $PM_{2.5}$ has not been included in Hong Kong IAQ objectives. However, concentrations of PM_{10} not greater than 20 μg/m^3 over 8-h period are classified as ‘Excellent’ IAQ. If the PM_{10} concentration is less than 180 μg/m3 over 8-h period, the IAQ classification is ‘Good.' The guideline for a 'Excellent' classification of TVOCs is 200 μg/m3, while the guideline for a 'Good' classification is 600 μg/m3 for an 8-h period.

For ‘Excellent' air quality, the temperature should be between 20 and 25.5 °C, and for ‘Good' air quality, it should be less than 25.5 °C. The HKSAR IAQ management group established standards of 40 - 70% RH for "Excellent" IAQ and less than 70% for "Good" IAQ.

2.5.4 Leadership in energy and environmental design (LEED) IAQ requirements

LEED is a green building rating system that establishes a framework for creating sustainable, energy-efficient, and cost-effective green buildings. LEED v4.1: Operations and Maintenance has been developed to pay close attention of the operation of existing buildings [71]. The prerequisites for this rating system for existing buildings are water efficiency, energy, and atmosphere. Indoor Environmental Quality Performance was added to the LEED rating system to evaluate a building's performance in terms of IAQ and comfort. An occupant satisfaction survey and an IAQ assessment are required as part of the Environmental Quality Performance. For IAQ assessment, points are awarded depending on the outcomes of CO_2 and TVOC measurements. The CO_2 scoring function used an industry benchmark of 1000 ppm of CO_2 concentration. The TVOC scoring function was established in the LEED rating system based on a TVOC level of 500 $\mu g/m^3$ [71]. According to LEED standards, the expected concentrations of $PM_{2.5}$ and PM_{10} are 12 and 50 $\mu g/m^3$ respectively in buildings under ventilation conditions typical for occupancy [72].

Table 6: Summary of WHO, ASHRAE, Hong Kong and LEED IAQ Guidelines

Parameters	ASHRAE	Hong Kong IAQ Objectives (8-h Avg) Excellent Class	Hong Kong IAQ Objectives (8-h Avg) Good Class	WHO	LEED
T	20-23.5 °C (winter) 22.5 °C-26.0°C (summer)	20 to < 25.5 °C	< 25.5 °C	-	-
RH	30-60% (winter) 40-60% (summer)	40 to < 70 %	< 70 %	-	-
CO_2	700 ppm (above outdoor level)	< 800 ppm	< 1000 ppm	-	1000 ppm
CO	9 ppm (8-h Avg)	< 2,000 μg/m^3 < 1.7 ppm	<10,000 μg/m^3 <8.7 ppm	100 mg/m^3 (15-min) 35 mg/m^3 (1-h) 10 mg/m^3 (8-h) 7 mg/m^3 (24-h)	-
$PM_{2.5}$	15 μg/m^3 (Annual)	-	-	10 μg/m^3 (Annual) 25 μg/m^3 (24-h)	12 μg/m^3
PM_{10}	50 μg/m^3 (Annual)	< 20 μg/m^3	< 180 μg/m^3	20 μg/m^3 (Annual) 50 μg/m^3 (24-h)	50 μg/m^3
TVOC	-	< 200 μg/m^3	< 600 μg/m^3	-	500 μg/m^3

Source [67, 69, 71, 9, 31, 70]

2.6 Research questions

In order to discover the factors affecting IQA in an office space in Sri Lanka, the following research questions were listed for further study based on the literature review.

- How bad is the air quality in the office buildings in Sri Lanka?
- What are the most significant factors affecting office IAQ?
- What standards are to be used to assess the IAQ of the office buildings in Sri Lanka?
- What methods can be used to enhance the IAQ in office buildings?

Studying the above questions is essential in order to improve the IAQ of an office space. However, stakeholders' awareness of IAQ is an important factor in improving IAQ in an office. Occupants should be knowledgeable about IAQ in order to report complaints about IAQ issues. The experience of facility managers or the building maintenance team should be able to take effective steps to enhance IAQ. According to the literature review, Sri Lankans have limited awareness and concern about IAQ. Initially, occupants and facility managers should be aware that their building has IQA issues. Then it's time to figure out what's behind the bad IAQ. Following that, solutions to improve IAQ should be implemented based on the available IAQ guidelines. As a result, the first two research questions on the above list are given top priority in this research, as they are critical to finding solutions to prevent poor IAQ in office buildings.

CHAPTER 03: DATA COLLECTION

Office buildings near Colombo Fort were selected for the field study, since all type transportation through sea, land and rail affect the IAQ in this area [73]. In situ data collected for this study through the following of a walk through inspection. This chapter presents design for data collection and data collection through in situ measurements.

3.1 Design for data collection

Initially, a walk-through inspection was conducted to select offices in order to set up measuring devices for collection of data in order to reduce the cost for data collection. According to the findings of the literature review, offices with low ventilation and high occupancy density were prioritized for in situ measurements. Two office spaces were selected for further investigation based on the preliminary inspection. Selected office space number 1 is a set of offices in a 14-story building's basement. Selected office space number 2 is a single-story building with an Information Technology Unit.

3.1.1 Office space number 1

The Basement of a 14 storied building was selected as the office space no 01. This Basement is a semi underground floor. The construction of the 14-story building was completed in 2004. Seven offices and one store are available at the Basement of this building. The total floor area of the Basement is 508 m^2. No sanitary facilities are available at this floor and occupants are using the washrooms available at the Ground floor. This building is located 50 m away from the main road near Beira lake.

The layout of the Basement is shown in Figure 3. In addition to the elevators, three numbers of entrances to the Basement are available including Fire Exits. Walls are made of concrete and finished with cement plastering. Walls are painted in October or November every year. The floor is finished with terrazzo. Suspended type gypsum ceiling is available for this Basement and ceiling height is 8 feet. Most of the partitions used to separate the offices are 7 feet portions. As such, air circulation among the offices is possible over the available one foot of space. Partitions are made of poly vinyl chloride boards, laminated plywood boards and glasses.

Two types of working periods are available for occupants of the office space. Those are general working period and shift duty period. The shift duty period is from 12 noon to the next day that same time. Electronic devices used in telecommunication system control are available in this floor in addition to general office equipment such as computers, printers and photocopy machines. Occupancy distribution and electronic equipment used in each office are shown in Table 7.

a. Air conditioning and ventilation of the office space no 01

Water cooled, flooded type central air conditioning system is available for this building. This air conditioning system has been installed in the year 2004. Cooled air is distributed to the floor through ducts and diffusers from the Air Handling Unit (AHU). A negative pressure is maintained at AHU room and 8'x1.5' louvre type window is available for infiltration of fresh air to the AHU room. Return air ducts are not available for air circulation. Ceiling plenum is used as the return air duct. This air conditioning system is functioned from 5.00 a.m. to 5.30 p.m. during working days and from 5.00 a.m. to 12.30 p.m. on Saturday. No air conditioning facility is available for Sunday. Only Exchange and System Control Unit are available split type air conditioners. One split type air conditioner is available at Exchange and it is used when the central air conditioning system is shut down. Two split type air conditioners are available at System Control Unit and both of them are working throughout the day in order to cater the thermal load of the electronic equipment.

Two exhaust fans are available for the Basement. One is used to drain the air at R&D office area. This exhaust fan is programed to work at repeated intervals. Working time is one hour and off time is half an hour. The exhaust fan available at stores is working from 7.00 a.m. to 5.00 p.m. during weekdays only. Sealed type glass windows are available for receiving sun light and only two numbers of louvre type windows are available for ventilation. The main entrance to the Basement is kept open the majority of the time. Fire Exit 02 is seldom used, although Fire Exit 01 is commonly used.

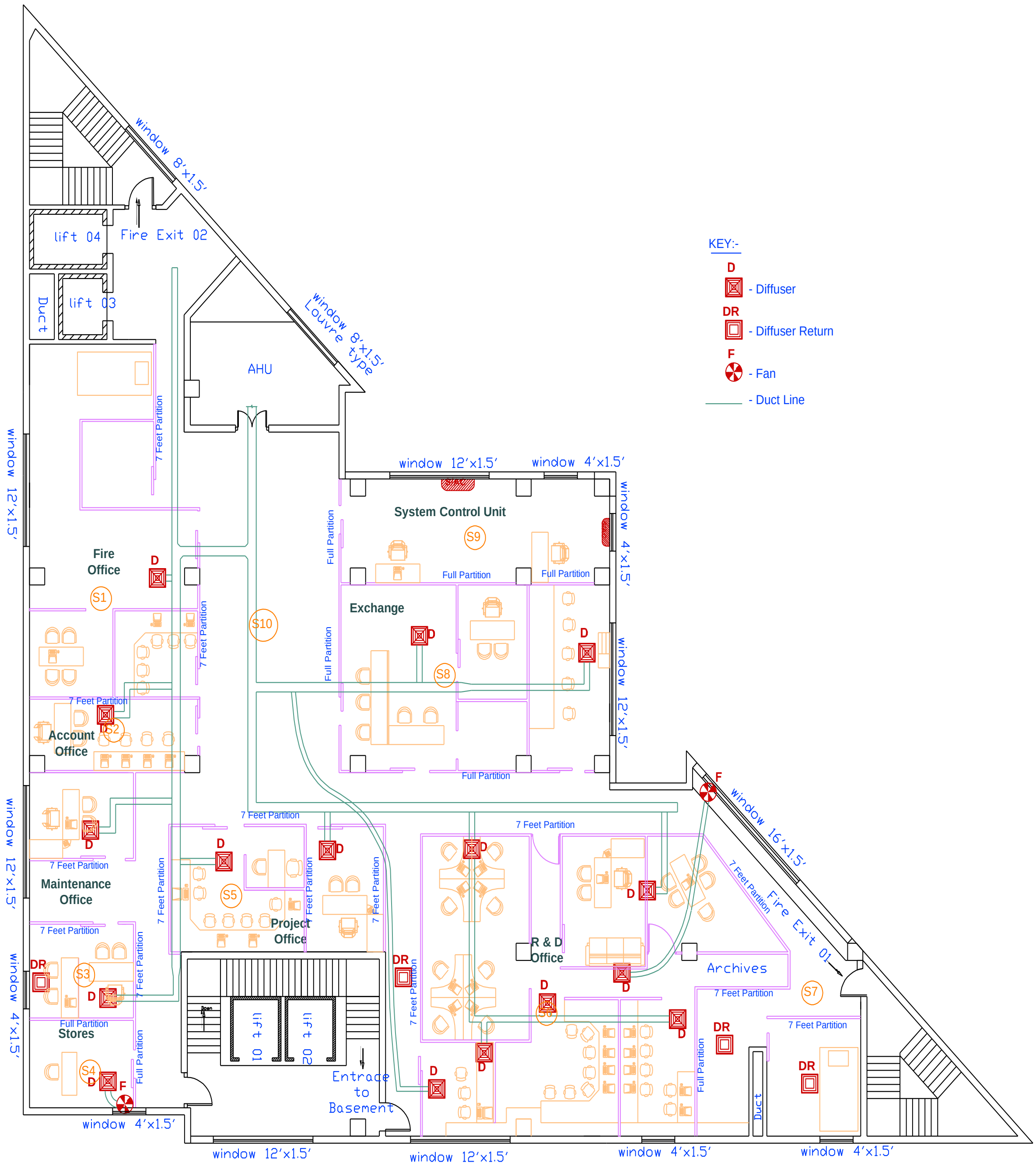

Figure 3: Layout of the Basement and selected locations for measuring indoor air pollutants; measuring points S1 to S10

Table 7: Occupancy density and electronic equipment used in each office of the Basement

Office	Floor Area (m^2)	Occupancy Density per m^2 (on working Day)	Occupancy Density per m^2 (on holiday)	Type of Work and Equipment Available
Fire office	72.9	0.04	0.05	Administration work and waiting area for fire fighters. Computers(CRT)-01, TV -01, Fire control panel- 01
Account office	13.4	0.37	-	Document work. Computers- 04, Printers (dot matrix-01 inkjet -01)
Maintenance office	29.8	0.20	0.07	Administration work. Computers- 03, Printers (dot matrix-01 inkjet -01)
Store	10.5	0.10	-	Stores for building maintenance. Used to keep paints, tools and electrical maintenance items.
Project office	30.8	0.32	-	Administration work. Computers- 03, Laptop 01, Printer (Laser-01), Photo copier -01
R & D Office	104.6	0.18	-	Administration work. Coputers-20, Photo copier -01 , Fax machine- 01, Projector - 01, Printers (dot matrix-01, Laser -03)
Central Exchange	56.8	0.21	0.16	Telecommunication exchange. Computers-03, Fax machine – 02, Printers (dot matrix-01)
System Control Unit	30.5	0.06	0.06	System controlling work. PABX controller-02, Public addresses system-01, Network switches-04, Telecommunication links-02. Computer- 01

3.1.2 Office space number 2

Based on the information gathered during the walk-through inspection, the Information Technology Unit's IT Lab was selected as office space no 2 for this study.

Due to the extreme lack of ventilation and high occupancy density, the IAQ in the IT Lab was selected for this study. The layout of the IT Lab with Information Technology Unit (IT Unit) is shown Figure 4.

IT Unit and IT Lab are located in a single storied building, which is constructed in 1972. This building is made of bricks and cement. The walls of this building are painted in October or November every year. The roofing material for this building is asbestos. Gypsum sheets are used for the ceiling. Ceiling height is 10 feet. Only one door is available for access to the IT lab from the IT unit. Main entrance to the IT unit, IT lab and adjacent office is available through the corridor. The entrance to the adjacent office is across the IT Unit. The floor area of the IT Lab is 23.6 m^2. Most of the furniture used in this office is made of laminated plywood. Two years old carpet is used as floor finishes.

The occupants of the IT Lab perform 24-hour shift duty from 8.30 a.m. to the same time of the next day. An occupant engages in two minimum shift duties per week. A meeting for handing over and taking over is held at IT Lab every morning for a period of one hour beginning from 8.30 a.m. The occupancy at IT Lab increases more than double during this morning meeting. Occupancy distribution and electronic equipment used in IT Lab are shown in Table 8.

a. Air conditioning and ventilation of office space no 02

Two numbers of split type air-conditioners are used in IT Lab. During the day, all air-conditioners are being used and only one air-conditioner at IT Lab is used during night. At the IT Lab, there are no windows or mechanical ventilation systems.

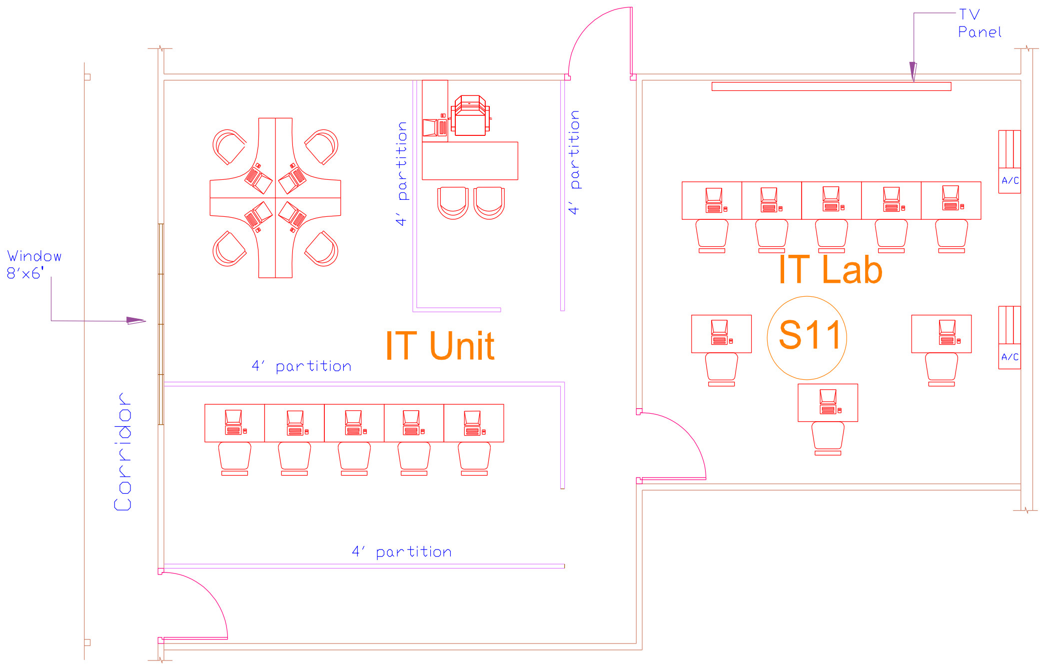

Figure 4: The arrangement of the IT Lab and its IAQ measuring point S11

Table 8: Occupancy distribution and electronic equipment used in in IT Unit and IT Lab

Office	Floor Area (m^2)	Occupancy Density per m^2 (at Day Shift)	Occupancy Density per m^2 (at Night Shift)	Type of Work and Equipment Available
IT Lab	23.6	0.42	0.29	Cyber work. TV(48") -18 , computers -12, Network Switches - 02

3.2 Data collection through in-situ measurements

The arrangement of devices used for the in situ measurement of IAQ and data collection process of the Basement and IT Lab are discussed under this topic. This section also includes information on measuring TVOC after conducting an experiment with air fresheners and incense smoke.

3.2.1 In situ data collection approach

Based on the observations of the walk through inspection, all of the offices and two common locations in the Basement were selected to measure IAQ levels (see Figure 3 and Table 9). Further, the IT Lab of the Information Technology Unit was also selected to take in situ measurements based on the lack of ventilation for this office. It was decided to measure the level of T, RH, CO, CO_2, $PM_{2.5}$, PM_{10} and TVOC at the all selected locations, since many previous studies have selected these parameters to measure office IAQ. The IAQ was measured using a DM106A Air Quality monitor, Air Visual Pro, and AS8700A Carbon Monoxide Meter. During the initial visit, it was noted that TVOC and CO concentrations were not changing rapidly. Further, using a DM106A Air Quality Monitor and an AS8700A Carbon Monoxide Meter, TVOC and CO levels were to be manually recorded. As a result, for 1 and 8 hours measuring periods, 30-minute measuring intervals for TVOC and CO levels were selected. Due to the ease of taking in situ measurements, TVOC and CO levels were measured every hour for the entire 24-hour span. However, due to the obvious higher concentration of TVOC, TVOC levels were recorded every 5 minutes during the experiments conducted in this study. Throughout all of the measuring times, all other parameters were recorded every minute.

Since many IAQ guidelines concern the hourly average of the indoor air contaminants [2, 3], all of the concerned parameters at the selected locations of the Basement were initially recorded for one-hour periods. For the purpose of comparing IAQ levels, one-hour concentrations of indoor pollutants were recorded at the same locations in the Basement on a holiday and a working day. Then the center location of the Basement (S10) was selected to measure IAQ for 8-hour's period, since the center location is appropriate for representing the Basement's IAQ. Further, 8 hours' duration was selected to measure IQA, since most of the occupants in the Basement perform an 8-hour' working period.

After the Basement of the 14 storied building, IAQ was measured at IT Lab of the selected office space no 2 for a period of 24 hours, since 24-hour shift duty is being carried out by the occupants of the IT Lab. After using air fresheners and incense smoke in the system control unit and the Basement Store, a real-time experiment was performed to measure TVOC levels.

IAQ was measured in the Basement's AHU room to determine the impact of outdoor air quality on IAQ. Measurements of the return air flow were taken as it depicts the IAQ while, measurements were taken at the fresh air inlet to the AHU which depicts the outdoor air quality.

Table 9: Measuring points of indoor air pollutants at the Basement

Measuring Point	Location
S1	Fire office
S2	Account office
S3	Maintenance office
S4	Store
S5	Project office
S6	R & D Office
S7	Location on the corridor near Fire Exit1
S8	Central Exchange
S9	System Control Unit
S10	Location on the corridor near the center of the Basement

3.2.2 Arrangement of instrument for in situ measurement

In situ measurements on IAQ were conducted using DM106A Air Quality sensor, Air visual pro and AS8700A Carbon Monoxide meter. Details of the instruments are shown in Table 10. These instruments were calibrated prior to use for this project by NBRO Sri Lanka.

The average height to the breathing zone of sedentary personnel was selected as the measuring height of indoor air pollutants. Three sedentary personnel were selected arbitrarily from each office and height from the ground level to the breathing zone was measured. The measured heights are shown in Appendix-1. Considering the average, measuring height for IAQ was selected as 1.14 m. This height is in accordance within the rage of measuring heights of previous studies [65, 26].

Table 10: Details of instruments used for IAQ measurements

Instrument	IAQ Parameter	Range
DM106A Air Quality monitor	TVOC	0 ~ 9.999 mg /m³
Air visual pro	CO_2	400 ~10,000 ppm
	$PM_{2.5}$	1 ~1000 ppm
	PM_{10}	1 ~1000 ppm
	Temperature	-10 to 40 ^{0}C
	RH	0 to 95 %
AS8700A Carbon Monoxide meter	CO	1~1000 ppm

3.2.3 Measurement at the office space number 1

It was planned to compare the concentrations of pollutants on a holiday and a working day. As such, levels of T, RH, CO, CO_2, $PM_{2.5}$, PM_{10}, and TVOC were measured at selected ten numbers of locations of the Basement on 01st and 2nd September 2020. 1st of September 2020 was a holiday and 2nd of September 2020 was a working day. CO_2, $PM_{2.5}$, PM_{10}, T, and RH were measured every minute during a one-hour period on both days. For each of the parameters CO_2, $PM_{2.5}$, PM_{10}, T, and RH, 1200 data points were collected on both days. On the holiday and working days, CO and TVOC were measured every 30 minutes for an hour at each location of the Basement. On both days, 60 data points for each of the parameters TVOC and CO were collected. IAQ of the Account Office and the R&D Office were closed during holidays. Hence, IAQ of these offices were not measured on the holiday due to the inaccessibility.

The IAQ of the center location (S10) of the Basement were measured for 8-hour period 03rd September 2020, which was a working day. CO_2, $PM_{2.5}$, PM_{10}, T, and RH were measured every minute during an 8-hour period. For each of the parameters CO_2, $PM_{2.5}$, PM_{10}, T, and RH, 481data points were collected on this day. CO and TVOC were measured every half an hour during this 8-hour' period. 17 data points for each of the parameters TVOC and CO were collected.

3.2.4 Measurement at office space number 2

The IAQ of IT Lab was measured on 4th September 2020, which was a working day. Measuring CO, CO_2, $PM_{2.5}$, PM_{10}, T and RH was conducted every minute for a period of 24-hour since a 24-hour shift duty was being performed in this office. For each of the parameters CO_2, $PM_{2.5}$, PM_{10}, T, and RH, 1441 data points were collected during the 24-hour period. CO and TVOC were measured every hour during this 24 hour' period. 25 data points for each of the parameters TVOC and CO were collected.

3.2.5 TVOC concentration with air fresheners and incense smoke

Measuring of air fresheners was conducted as an experiment using real offices on 7th September 2020, which was a working day. The concentrations of TVOC were recorded every 5 minutes while 50 ml of air freshener was sprayed over the System Control Unit (S9). After the concentration of TVOC fell below the previous level, the measurement of TVOC level was stopped. After spraying air fresheners, it took 70 minutes to return to the previous level of TVOC. During the 70-minute duration, 15 members of TVOC data points were collected.

TVOC levels were measured with the presence of incense smoke using the Store at the Basement on 8th September 2020, which was a working day. DM106A Air Quality monitor was positioned approximately 0.5 meters from the incense stick. The exhaust fan available at the Stores was switched off prior to measuring of TVOC with incense smoke. TVOC concentrations were measured every 5 minutes while the incense stick was lit and held for 1 hour. Recording of TVOC levels was stopped when the previous TVOC level was observed. As a result, it took 110 minutes to complete this experiment. During the 110-minute duration, 23 members of TVOC data points were collected.

3.2.6 In situ measurement in the AHU room of the office space number 2

Air quality measurements were taken in the Basement's AHU room for 5 working days and there was no significant difference of climate condition between the working days and the climate condition throughout the month of February was found to be more or less uniform. Temperature variations in Colombo for February 2022 are shown in Figure 5.

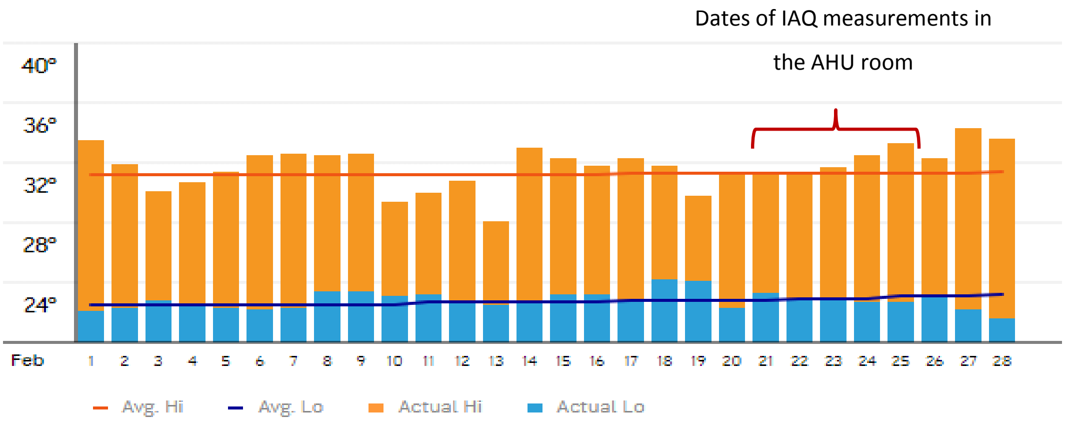

Figure 5:Temperature variations in Colombo for February 2022, Source: [74]

Since the AHU room receives total air volume from the Basement, it was selected for the measurements. It also has a fresh air intake which, was used to assess the quality of the outdoor air. CO, CO_2, $PM_{2.5}$, PM_{10}, TVOC, T, and RH were measured every 20 minutes for a total of 10 hours per day. During the 5-day period, 5,250 data points were collected for the seven parameters CO, CO_2, $PM_{2.5}$, PM_{10}, TVOC T, and RH at the return and fresh air intake.

3.2.7 Summary of the data points collected during in situ measurements

Parameter	No of Data Points
T	3,277
RH	3,277
$PM_{2.5}$	3,277
PM_{10}	3,277
CO_2	3,277
TVOC	290
CO	252
Total	**16,675**

Table 11:Total numbers of data points collected for all the IAQ parameters of the research

16,675 number of data points were collected for all the IAQ parameters of this research as shown in Table 11. Appendix-2 summarizes the data points collected for each of the parameters T, RH, $PM_{2.5}$, PM_{10}, and CO_2. Appendices 3 and 4 summarize the data points collected for TVOC and CO, respectively.

CHAPTER 04: ANALYSIS AND RESULTS

Data gathered through in situ measurements of offices at office space no 1 (Basement) and office space no 2 (IT Lab) were analyzed using Microsoft Excel 2016 software to determine the factors affecting the indoor air quality.

4.1 Carbon Monoxide (CO)

All levels of measured carbon monoxide (CO) were zero. The CO level existed was less than 1 ppm, which is the minimum reading of the AS8700A CO meter. This could be owing to the surrounding of the building. It is 50 meters away from the main road from south, and Beira Lake is located in north side adjacent to the building. There is a building from East and the sea is on the west side of this building. Reduced concentration of CO is due to the coastal winds.

4.2 Temperature (T)

The temperature levels during the one-hour' period at selected locations of the Basement on the holiday and working day are shown in Figure 6 and Figure 7 respectively. The temperature of the measured locations at Basement on the holiday varied from 21.8 to 30.4 ^{0}C. Except S8 and S9, the average temperature of other locations was over 28 ^{0}C. The temperature of these locations were around the average temperature of outdoor area on the holiday, which was 28.6 ^{0}C. Only S8 and S9 locations have the air-conditioning facility during a holiday.

On the working day, temperature varied from 20.6 to 27.8 ^{0}C. This range was well below the outdoor average temperature due to the operation of central air conditioning system. Variations in average temperature of the selected locations of the Basement were observed on the working day. The highest average temperature was reported as 27.5 ^{0}C at the store room (S4). No diffusers are available at this location and an exhaust fan is available for removing the air to the outside. The lowest average temperature (21.61 ^{0}C) was at location S9. The availability of both central air conditioning system, spilt type air conditioners and low occupancy are the reasons to indicate the lowest temperature at this location.

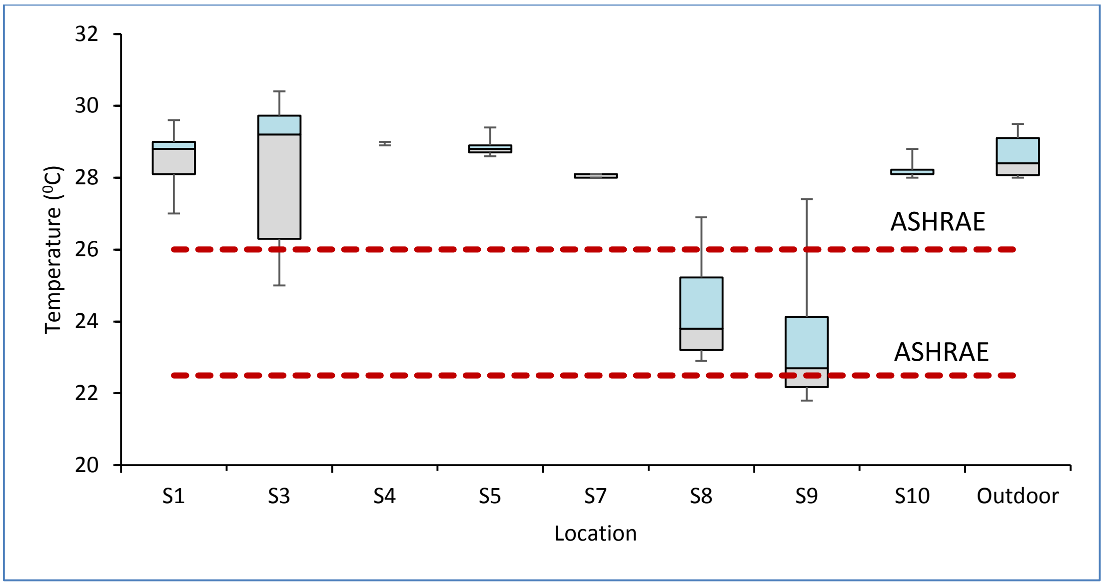

Figure 6: Levels of temperature during the one-hour' period at the selected locations of the Basement on holiday

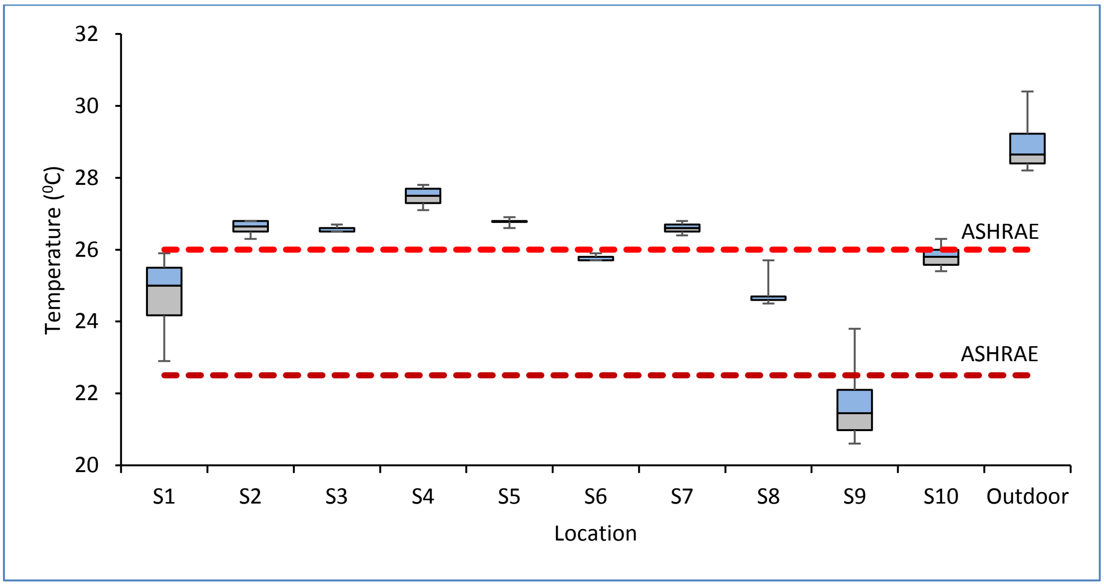

Figure 7: Levels of temperature during the one-hour' period at the selected locations of the Basement on working day

The temperature profile at location S10 of the Basement during 8 hours' period is shown in Figure 8. The temperature at S10 varied from 24.8 ^{0}C to 25.9 ^{0}C by maintaining 25.67 ^{0}C of average temperature for 8 hours for the working day. IAQ of location S10 was measured on 03rd September 2020.

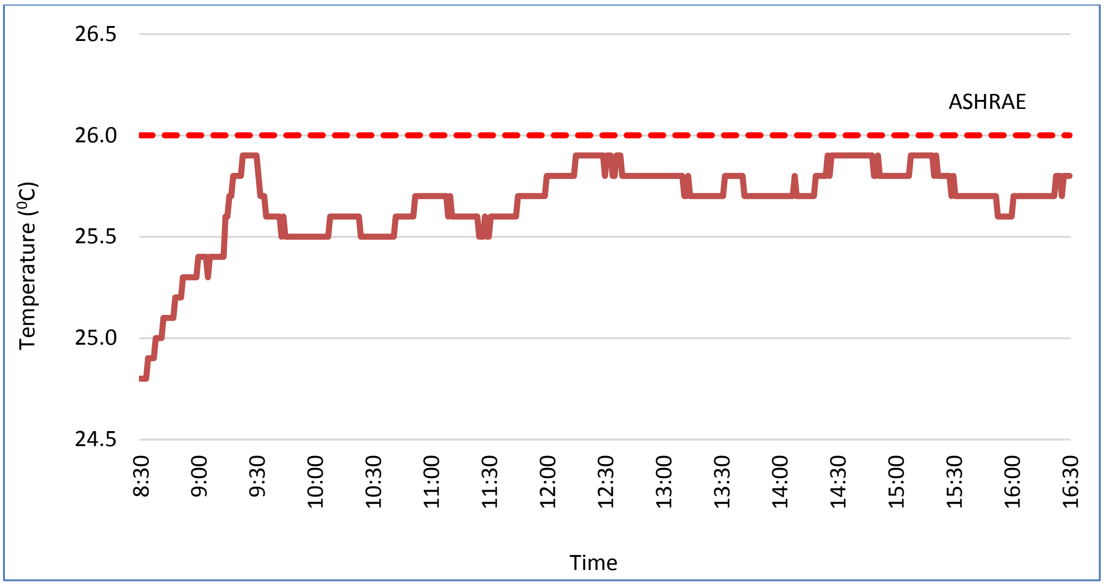

Figure 8: The temperature profile at location S10 for 8 hours' duration

An average temperature of 24.74 ^{0}C was observed at IT Lab as per the measurement obtained on 04th September 2020. The temperature varied from 23 to 26 ^{0}C for 24 hours of period. During handing over/ taking over meeting, a rise in temperature was observed due to the sudden increase in occupancy. Further, decrease in temperature was observed during lunch and dinner times. The temperature profile of the IT Lab during 24 hours' period is shown in Figure 9. No windows are available for this office and fresh air is received by means of the door. Two split type air conditioners are available for this office. Temperatures of these air conditioners were set to 22 ^{0}C normally. One air conditioner is switched off and temperature of the other air conditioner is set to 25 ^{0}C at late night in order to keep a favorable temperature inside the office. Hence, increase in temperature after midnight was observed. Around 6.30 a.m. occupants leave this office to prepare for next day. During this time, decrease in temperature was observed. Both air conditioners were turned back on to normal operation around 7.30 a.m. Variations of temperature were observed at this office, since temperature is controlled by two separate thermostat of the available air conditioners.

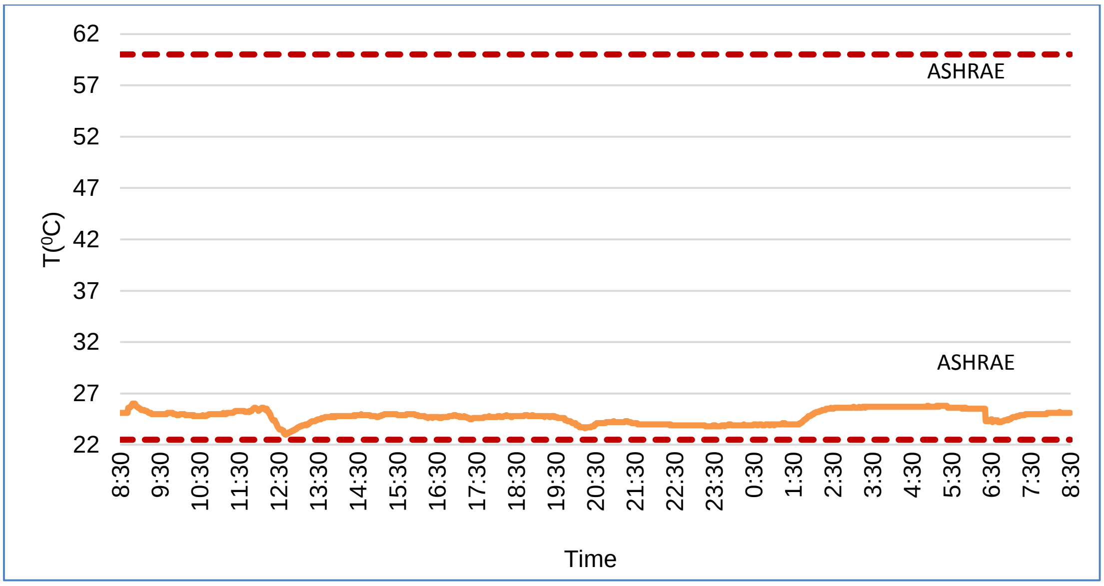

Figure 9: Temperature profile of the IT Lab during 24 hours' period

The temperature variations of outdoor air and return air to the AHU are shown in Figure 10. The temperatures of the return air to the AHU ranged from 29.2 ^{0}C to 32.1 ^{0}C, while the outdoor temperatures ranged from 27.7 ^{0}C to 32.8 ^{0}C.

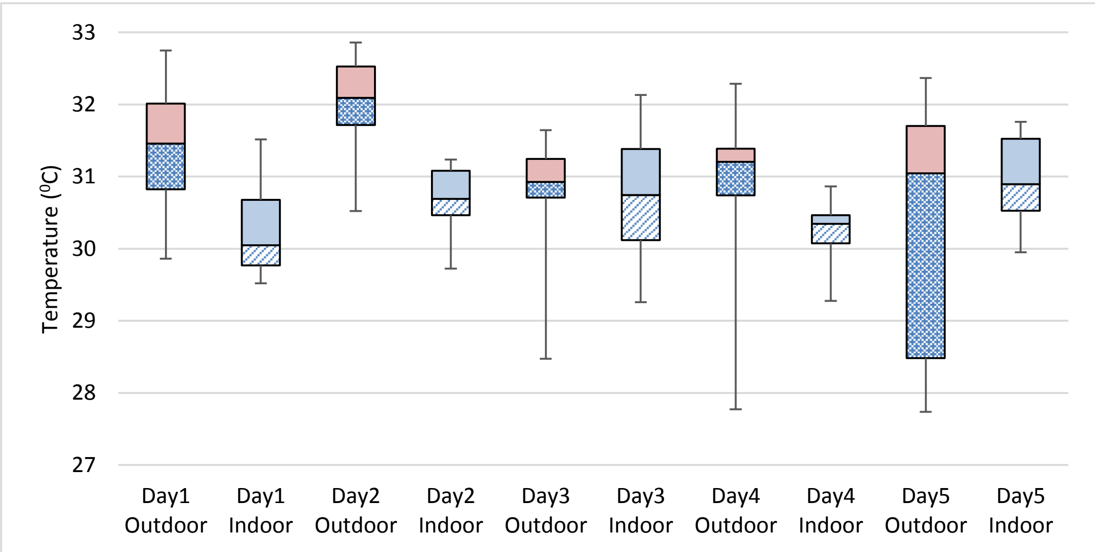

Figure 10:The variations of outdoor and indoor temperatures

Hourly average variations of the temperature with occupancy during the Day1 is shown in Figure 11 and the hourly average temperature variations of the all 5 days are shown in Appendix-5.

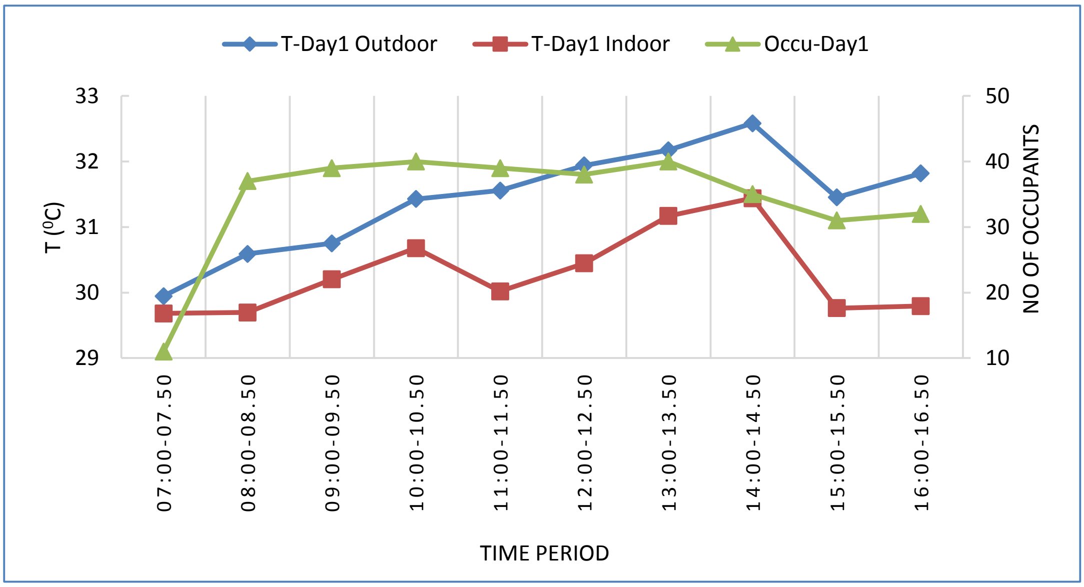

Figure 11: Hourly average of T and occupancy at the Basement during day 1

As it can be observed in Figure 11, return air to the AHU followed the outdoor air temperature in a parallel curve. Indoor air temperature in the Basement is maintained fairly constant around 25 ^{0}C. The return air from the Basement is released to the ceiling plenum and then it is supplied to the AHU. Based on above observations, it is clear that return air absorbs heat while going through the ceiling plenum. Since the measurements were taken while the central air conditioner was running, the indoor air temperature was almost always lower than the outdoor air temperature. Reason for the high temperature of the Basement from 8:00 a.m. to 12:00 p.m. is high occupancy.

4.3 Relative humidity (RH)

RH levels of the selected locations of the Basement during 1-hour' period on holiday and the working day are shown in Figure 12 and Figure 13 respectively .

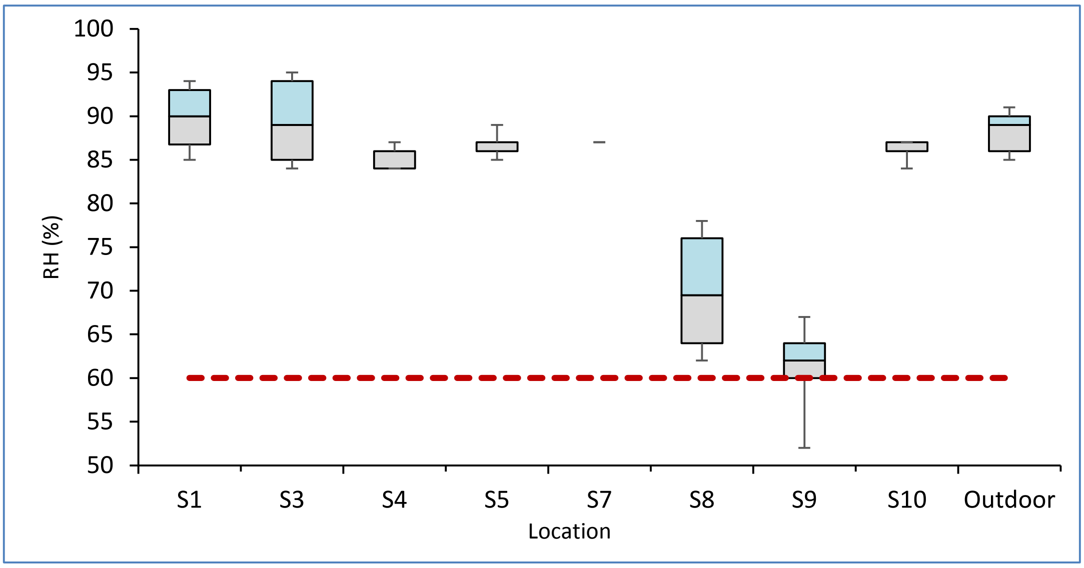

Figure 12: RH levels of the selected locations of the Basement during 1-hour' period on holiday

The average Relative Humidity (RH) of non-air conditioned locations of the Basement was approximately equal outdoor average RH, since the doors are kept open on holidays. Relative humidity of the Basement varied from 52% to 95% during the holiday. Variation of the RH on the working day was from 58% to 75%. The average RH at respective locations of the Basement on holiday was higher than that of the working day except locations S8 and S9. The average RH of the Basement reduces due to the operation of central air conditioning system on the working day. The average RH of location S8 and S9 was lower than the other locations of the Basement on the holiday, since these locations have spit type air conditioners.

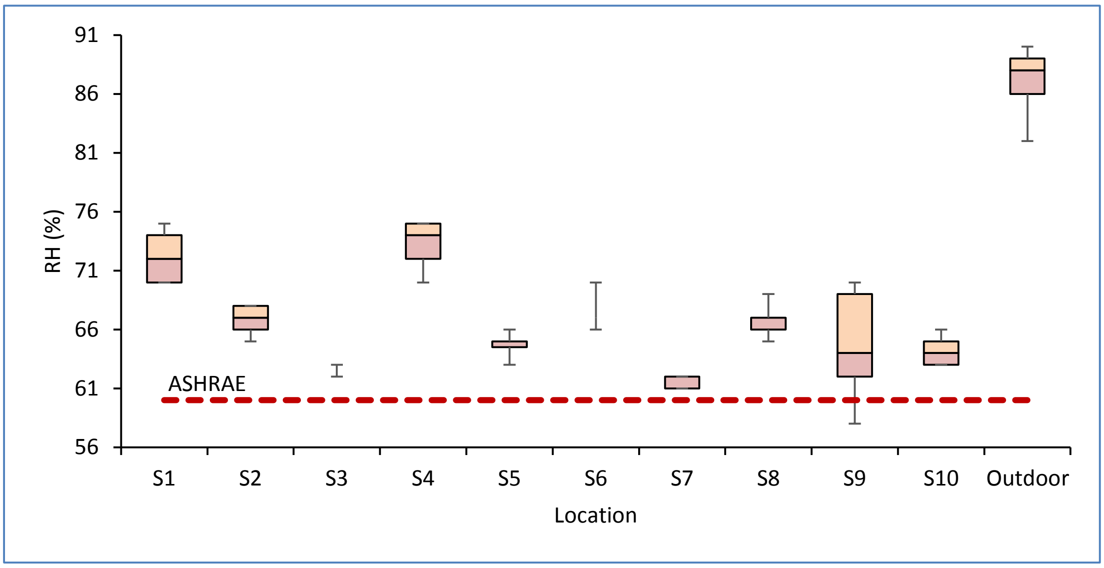

Figure 13: RH levels of the selected locations of the Basement during 1-hour' period on working day

RH profile of location S10 at the Basement for 8 hours' period on a working day is shown in Figure 14. An average of 63% RH level was observed at location S10 for 8 hours. RH was at a higher level at about 8.30 a.m., since occupants enter their offices through the location S10. There were no high variations in RH, since the central air conditioning system is available for this location on working days.

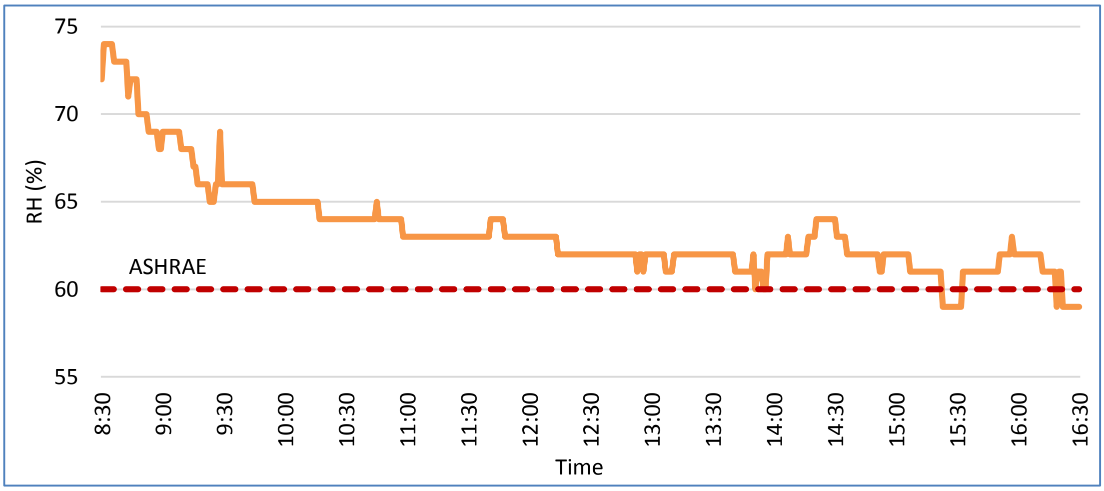

Figure 14: RH profile of location S10 of the Basement for 8 hours' period on a working day

RH profile of the IT Lab during 24 hours' period is shown in Figure 15. RH of IT lab varied from 50% to 83%. High variations in RH were observed at this location, since this office is air-conditioned using two split type room air conditioners. Further, room volume is low and occupancy density is considerably high. Hence, the change in the occupancy directly affects the RH level of the IT Lab. RH has increased after 1.30 a.m., since one air conditioner switched off without changing occupancy.

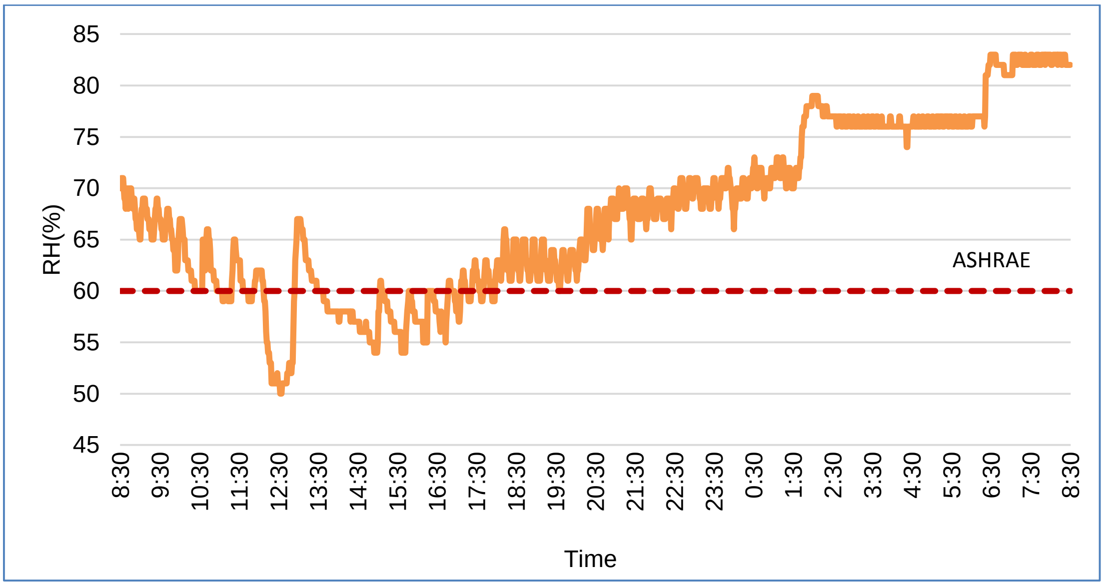

Figure 15: RH profile of the IT Lab during 24 hours' period

Hourly average variations of the RH with occupancy during the Day1 is shown in Figure 16 and the hourly average of RH during all 5 days are shown in Appendix-6. The outdoor air had a minimum and maximum RH of 52.7 % and 71.8 %, respectively, while the indoor air had a minimum and maximum RH of 44.8 % and 54.7 %, respectively. RH levels of the outdoor air were always high, since the central air conditioner was in operation during the measuring periods. The indoor RH levels were directly proportional to the outdoor RH levels, as shown by hourly average RH graphs.

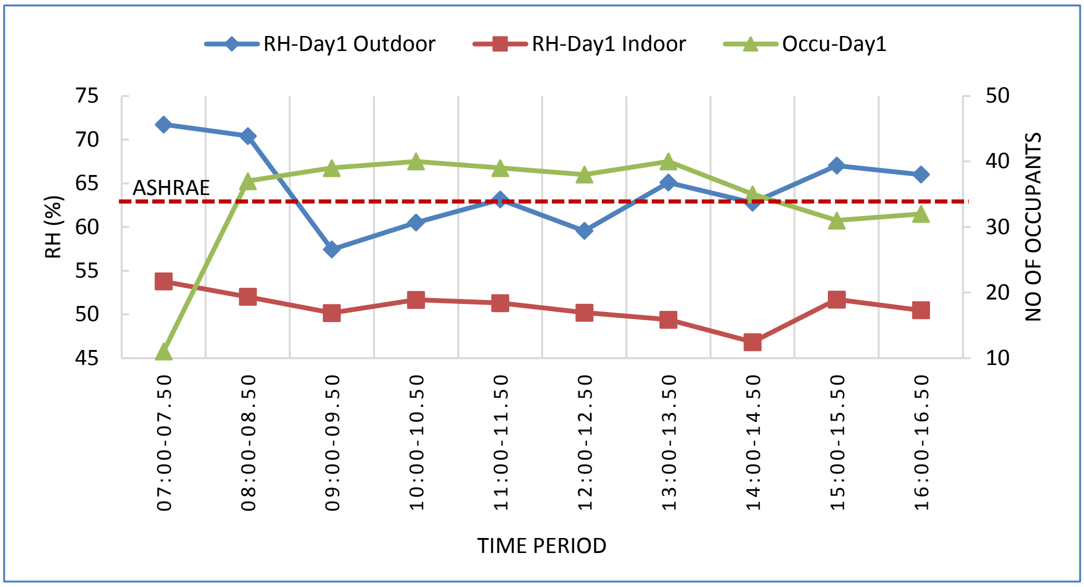

Figure 16:Hourly average of RH and occupancy at the Basement during day 1

4.4 Carbon dioxide (CO_2)

CO_2 levels of selected locations of the Basement for 1 hour' period on holiday and working day are shown in Figure 17 and Figure 18 respectively. CO_2 concentrations at the selected locations of the Basement varied from 416 ppm to 1216 ppm on the holiday. The highest CO_2 level of 1216 ppm and the highest average CO_2 level of 951.52 ppm were reported from the location S8 (Central Exchange). This office is fully covered with a partition and air-conditioned by a split type air conditioner. A 24-hour' shift duty is being performed in this office and occupancy density is higher on holiday. Concentration of CO_2 was higher at location S9 (System Control Unit) next to S8, since this office is also covered with full partitions and air-conditioned with spilt type room air conditioners.

Except S8 and S9, other locations of the Basement indicated low CO_2 levels on the holiday and they were slightly higher than outdoor CO_2 level. The low occupancy is the main reason for the reported low concentration of CO_2. Further, available doors of the Basement keep open for non-working days. The lowest CO_2 level of 416 ppm and the lowest average CO_2 level of 425.7 ppm were reported from location S7 on the holiday. S7 is a location near Fire Exit 01, as shown in Figure 3. Fire exit door 01 is kept open on holidays and location S7 is near the fixed type aluminum window. Hence, the availability of fresh air at this location is higher than the other selected locations. As such, CO_2 concentration at location S7 is the minimum.

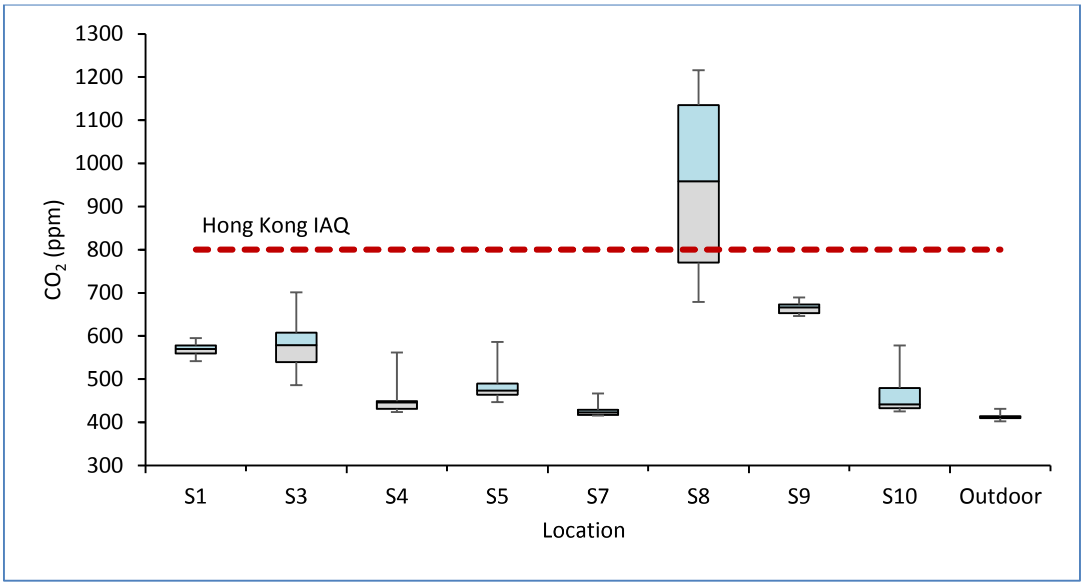

Figure 17: CO_2 levels of the selected locations of the Basement for a 1 hour' period on holiday

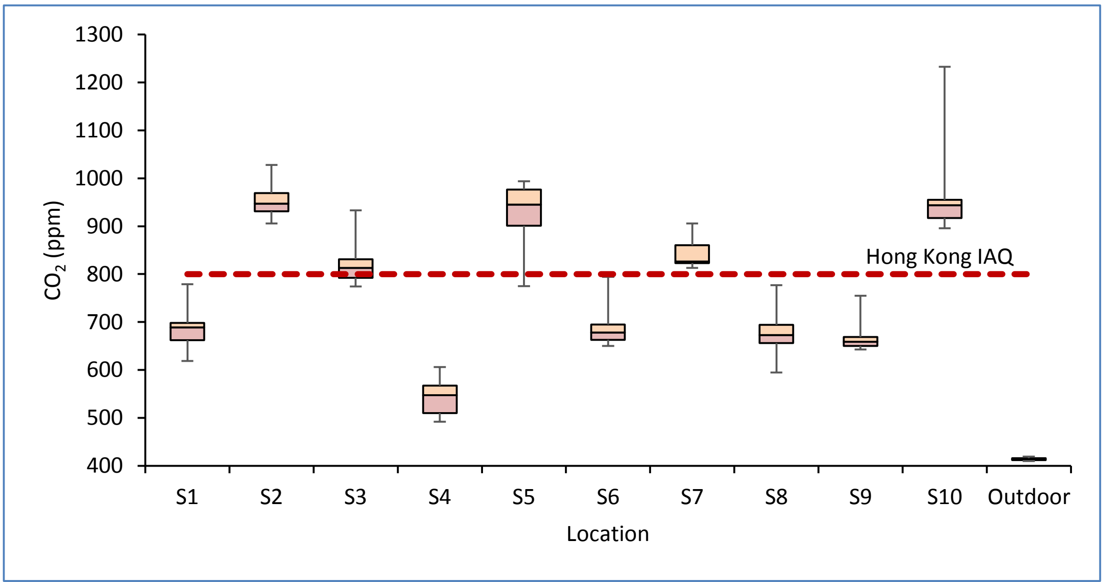

Figure 18: CO_2 levels of the selected locations of the Basement for a 1 hour' period on working day

With the increase in occupancy and operation of the central air conditioning system on the working day, average concentrations of CO_2 at selected locations of the Basement have gone up except Central Exchange (S8). CO_2 concentration of location S8 reduces on the working day with the circulation of air by the central air conditioning system. Two diffusers and one return diffuser are available at the Central Exchange for better air circulation. The average CO_2 levels for a 1 hour' period on holiday and working day at different locations of the Basement are shown in Figure 19.

Highest average CO_2 level of 951.52 ppm in the Basement was observed at location S10 on the working day. This area is a corridor and no any diffusers are available for this area. S10 is located at the middle of the Basement and surrounded by the offices. The air circulation is poor in S10 area. Further, the occupants use this area frequently. Hence, a high level of CO_2 was observed at location S10 on the working day. Location S4 (Store) indicated the minimum level of CO_2. The availability of one exhaust fan and low occupancy has caused to observe the lowest 1-hour level of CO_2 at the Store.

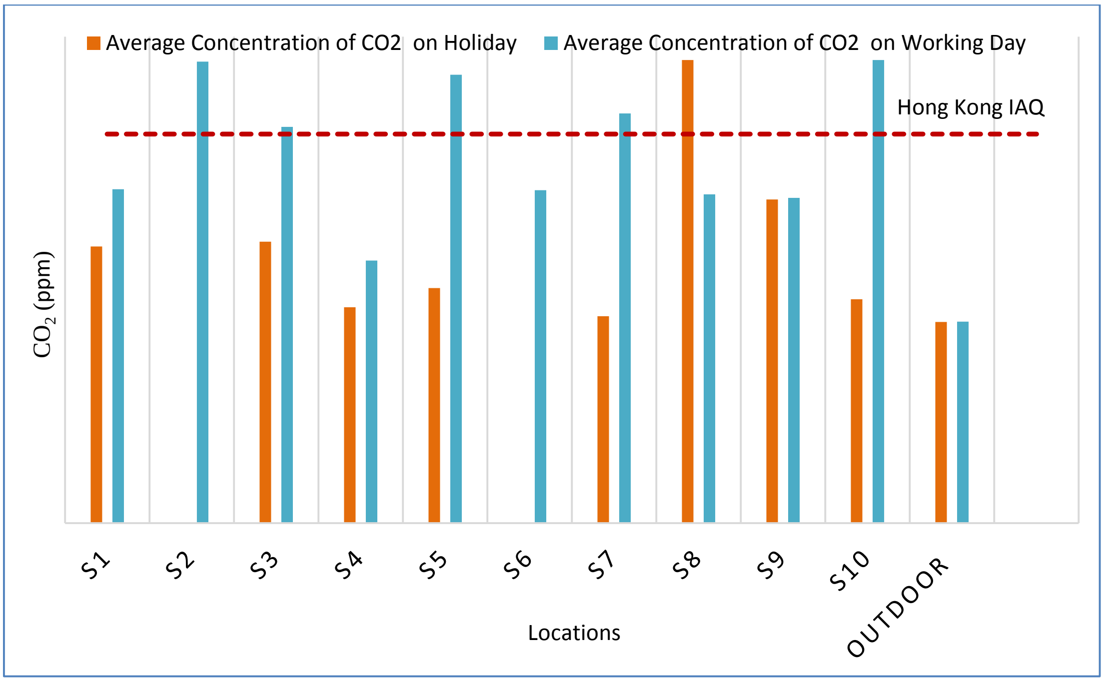

Figure 19: The average CO_2 levels for 1-hour period on holiday and working day at different locations of the Basement.

CO_2 profile for 8 hours' period at location S10 on a working day is shown in Figure 20. It was observed that concentration of CO_2 was increasing from 637 ppm to 1137 ppm with time. 909.89 ppm of 8 hours' average concentration of CO_2 was observed at this location. This might be due to the accumulation of CO_2 at location S10.

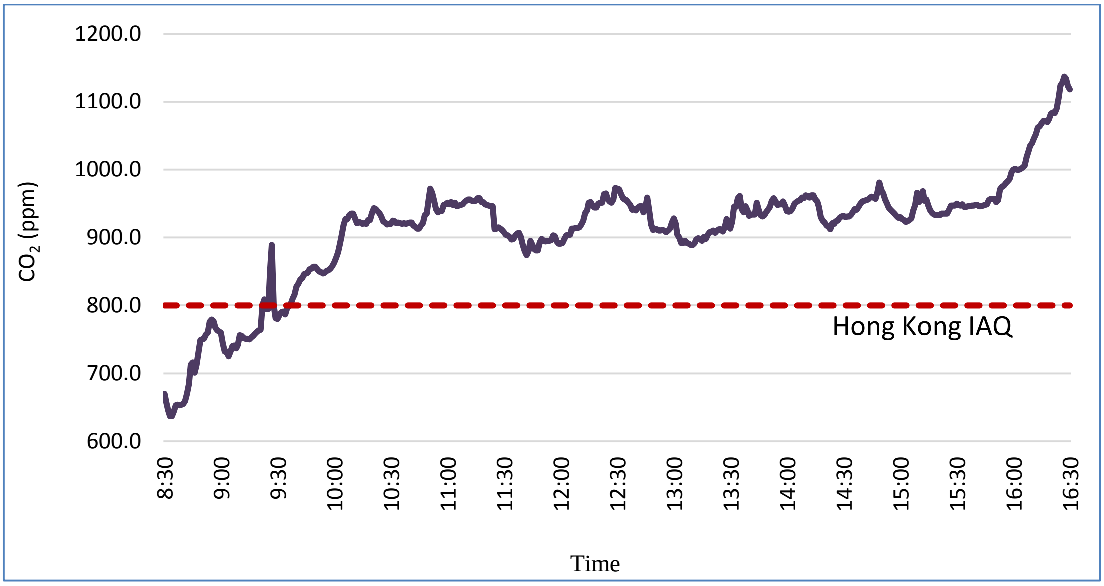

Figure 20: CO_2 profile for 8 hours' period at location S10 on a working day

24 hours CO_2 profile of the IT Lab is shown in Figure 21. Highest level of CO_2 (2923 ppm) was reported from 8.30 a.m. to 9.30 a.m. during the morning meeting. The average concentration of CO_2 from 8.30 a.m. to 9.30 a.m. of next day was 2325.37 ppm. It was observed that CO_2 level during day time was more than 1500 ppm and 8 hours' average during day time was 1918.73 ppm. The decrease in CO_2 was observed during night time after 7.30 p.m. An average of 1442.91 ppm of CO_2 level was observed from 7.30 p.m. to 8.30 a.m. of the next day. CO_2 concentration in the IT Lab depends on the occupation pattern and hence, variations of the CO_2 level are observed during day time.

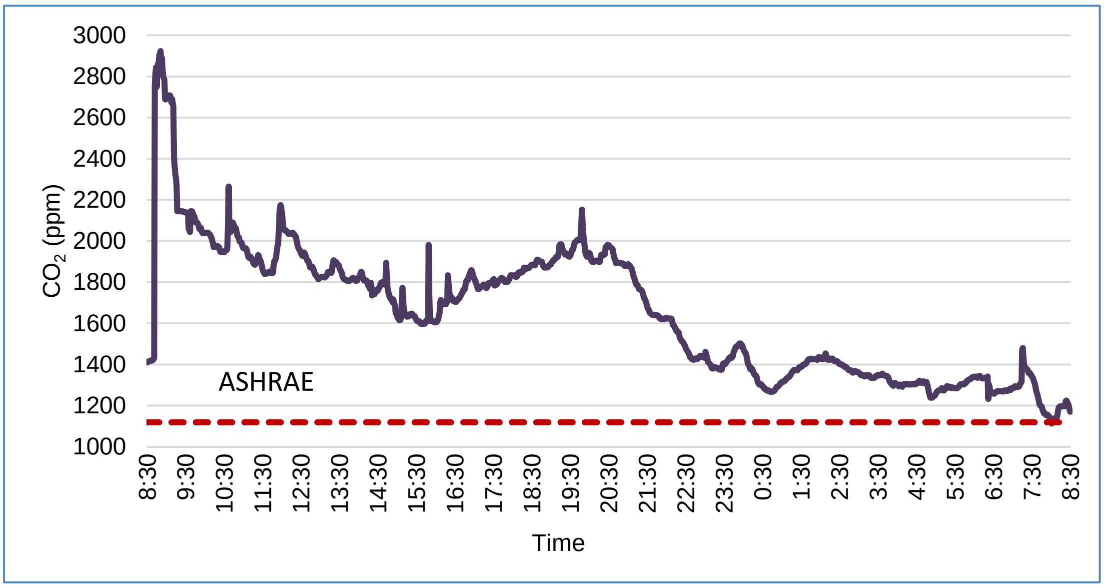

Figure 21: 24 hours' CO_2 profile of the IT Lab

Hourly average variations of the CO_2 with occupancy during the Day1 is shown in Figure 22 and the hourly average of CO2 during all 5 days are shown in Appendix-7. The outdoor air had a minimum and maximum CO_2 of 410 ppm and 606 ppm, respectively, while the indoor air had a minimum and maximum CO_2 of 498 ppm and 740 ppm, respectively. CO_2 levels of the outdoor air were lower than the that of indoor air. Furthermore, indoor CO_2 levels were found to be directly proportional to occupancy. As a result, the main cause of higher CO_2 levels in indoor air is occupancy.

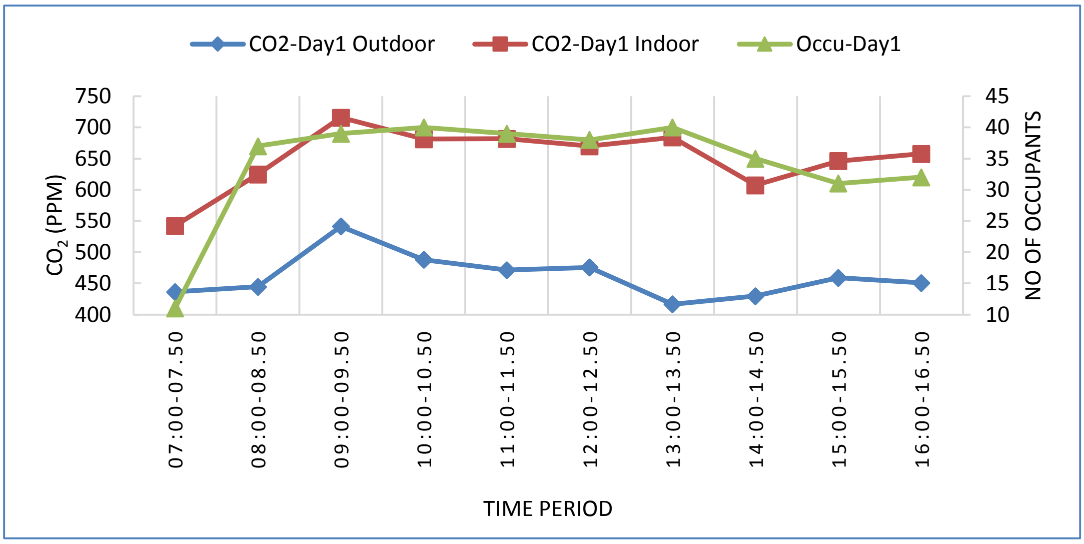

Figure 22:Hourly average of CO_2 and occupancy at the Basement during day 1

4.5 Particulate matter ($PM_{2.5}$ and PM_{10})

The 1-hour average $PM_{2.5}$ levels at selected locations of the Basement on the holiday and the working day are shown Figure 23. The average $PM_{2.5}$ levels varied from 1.41 to 8.23 μg/m^3 on the holiday. The locations, which has split type room air conditioners were observed with lower levels of $PM_{2.5}$ than the outdoor $PM_{2.5}$ level. The reason for this reduction is the availability of filters in air conditioners.

The highest 1-hour average concentration of $PM_{2.5}$ was observed at the location S9 (System Control Unit) on the working day. System Control Unit consists of electronic equipment and operation of this equipment is the reason for the highest level of $PM_{2.5}$. Next to the S9, location S10 indicated with higher 1-hour average level of $PM_{2.5}$. Movements of occupants through this area are the main reason for this higher level of $PM_{2.5}$. The position of S10 in the Basement and lack of ventilation are the other reasons for this level of $PM_{2.5}$. 1-hour average of $PM_{2.5}$ at the location S7 was also higher than the outdoor $PM_{2.5}$ level, since S7 is located on a passage near Fire Exit 01. Movements of occupant are the main cause for this increased level of $PM_{2.5}$ on the working day. Other locations except S7, S9, and S10 have a lower 1-hour average level of $PM_{2.5}$ and these levels are lower than the outdoor $PM_{2.5}$ level, due to the effect of filtering system available in central air conditioning system.

1-hour average PM_{10} levels at selected locations of the Basement on the holiday and the working day are shown in Figure 24. The 1-hour concentration of PM_{10} was higher than the $PM_{2.5}$ level at respective locations.

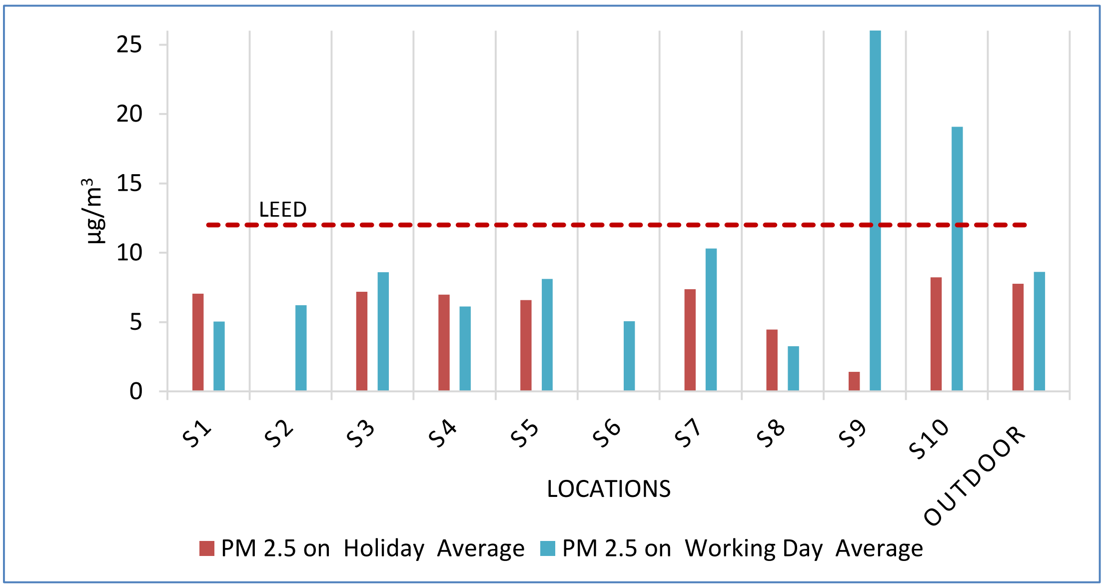

Figure 23: 1-hour' average $PM_{2.5}$ levels at selected locations of the Basement on the holiday and the working day

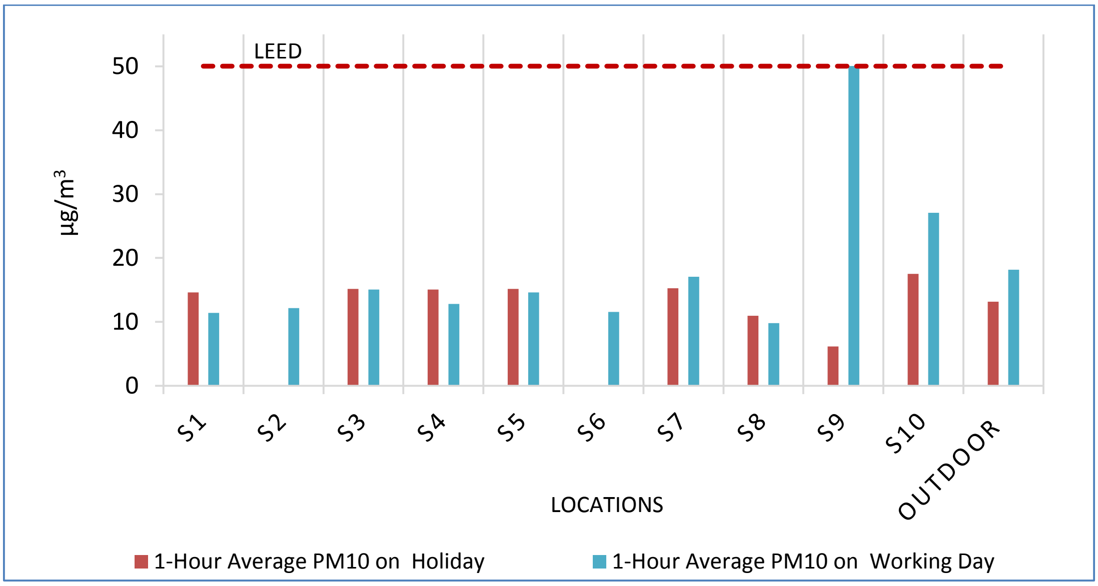

Figure 24: 1-hour average PM_{10} levels at selected locations of the Basement on the holiday and the working day

$PM_{2.5}$ and PM_{10} profiles for 8-hours' period at location S10 are shown in Figure 25. It was observed that concentration pattern of $PM_{2.5}$ and PM_{10} is similar. The average 8-hour' concentrations of $PM_{2.5}$ and PM_{10} at this location were 14.1 and 19.3 µg/m^3

respectively. The concentration of particulate matter is higher in the morning and evening due to the movement of occupants.

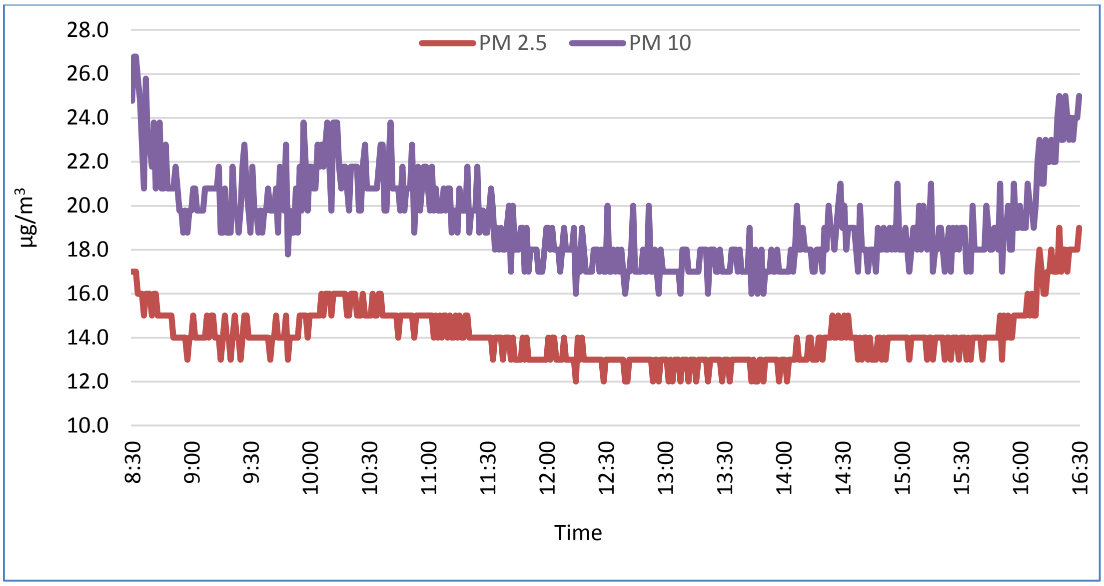

Figure 25: $PM_{2.5}$ and PM_{10} profiles for 8 hours period at location S10

24-hour' concentration of $PM_{2.5}$ and PM_{10} at the IT Lab is shown in Figure 26. The average 24-hour' concentrations of $PM_{2.5}$ and PM_{10} inside the IT Lab were 2.16 and 7.68 µg/m^3 respectively.

These concentrations are well below the guidelines of WHO. The occupants of this office moved less since they were doing sedentary work. This office has also been air-conditioned with two split-type air conditioners. These could be the reasons for the lower levels of particulate matter in this office. However, at around 6.30 a.m., $PM_{2.5}$ and PM_{10} levels reached their maximums of 40 and 123.23 µg/m^3, respectively. It was found that the floor carpet was cleaned around 6.30 a.m. The resuspension of deposited particulate matter on the carpet during the cleaning process could be the cause of this sudden increase in particulate matter concentrations.

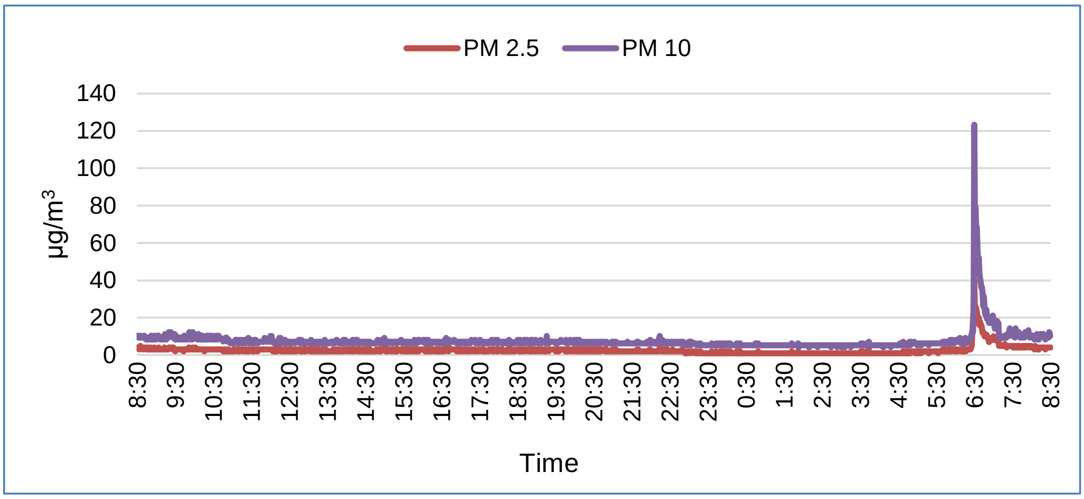

Figure 26: 24-hours concentration of $PM_{2.5}$ and PM_{10} at the IT Lab

Hourly average variations of the $PM_{2.5}$ with occupancy during the Day1 is shown in Figure 27 and the hourly average of $PM_{2.5}$ during all 5 days are shown in Appendix-8. The outdoor air had a minimum and maximum $PM_{2.5}$ of 23 µg/m^3 and 91 µg/m^3, respectively, while the indoor air had a minimum and maximum $PM_{2.5}$ of 13 µg/m^3 and µg/m^3, respectively.

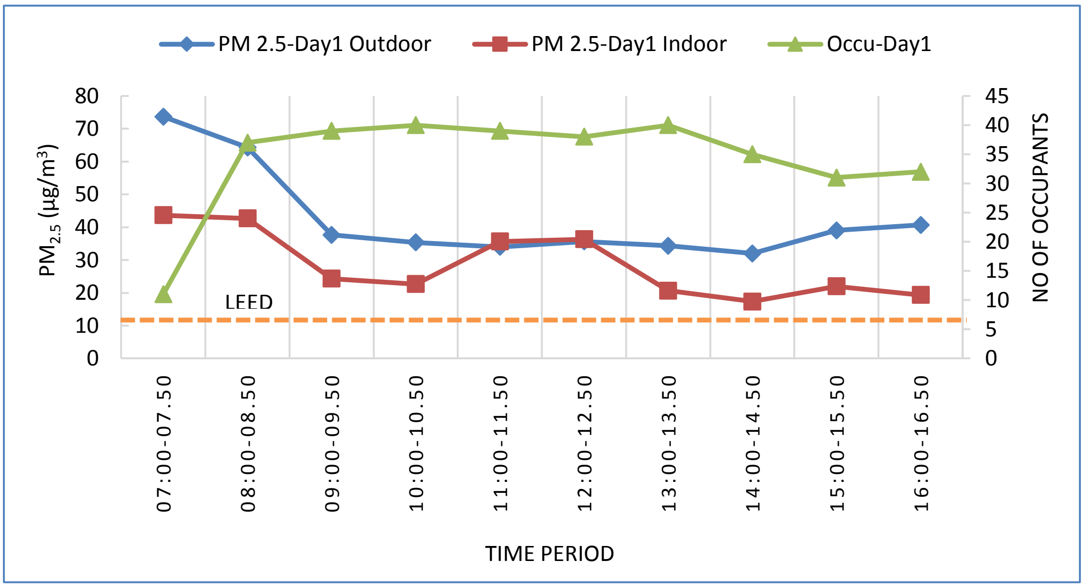

Figure 27:Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 1

Hourly average variations of the PM_{10} with occupancy during the Day1 is shown in Figure 28 and the hourly average of PM_{10} during all 5 days are shown in Appendix-9. The outdoor air had a minimum and maximum PM_{10} of 26 µg/m^3 and 95 µg/m^3, respectively, while the indoor air had a minimum and maximum PM_{10} of 15 µg/m^3 and 80 µg/m^3, respectively. The daily average PM_{10} of the outdoor air ranged from 39.23 to 64.8 µg/m^3, while the daily average PM_{10} of the indoor air was 26.03 to 45.5 µg/m^3.

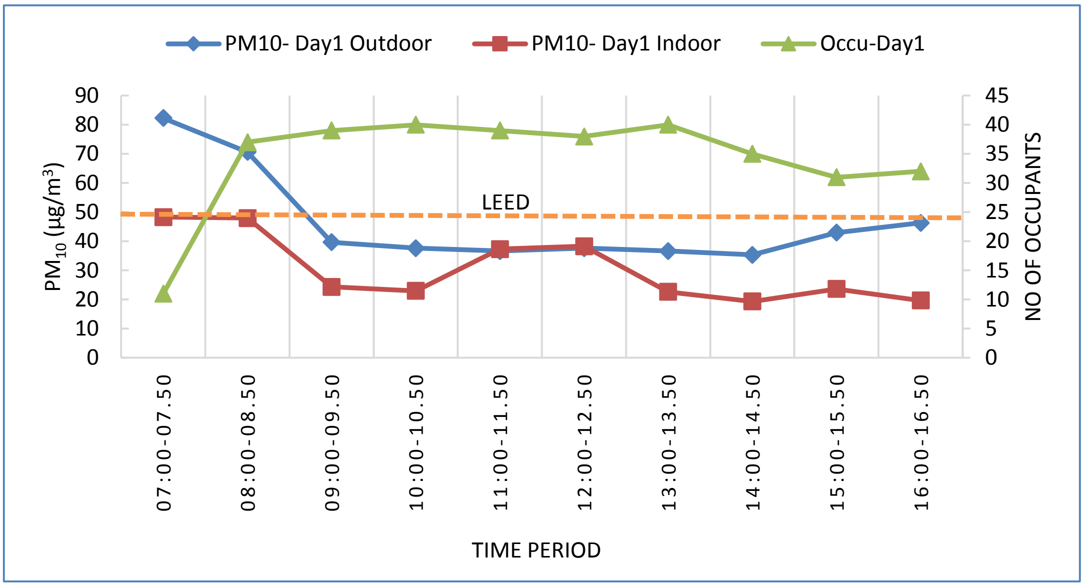

Figure 28:Hourly average of PM_{10} and occupancy at the Basement during day 1

The hourly average of Particulate Matter in outdoor air was directly proportional to that in indoor air. The outdoor Particulate Matter concentration was always higher than the indoor Particulate Matter concentration. Outdoor air is the primary source of Particulates in buildings. Since the supply air to the office spaces is filtered by the AHU, Particulate Matter levels in the return air to the AHU room were higher than Particulate Matter levels in the indoor spaces of the Basement. In addition, the ceiling plenum uses as the building's returned air duct. The concentration of Particulate Matter in the retuned air to the AHU room was increased due to the accumulation of Particulate Matter on the ceiling.

The concentration of Particulate Matter has increased from 11 a.m. to 1 p.m., according to the Particulate Matter graphs. During this time, people move around for lunch, and more outdoor air enters the indoor spaces through doors. As a result, Particulate Matter levels have risen.

4.6 Total Volatile Organic Compound (TVOC)

Measured values of TVOC at the selected locations of the Basement on the holiday and working day are shown in Figure 29. The highest concentration of TVOC (160 μg/m^3) was observed at the Store (S4) on the holiday. The store is rarely opened on holidays and emissions from used paint buckets are accumulated in the Store due to the unavailability of ventilation. Next to the Store (S4) location S7 and S3 were indicated a higher level of TVOC. S7 is near the Fire Exit 01 and this location affects illegal smoking on the Fire Staircase. S3 is the adjacent location to the Store. Hence, locations S3 and S7 indicate a higher level of TVOC.

TVOC levels of the Basement were varied from 6 to 86 μg/m^3 during the working day. Higher variation of TVOC concentration was not observed on working day subjected to the air circulation of the central air conditioning system. The highest concentration was reported from System Control Unit (S9) on the working day. The emissions from the electronic equipment might be the cause for this higher level of TVOC at System Control Unit. S10 was the location, which indicated a higher level of TVOC next to the S9. TVOC concentrations at all the location except S9 and S10 in the Basement on working day were lower than that of on holiday. The main reason for this reduction of TVOC levels on working day is the air circulation due to the function of Central Air Conditioning system.

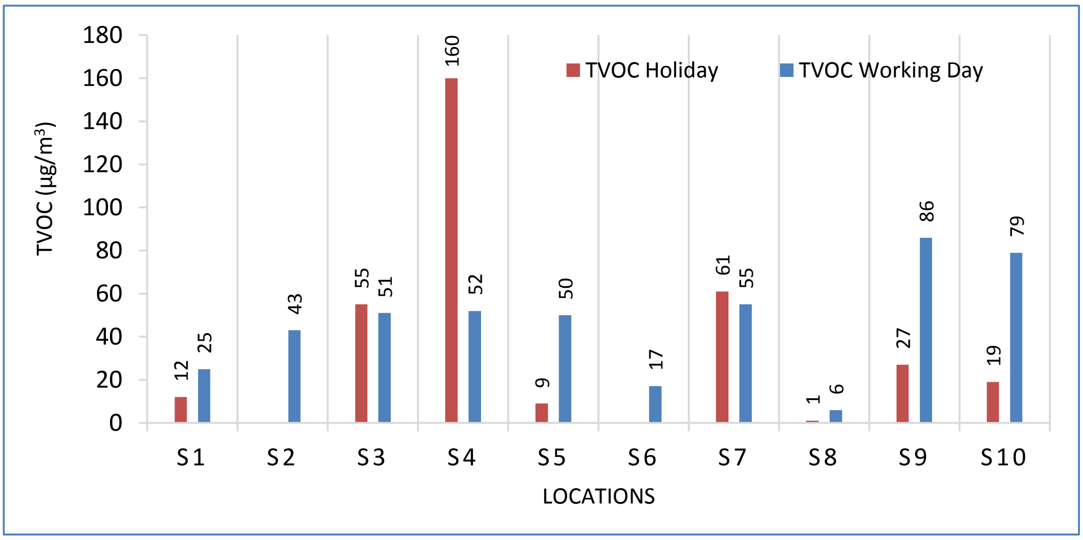

Figure 29: TVOC levels at the selected locations of the Basement on the holiday and working day

TVOC profile for 8-hours of period at location S10 of the Basement on the working day is shown Figure 30. Concentration of TVOC varied hourly from 2 to 180 μg/m^3 during 8-hours of period. 8-hours' average of TVOC at this location was 63.5 μg/m^3. Fluctuation of TVOC levels at this location was observed. The operation of the electronic equipment at nearby location S9 might be the reason for this fluctuation.

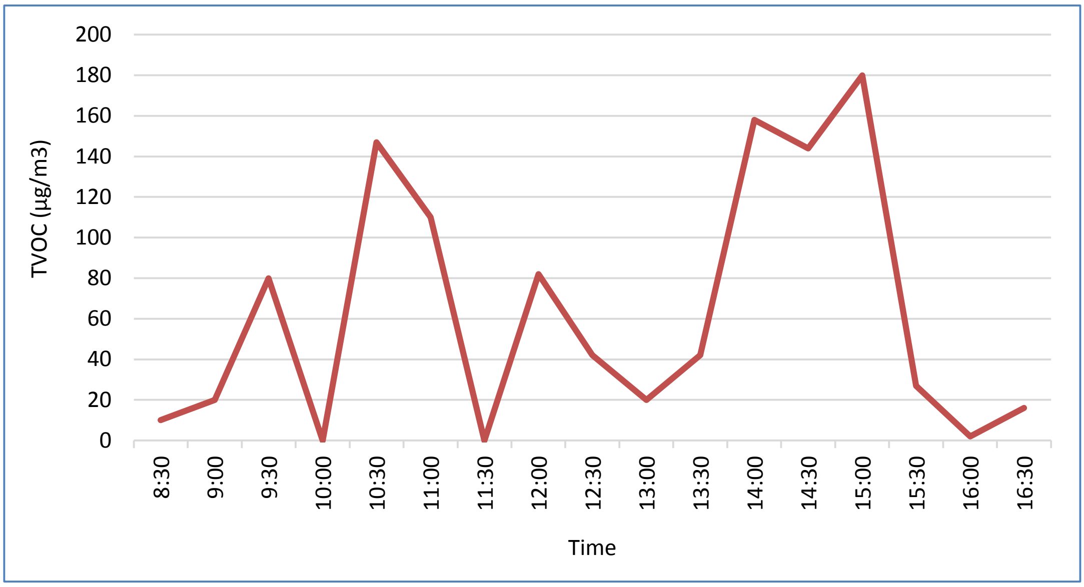

Figure 30: TVOC profile for 8-hours of period at location S10 of the Basement on the working day

24-hour TVOC profile at IT Lab on a working day is shown in Figure 31. 24-hour' average of TVOC concentration in this office was 273 μg/m^3. The minimum and maximum levels of TVOC were 228 μg/m^3 and 393 μg/m^3 respectively. Confined space and unavailability of ventilation system lead to a higher concentration of TVOC at the IT Lab. Variations of the TVOC levels are observed during 24-hours of period. However, no pattern of variation is observed. Operation and idling period of the electronic equipment available at this location might be the reason for the variations of TVOC levels.

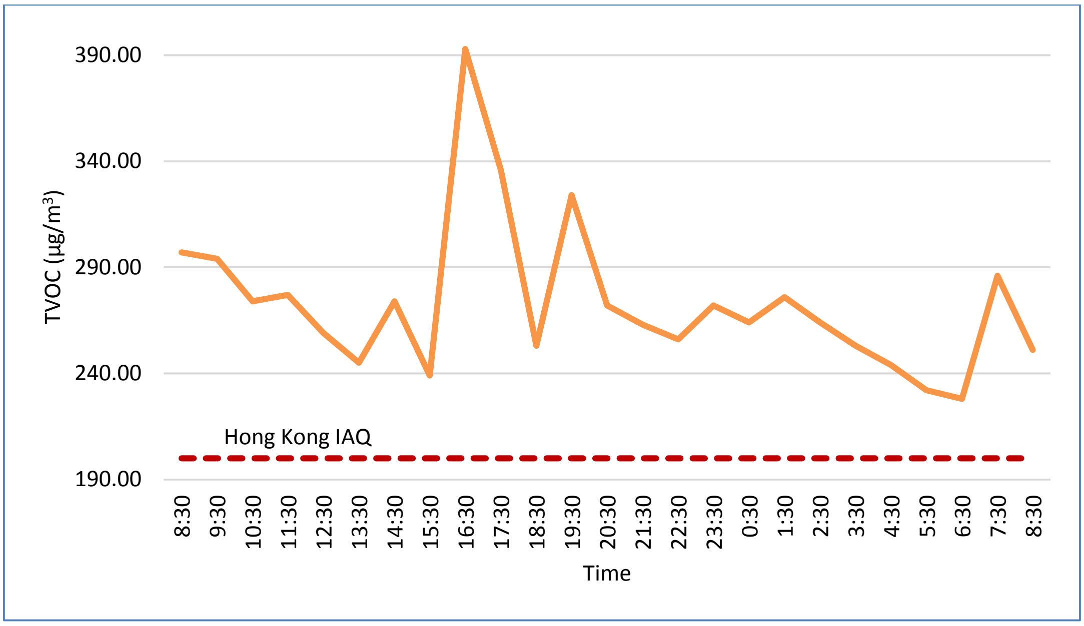

Figure 31: 24 hour' TVOC profile at IT Lab on a working day

In outdoor air, all TVOC levels were zero. Hourly average variations of the TVOC in indoor air at Basement are shown in Figure 32. During these five days, the minimum and maximum TVOC levels recorded were 0 and 341 µg/m^3, respectively. Morning TVOC levels are higher than evening TVOC levels. This means that electronic equipment operations are higher in the morning.

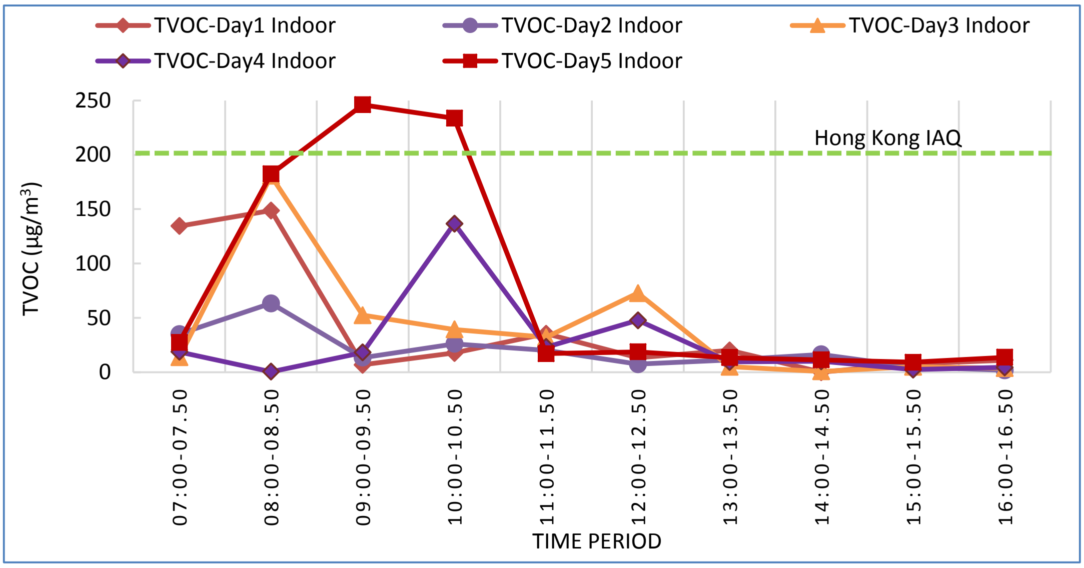

Figure 32: Hourly average of TVOC of the Basement during 5 days of period

4.6.1 TVOC with air fresheners

After the dispersion of air fresheners to the System Control Unit (S9), concentration of TVOC level was increased from 226 µg/m^3 to a maximum of 1009 µg/m^3 within 5 minutes of period. It was taken 65 minutes to reach the initial concentration of TVOC after dispersion of air fresheners. Variations of TVOC concentration with the dispersion of air fresheners inside the System Control Unit of the Basement are shown in Figure 33. Room volume of this office is 74.4 m^3 and air circulation is poor due to the non-availability of diffusers. Split type air conditioners are used inside this office and this office is fully partitioned. As such, TVOC level was risen with dispersion of air fresheners and a significant period was required to dilute the indoor TVOC.

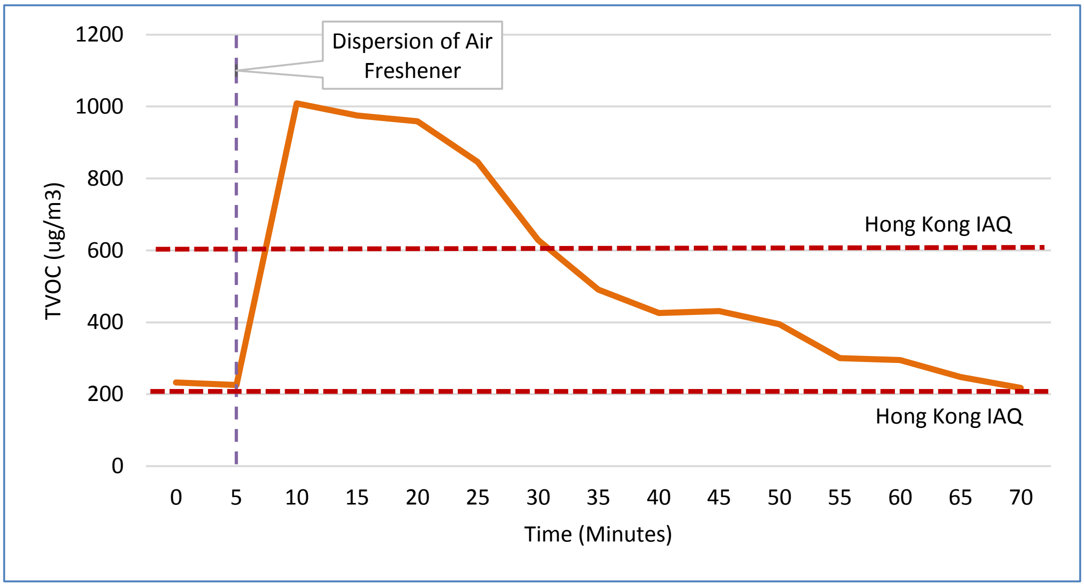

Figure 33: Variations of TVOC concentration with dispersion of air fresheners inside the System Control Unit of the Basement

4.6.2 TVOC with incense smoke

TVOC concentration inside the Store (S4) was 68 µg/m^3 when the incense stick was lit. The concentration of TVOC was increased up to 281 µg/m^3 when the incense stick was put out after 55 minutes. It was observed that 45 minutes of time was taken to reach the previous TVOC level after the incense stick was put out inside 25.2 m^3 of room space. Variations of TVOC with incense smoke inside the Store are shown in Figure 34.

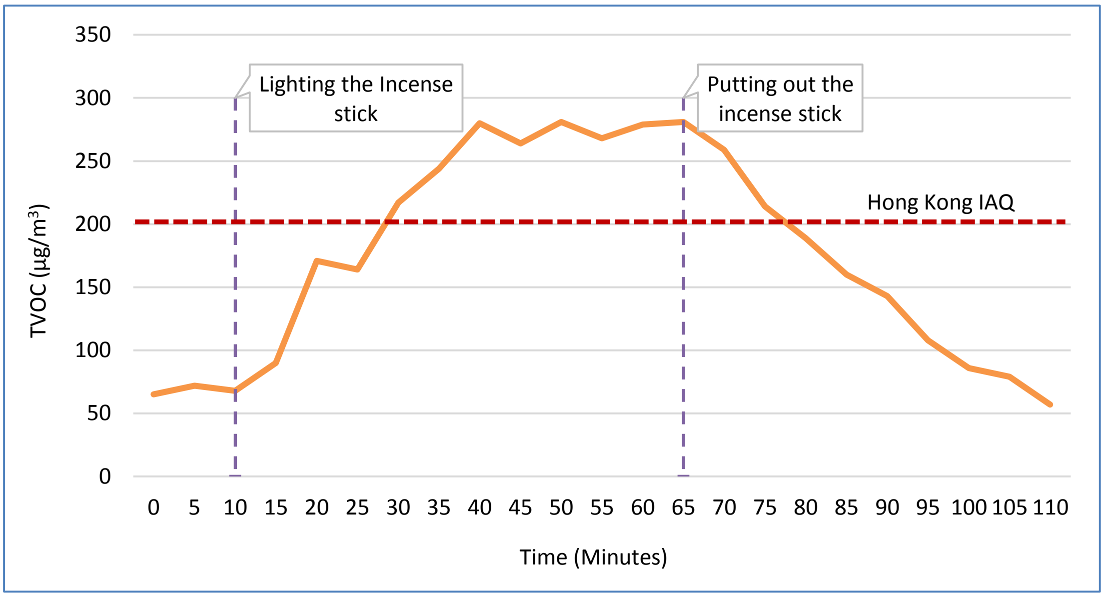

Figure 34:Variations of TVOC with incense smoke inside the Store

CHAPTER 05: DISCUSSION

It is expected to review the analyzed data to make recommendations on the factors affecting the IAQ of the office space no 1 (Basement) and office space no 2 (IT Lab). Comparison of the existing air quality of the selected offices with IAQ guidelines were conducted for enhancing the IAQ of the Basement and IT Lab.

5.1 Carbon Monoxide (CO)

CO levels of the selected buildings and surroundings were below 1 ppm. The reason for this low level of CO is the distance from the main road and unavailability of CO sources in the closed proximity to these buildings. No nearby or underground vehicle parking is available for the selected buildings of this research.

5.2 Temperature

The average temperatures of the selected locations of the Basement on holiday except S8 and S9 were above 28 ^{0}C. Further, maximum temperature of these location during 1-h period exceeded 26 ^{0}C. These temperature levels are higher than recommended values by ASHRAE (See Table 6). The maximum temperatures at locations S2, S3, S4, S5, S7 and S10 are higher than 26 ^{0}C on the working day. That means these locations are not in accordance with ASRAE standards even though central air conditioning system was in operation. 8 hours' average temperatures of location S10 of the Basement day was 25.67 ^{0}C. Hence, the temperature of S10 is not in accordance with Hon Kong guidelines. Thermal load of the Basement is required to be re-evaluated and necessary improvements of the central air conditioning system are to be carried out in order to achieve the recommended temperature levels by ASHRAE and Hong Kong guidelines on working days. Further, an installation of a ventilation system is recommended for the Basement except S8 and S9 locations in order to reduce the temperature during holidays.

The 8-hour' average of the temperature at IT Lab from 8.30 a.m. to 4.30 p.m. was 24.83 ^{0}C. As such, the temperature of the IT Lab was in Excellent Class according to Hong Kong guidelines. Further, in IT Lab, temperature was varied from 23 to 26 ^{0}C during a period of 24 hours. The 24-hour average temperature of this office was 24.74

^{0}C. Hence, this IT lab is maintaining good thermal performance according to the ASHRAE and Hong Kong guidelines.

Since the temperature of the building return air to the AHU room is always higher than the temperature inside the building, the indoor air temperature of the Basement could not be compared to the available guidelines based on temperature levels measured at the AHU room. The minimum temperature recorded at AHU was 29.2 ^{0}C, which is higher than the ASHRAE and Hong Kong guidelines' recommended maximum temperature values.

Only the 50% of the ground floor of the 14 storied building has been air conditioned. Therefore, 50% of the slab area of the Basement is at outdoor air temperature. Since the ceiling plenum of this building is used as the return air duct, return air to the AHU gain heat through the unconditioned slab area and the wall area exposed to the ceiling plenum. Therefore, the temperature levels in the return air to the AHU were higher than the temperature levels in the Basement's indoor spaces. The Central Air Conditioning system requires an additional 5.395 kW of energy to cater for this heat gain at the ceiling plenum, which costs Rs. 402,005.19 per year, as shown in Apendix-10.

5.3 Relative humidity (RH)

The RH of the selected locations of the Basement was higher than 60% on both holiday and working day. RH of these locations was unacceptable according to the ASHRAE standard (See Table 6). 1-h average RH levels of the Basement on holiday are higher than 80% except location S8 and S9 which have split type air conditioners. But on working day, RH levels have not exceeded 74% with the availability of central air conditioning system. The air handling unit in the Basement was installed in 2004, and the cooling coil's efficiency is low due to prolonged usages. As a result, the cooling coil must be replaced in order to meet ASHRAE RH guidelines.

The 8-hour average of RH at location S10 and IT Lab was 63.39% and 60.32%, respectively. Hence, S10 and IT Lab locations were in the Excellent Class of RH according to Hong Kong guidelines.

Lower RH levels were found in the return air to the Basement's AHU. RH level was fluctuated between 44.8 and 54.7 % during 5 working days. In comparison to the RH levels measured in September, the RH level in February is much lower, as shown in Figure 12, Figure 13 and Figure 16. As a result, in February, the return air RH levels are within the ASHRAE and Hong Kong guidelines' recommended values.

5.4 Carbon dioxide (CO_2)

The maximum outdoor concentration of CO_2 was 431 ppm on holiday. As such, acceptable CO_2 level is 1131 ppm (431+700 ppm) according to ASHRAE guidelines (See Table 6). The maximum levels of CO_2 of the measured locations except Central Exchange (S8) were lower than 1131 ppm of CO_2 on the holiday. The maximum reported level of CO_2 at S8 (1216 ppm) was little bit higher than ASHRAE guideline. The higher occupancy density and the use of split type air conditioners in a confined space are the reasons for this higher level of CO_2 at Central Exchange (S8). All other locations indicated maximum CO_2 levels lower than 701 ppm on holiday. Hence, CO_2 levels of all these locations are acceptable according to ASHRAE and LEED ratings.

The acceptable level of CO_2 on working day was 1119 ppm (419 + 700 ppm) according to ASHRAE guidelines, since outdoor level of CO_2 was 419 ppm on the working day. Only the location S10 has exceeded this limit as the maximum reported CO_2 level was 1233 ppm at S10. CO_2 levels at S2 and S10 were above 1000 ppm. Hence, CO_2 levels at all selected locations of the Basement other than S2 and S10 were accepted according to the benchmark of LEED ratings. 8-hours' average of CO_2 at location S10 was 909.89 ppm. Hence, S10 of the Basement was in the Good Class according to Hong Kong guidelines (See Table 6). CO_2 level at S10 on a working day is also acceptable according to both the ASHRAE guideline and LEED ratings.

The 8-hour average of CO_2 at IT Lab was 1918.73 ppm. Hence, 8-hour' average of CO_2 concentration at IT Lab was much beyond the acceptable levels introduced by all guidelines (See Table 6). The 24-hour' average of CO_2 at the IT Lab was 1651 ppm. High occupancy density and unavailability a ventilation system are the reasons for this higher level of CO_2 in the IT Lab. Hence, a mechanical ventilation system is recommended for this office for providing the required rate of fresh air.

In February 2022, the maximum outdoor CO_2 level measured was 606 ppm over a 5-day period. The maximum permissible indoor CO_2 level, according to ASHRAE guidelines, was 1306 ppm (606 +700 ppm). The CO_2 levels in the return air to the AHU room were all below 1306 ppm. As a result, the CO_2 levels in the basement were consistent with the ASHRAE guidelines. Moreover, during these 5 days, the maximum 8-hour CO_2 average was 651 ppm. Therefore, the Basement's CO_2 concentration was in the “Excellent Class” according to the Hong Kong guideline, as well as below the LEED benchmark. However, higher levels of CO_2 were detected at various locations within the building depending on the internal partitions, ventilation, and occupancy density of the respective location.

5.5 Particulate matter ($PM_{2.5}$ and PM_{10})

On the holiday, the maximum $PM_{2.5}$ and PM_{10} concentrations in the Basement were reported to be 10 μg/m^3 and 21.78 μg/m^3, respectively. As a result, on a holiday, the levels of $PM_{2.5}$ and PM_{10} in these locations were in line with LEED ratings. On a working day, the maximum $PM_{2.5}$ level at locations S7, S9, and S10 was greater than 12 μg/m^3. As a result, the $PM_{2.5}$ levels in these locations did not meet the LEED requirements. Furthermore, all of the PM_{10} levels in the Basement, with the exception of S9, were within the LEED ratings.

The 8-hour’ averages of PM_{10} at location S10 (19.34 μg/m^3) and IT Lab (7.71 μg/m^3) were in Excellent Class according to the Hong Kong guidelines. However, concentration at S10 has reached to the upper limit (20 μg/m^3) of the excellent class. Only the primary filter is available on the AHU in the basement. The introduction of a suitable secondary filter for the AHU can reduce particulate matter levels during working days.

At IT Lab, the 24-hour average of $PM_{2.5}$ and PM_{10} was 2.63 and 7.68 μg/m3, respectively. This value is well below the WHO's $PM_{2.5}$ (25 μg/m3) and PM_{10} (50 μg/m3) guidelines. However, in the IT Lab, the maximum levels of $PM_{2.5}$ and PM_{10} were 40 and 123.23 μg/m3, respectively. As a result, $PM_{2.5}$ and PM_{10} concentrations in the IT Lab did not meet LEED requirements.

The $PM_{2.5}$ levels in the return air to the Basement's AHU room were higher than those in the Basement's indoor space. The minimum $PM_{2.5}$ level recorded during the measurements at the AHU room was 24.17 µg/m^3, which is higher than the LEED ratings' expected level.

The average PM_{10} from 9 p.m. to 5 p.m. in the AHU room ranged from 24.17 to 43.03 µg/m^3. Because the average PM_{10} concentrations were less than 180 µg/m^3, the entire Basement met the "Good Class" of Hong Kong guidelines for PM_{10} concentration. However, PM_{10} levels recorded in the AHU room occasionally exceeded 50 µg/m^3. As a result, the Basement's PM_{10} concentration did not meet LEED standards.

Outdoor $PM_{2.5}$ levels were 37 to 53% higher than indoor levels, while outdoor PM_{10} levels were 42 to 52% higher than indoor levels. As a result, outdoor air is the primary source of particulate matter in indoor air. According to the levels of particulate matter recorded at various locations throughout the Basement, the observed level of particulate matter at a given location is dependent on factors such as electronic equipment availability, occupancy density, type of activity, and ventilation.

5.6 Total Volatile Organic Compounds (TVOC)

According to LEED standards, TVOC level should be less than 500 µg/m^3 [72]. The maximum levels reported at the Basement's selected locations during the holiday and working day were 160 and 86 µg/m^3, respectively. Further, TVOC concentrations of the location S10 of the Basement were varied from 0 to 180 µg/m^3 during 8-hours of period. As a result, the TVOC levels in the Basement were in line with LEED ratings based on IAQ measurements taken over 1- and 8-hour periods. However, this location was not included in Hong Kong's IAQ objectives' "Excellent class". Since the 8-hour average of TVOC at S10 was 53 µg/m3, it is in Good Class (See Table 6).

The maximum TVOC value reported from IT Lab was 393 µg/m^3 during 24 hours of period. Hence, IT Lab was in accordance with LEED standards. It was in "Good Class" of Hong Kong guidelines, since 8-hour' average level of TVOC at the IT Lab was 283.5 µg/m^3.

Because the maximum level of TVOC (341 μg/m^3) reported at the Basement during the 5-day period was less than 500 μg/m^3, the Basement's TVOC level met LEED requirements.

The average TVOC in the AHU room from 9 p.m. to 5 p.m. ranged from 13.96 to 70.33 μg/m^3 over the 5-day period. The entire Basement met the “Excellent Class” of Hong Kong guidelines for TVOC concentration because the average TVOC concentrations were less than 200 μg/m^3.

5.6.1 TVOC with dispersion of air freshener

Prior to the spraying of air fresheners, concentration of TVOC inside the System Control Unit (S9) was 226 μg/m^3. If this level remained as an average value, it would be under the category of Good Class according to Hong Kong Guidelines (See Table 6). The dispersion of air fresheners has increased TVOC level to 1009 μg/m^3 within 5 minutes. The existing level of TVOC has been increased by 346% after the dispersion of air freshener. Hence, the frequent use of air fresheners without having a proper ventilation system causes poor indoor air quality.

5.6.2 TVOC with incense smoke

The concentration of TVOC increased from 68 to 281 μg/m^3 during a period of 55 minutes with the presence of incense smoke. This maximum value is under the category of Good Class of Hong Kong guidelines (See Table 6). Only one incense stick was used to generate incense smoke in the Store. Measuring distance is about 0.5 meters. The concentration of TVOC has not indicated direct increment, since the flow direction of the incense smoke was changing. However, it was understood that incense smoke has an impact on indoor air quality.

5.7 Outdoor air flow rate required for IT Lab

Considering the concentrations of indoor air contaminants, it was observed that IAQ was poor inside the IT Lab. The reason for this poor IAQ was non-availability of proper ventilation system. Hence, a mechanical ventilation system is vital in order to provide outdoor air for the IT Lab. The outdoor air flow rate is calculated using Equation 1.

$$V_{out} = R_p \times P_z + R_a \times A_z \qquad \text{(Equation 1)} \quad \text{Source: [67]}$$

Where,

V_{out} - Required outdoor air flow rate for the IT Lab

R_p - Outdoor airflow rate required per person working in the office

P_z - Number of occupants working in the office

R_a - Outdoor airflow rate required per unit area

A_z - Floor area of the office

$A_z = 23.6\ m^2$

$P_z = 10$ (Considering day shift)

$R_a = 0.6\ L/s.m^{2,}$ $R_p = 5\ L/s$ (from Table 6.2.2.1 of ASHRAE Standard 2016 [67])

$V_{out} = 5\times 10 + 0.6 \times 23.6 = 64.16\ L/s$

According to the calculations, a minimum ventilation rate of 64.16 L/s of outdoor air to be supplied for IT Lab in order to maintain an acceptable IAQ level.

CHAPTER 06: CONCLUSION

This study aimed to investigate the factors affecting IAQ of office buildings. In situ measurement of two separate office buildings was recorded to achieve the aim of this study. This Chapter presents the key findings, limitations, recommendations and future work of the study.

6.1 Key findings

Based on the analysis, location of the building, occupancy related activities, office equipment, ventilation and air-conditioning system are identified as factors affecting IAQ of office buildings.

6.1.1 Location of the building

All the selected location of this study has not indicated CO concentration, since these locations are 50 m away from main traffic stream. Further, no vehicle parking is available near these selected locations. Effect of traffic stream and vehicle parking are proved by previous studies [27]. The central air conditioning system in office space 01 draws fresh air from the Beira lade side. As a result, no polluted air enters office space no 01.

6.1.2 Occupancy related activities

Occupancy increases the indoor concentration of CO_2. This is proved by this study in comparison of CO_2 concentrations in the Basement on the holiday and the working day the in situ results. The one-hour average of CO_2 at location S10 (center of the basement) has increased by 10.7 % on the working day with the increase in occupancy.

Rapid increment of CO_2 level was observed in IT Lab during the morning meeting due to high occupancy. It was reached at a maximum of 2923 ppm during this meeting with the increase in occupancy. The same observation was reported by a study conducted to compare the CO_2 measurements in Centralized and split unit air conditioning systems [75]. Further, it is observed that the CO_2 concentration of office building increases with time during working hours and reaches the maximum in the evening until the occupants leave.

PM on working day is higher than that of on the holiday due to the increase in movements of occupants. The concentration of PM is higher at corridors such as location S7 and S10 of the Basement due to the movements of occupants. PM levels of the office buildings reaches to its maximum level during the movement times of occupants such as in the mornings, lunch time and evenings.

According to the 24-hour PM profile of the IT Lab, it is observed that the concentration of PM increases for a short period during the daily cleaning process of the floors and carpets. The PM_{10} level in the IT Lab was less than 15 µg/m^3, but it suddenly increased to 123 µg/m^3 during the vacuuming process due to short-term resuspension [76].

According to the in situ measurement conducted at System Control Unit (S9) of the Basement, it is observed that the use of air fresheners enhances the concentration of TVOC rapidly. The concentration of TVOC was increased by 346% with the dispersion of 50 ml of air freshener for 5 minutes in this office, which has 74.4 m^3 of room volume. Further, the TVOC level increases with the presence of incense smoke. The effect of incense smoke on indoor TVOC level was observed during the field experiment conducted at the store (S4) of the Basement. The TVOC level was increased by 313% during the 55-minute period with the presence of incense smoke from one incense stick at 25.2 m^3 of room space. The concentration of air fresheners and incense smoke in indoor air depends on occupants' activities. Hence, it is observed that IAQ depends on occupancy related activities.

6.1.3 Function of the space

Presence of office equipment increases the indoor level of PM. In this study, System Control Unit (S9) of the Basement indicated a higher level of PM on working day than that of on the holiday (See Figure 23 and Figure 24). This observation is tallied with the results of previous study conducted in European offices [77]. In that study, a significant level of PM was observed during the operation of multi-functional electronic devices.

A higher concentration of TVOC identified in location S9 and IT Lab with the presence of electronic equipment. Variations of TVOC level in S9 and IT lab were observed according to the operation and idling times of electronic equipment. These variations of TVOC level is acceptable, since a previous study shows that the emission rates of VOCs from office' equipment is negligible when they are in "idling" or "off" periods in comparison to their "on" periods [78].

Places where use to store paint items in indoor environment shows a higher level of TVOC with the absence of proper ventilation system. In this study, the highest level of TVOC, 160 $\mu g/m^3$, was observed on the holiday in the store (S4) at the Basement (See Figure 29).

6.1.4 Ventilation & air-conditioning system

The concentration of indoor air pollutants reduces with presence of ventilation system. In this study, operation of central air conditioning system has reduced the concentration of TVOC. Unavailability of ventilation system has increased the TVOC level of the Store (S4) of the Basement on the holiday.

Places where use split type air conditioners shows poor IAQ due to the unavailability of fresh air. On the holiday, one-hour average CO_2 concentrations at locations S8 and S9 were 951 and 665 ppm, respectively, while other locations' one-hour CO_2 concentrations remained below 568 ppm (See Figure 19), since these locations used split type air conditioners without proper ventilation system. However, PM level reduces in air conditioned spaces. Locations S8 and S9 indicated lower levels of PM on the holiday in comparison to the other locations of the Basement. It is discovered that the influence of temperature on indoor PM level is statistically significant [79]. Further, the filters available in split type air conditioners in location S8 and S9 support to reduce the indoor PM level. PM levels of the Basement on the working day has reduced with the presence of central air conditioning system. Filters used in central air conditioning system leads to reduce indoor concentration of PM [80]. However, the PM level increases with the presence of central air conditioning system due to the occupant related activities.

According to air quality measurements taken at the AHU room and outdoor air, the outdoor air is the primary source of particulate matter in indoors. Proper filters must be used during the design stage of ventilation and air-conditioning systems to reduce the level of particulate matter in indoor air. It is also crucial to keep the filters in good working order.

Particulate Matter has impacted the Basement's IAQ because the basement's ceiling plenum has been used as the return air duct to the AHU room. Particulate Matter accumulation on the ceiling results in a higher concentration of Particulate Matter inside the building. The Basement's air conditioning system was designed in such a way that it failed to maintain the building's IAQ.

6.2 Limitations

The effect of climatic conditions such as monsoons was not considered for this study. Hence, a further study is needed to evaluate the IAQ in office buildings with the influence of weather patterns.

Considering the high cost of equipment, measurements for this study were taken with a limited number of equipment over a short period of time. This may have an impact on the accuracy of the results. By recording the measurements with more equipment over the duration of a year, the accuracy of the results can be improved. In future studies, it is recommended that continuous IAQ measurements be taken by using the equipment in conjunction with Building Management Systems.

6.3 Recommendations

According to the facts highlighted in the Chapter 04 and 05 of this research, worst scenario of the IAQ was observed in IT Lab. A mechanical ventilation system based on the concentration of CO_2 as shown Figure 35 is recommended to improve the IAQ of confined office spaces like IT Lab.

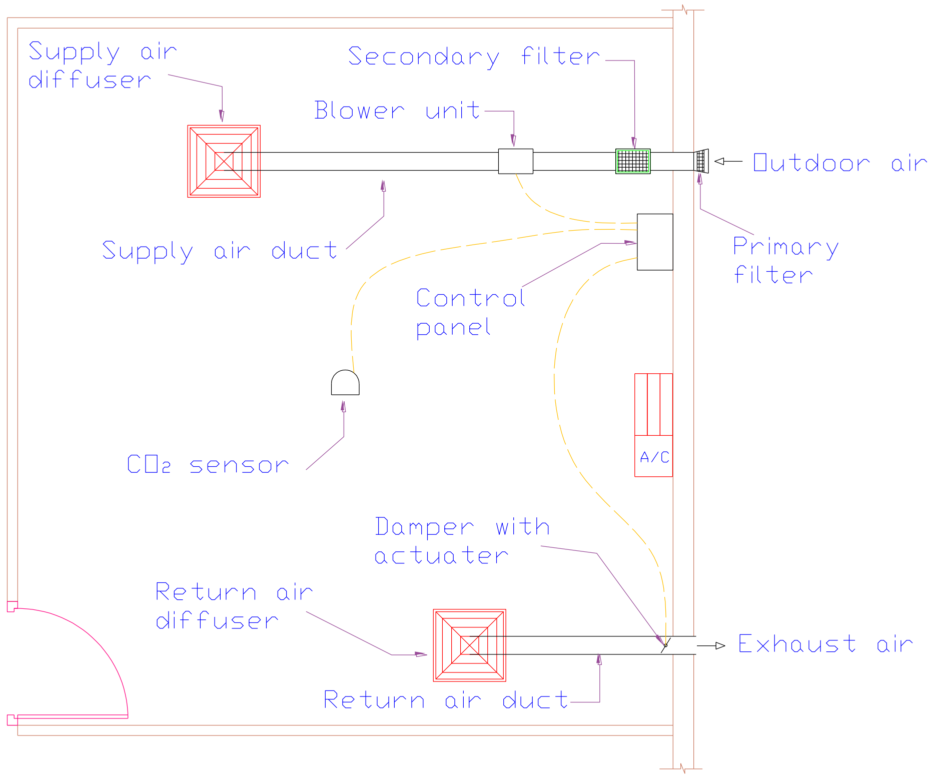

Figure 35:A mechanical ventilation system based on the concentration of CO_2 to improve the IAQ of confined office spaces like IT Lab

In the proposed mechanical ventilation system, a CO_2 sensor is used to measure the CO_2 level inside the office space. If the CO_2 level goes up beyond the recommended value, control panel starts the blower to provide outdoor air to the conditioned space. Meantime damper is opened to remove the stale air. As such, air change of the conditioned space is conducted until the CO_2 level reduces to the recommended value. Then the control unit stops the blower and closes the damper. Conditioning of the space remains with the operation of split type air conditioner. In this system, blower should be selected to cater the ventilation requirement discussed in section 5.7 of this report. Further, all the equipment including ducts are to be designed to maintain the minimum ventilation requirement of the ASHRAE standards 62.1 [67].

IAQ of the Basement has been reduced, since the ceiling plenum of the Basement has been used as the return air to the AHU room. Hence, a proper return air duct system for the Central Air Conditioning system is recommended Based on the return on investment.

6.4 Future work

After analyzing the results of this research, followings are identified as avenues for future researches in order to improve the IAQ of office buildings in Sri Lanka.

- Further research is required to improve the IAQ of the spaces such as 24 hours operating IT Labs with mechanical ventilation systems as proposed in section 6.3. IAQ parameters in this type of offices need to be recorded continuously and analyzed to monitor and improve ventilation of confined spaces where split type air conditioners are installed.
- Research on IAQ are needed to fully comprehend the effect of IAQ on Sri Lankan office workers. Based on the findings of these research, IAQ guidelines need to be developed for Sri Lanka.
- Indoor TVOC levels were found to be affected by the operation of electronic equipment, presence of air freshener and incense smoke in field experiments conducted in this study. However, further studies are needed to determine the variations in TVOC levels in office buildings and its effect on occupants.
- Use of ceiling plenum instead of a return air duct of Central Air Conditioning systems two decades ago. This was observed to cause energy waste and poor IAQ. Hence, further energy and economic analysis are needed to reconfigure the air supply and return systems of centrally air conditioned buildings.

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APPENDICES

Appendix 1:Measured height from ground level to breathing zone of sedentary personnel of each office at the Basement.

Office	Measured heights (m)
Fire office	1.15
	1.04
	1.12
Account office	1.16
	1.19
	1.13
Maintenance office	1.18
	1.10
	1.14
Project office	1.09
	1.16
	1.15
R & D Office	1.12
	1.10
	1.13

Exchange	1.23
	1.24
	1.19
System Control Unit	1.11
	1.01
	1.08
IT Unit and IT Lab	1.12
	1.21
	1.11
Average height	**1.14**

Appendix 2: Summary the data points collected for each of the parameters T, RH, $PM_{2.5}$, PM_{10}, and CO_2.

Date	Location	Duration	Interval	No of Data Points
01-09-2020 (Holiday)	S1	1 h	1 min	60
	S3	1 h	1 min	60
	S4	1 h	1 min	60
	S5	1 h	1 min	60
	S7	1 h	1 min	60
	S8	1 h	1 min	60
	S9	1 h	1 min	60
	S10	1 h	1 min	60
	outdoor	1 h	1 min	60
02-09-2020 (Working day)	S1	1 h	1 min	60
	S2	1 h	1 min	60
	S3	1 h	1 min	60
	S4	1 h	1 min	60
	S5	1 h	1 min	60
	S6	1 h	1 min	60
	S7	1 h	1 min	60
	S8	1 h	1 min	60
	S9	1 h	1 min	60
	S10	1 h	1 min	60
	outdoor	1 h	1 min	60
03-09-2020 (Working day)	S10	8 h	1 min	481
04-09-2020 (Working day)	IT Lab	24 h	1 min	1441
5 working days from 21to 25.02.2022	AHU room	5 x 10 h	10 min	150
Total no of data points				3277

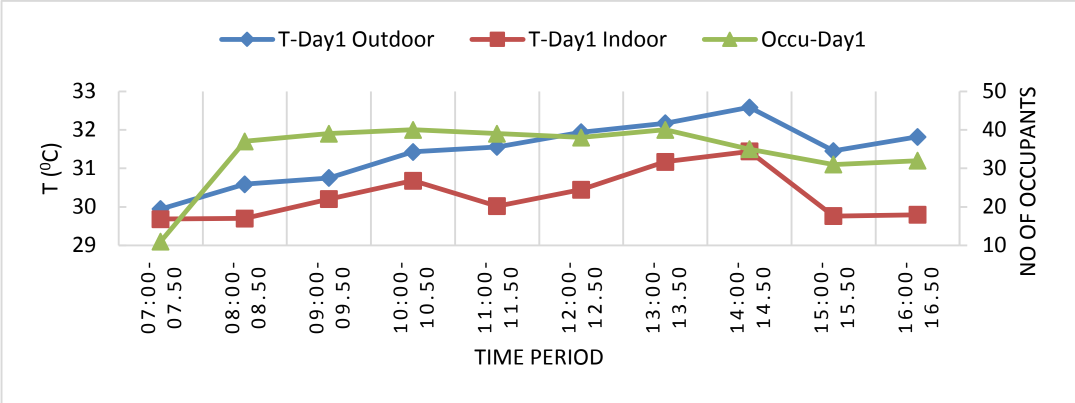
Appendix 3: Summary the data points collected for TVOC

Date	Location	Duration	Interval	No of Data Points
01-09-2020 (Holiday)	S1	1 h	30 min	3
	S3	1 h	30 min	3
	S4	1 h	30 min	3
	S5	1 h	30 min	3
	S7	1 h	30 min	3
	S8	1 h	30 min	3
	S9	1 h	30 min	3
	S10	1 h	30 min	3
	outdoor	1 h	30 min	3
02-09-2020 (Working day)	S1	1 h	30 min	3
	S2	1 h	30 min	3
	S3	1 h	30 min	3
	S4	1 h	30 min	3
	S5	1 h	30 min	3
	S6	1 h	30 min	3
	S7	1 h	30 min	3
	S8	1 h	30 min	3
	S9	1 h	30 min	3
	S10	1 h	30 min	3
	outdoor	1 h	30 min	3
03-09-2020 (Working day)	S10	8 h	30 min	17
04-09-2020 (Working day)	IT Lab	24 h	1 hour	25
07-09-2020 (Working day)	S9	70 min	5 min	15
08-09-2020 (Working day)	S4	110 min	5 min	23
5 working days from 21to 25.02.2022	AHU room	5 days	10 min	150
Total no of data points				290

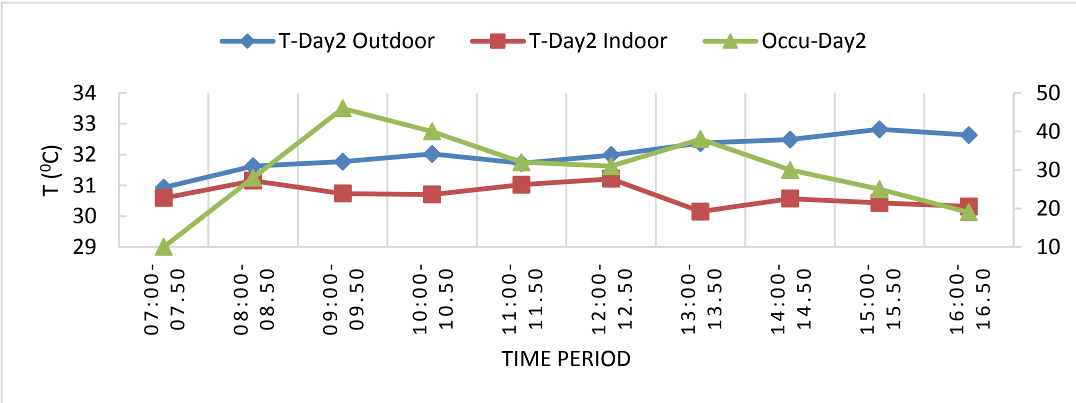
Appendix 4 Summary the data points collected for CO

Date	Location	Duration	Interval	No of Data Points
01-09-2020 (Holiday)	S1	1 h	30 min	3
	S3	1 h	30 min	3
	S4	1 h	30 min	3
	S5	1 h	30 min	3
	S7	1 h	30 min	3
	S8	1 h	30 min	3
	S9	1 h	30 min	3
	S10	1 h	30 min	3
	outdoor	1 h	30 min	3
02-09-2020 (Working day)	S1	1 h	30 min	3
	S2	1 h	30 min	3
	S3	1 h	30 min	3
	S4	1 h	30 min	3
	S5	1 h	30 min	3
	S6	1 h	30 min	3
	S7	1 h	30 min	3
	S8	1 h	30 min	3
	S9	1 h	30 min	3
	S10	1 h	30 min	3
	outdoor	1 h	30 min	3
03-09-2020 (Working day)	S10	8 h	30 min	17
04-09-2020 (Working day)	IT Lab	24 h	1 hour	25
5 working days from 21to 25.02.2022	AHU room	5 days	10 min	150
Total no of data points				252

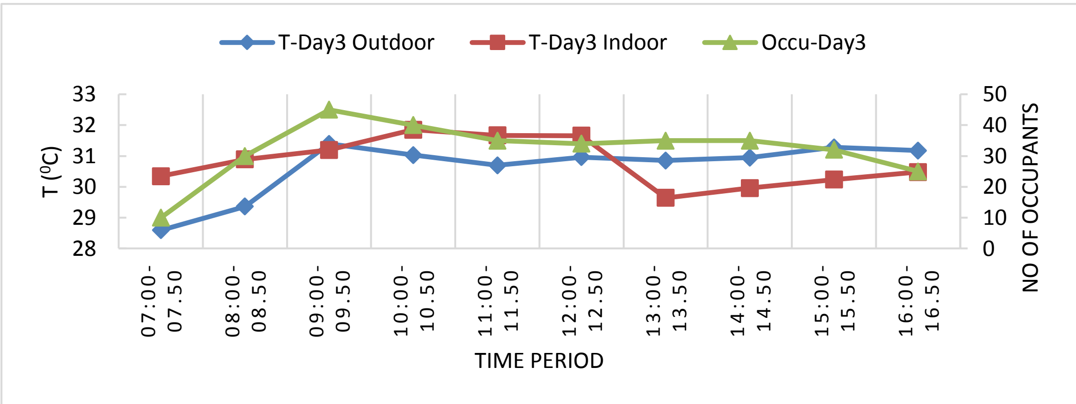
Appendix 5: Graphs of hourly average temperature variations with occupancy at AHU room of the Basement



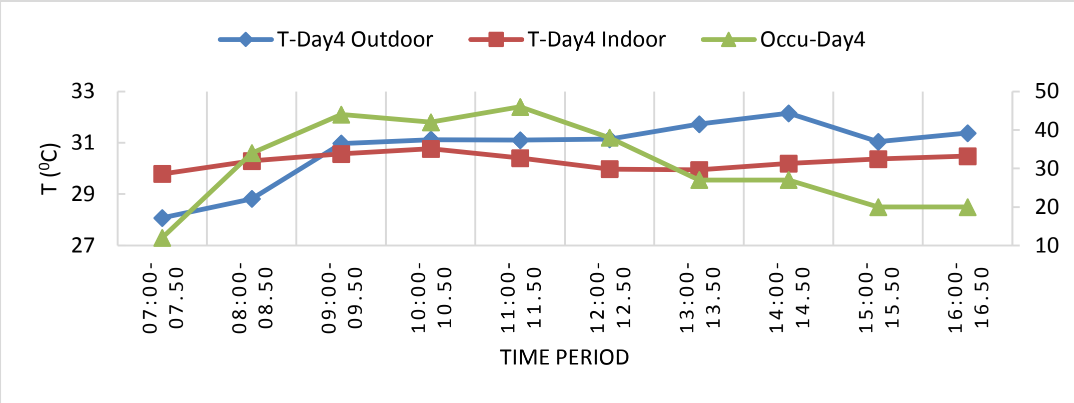
Hourly average of T and occupancy at the Basement during day 1



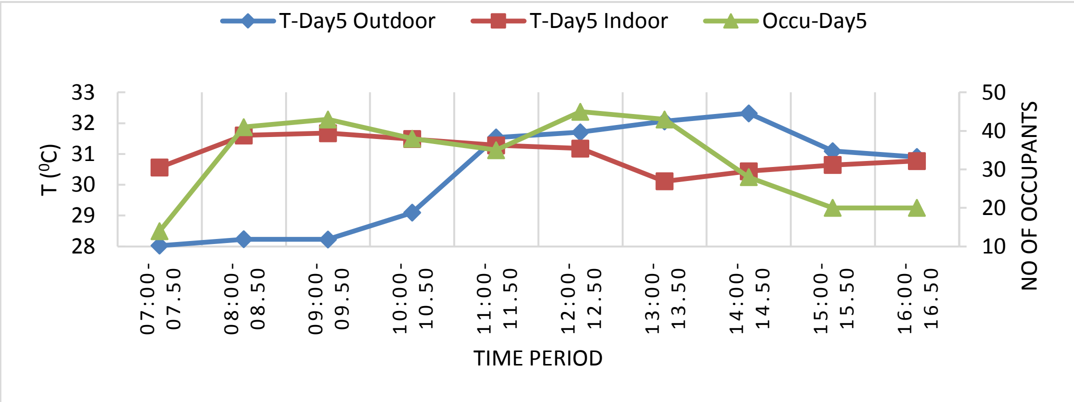
Hourly average of T and occupancy at the Basement during day 2



Hourly average of T and occupancy at the Basement during day 3

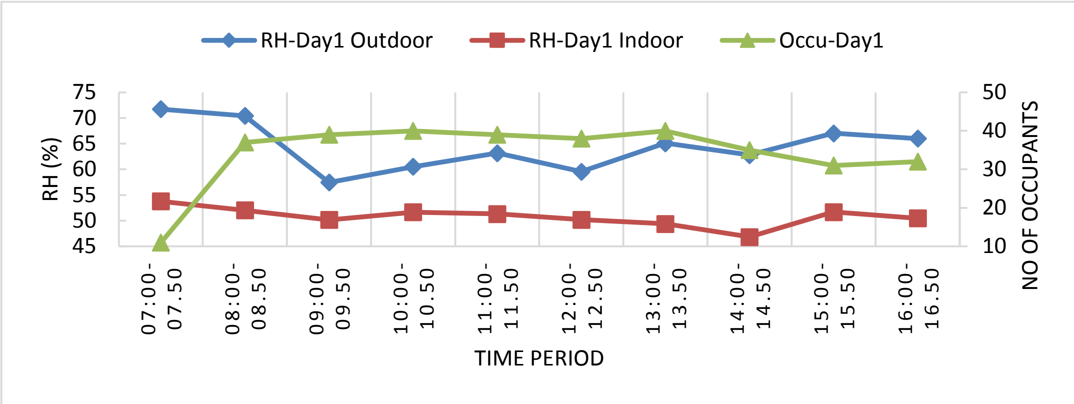


Hourly average of T and occupancy at the Basement during day 4

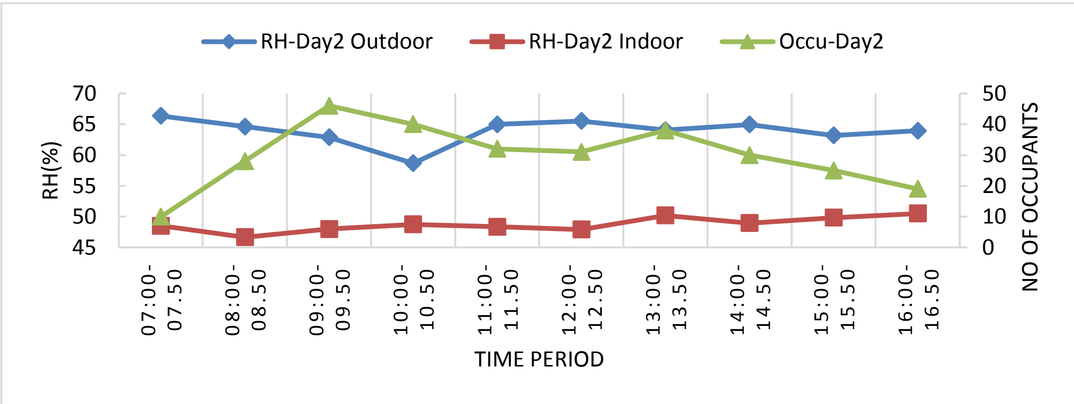


Hourly average of T and occupancy at the Basement during day 5

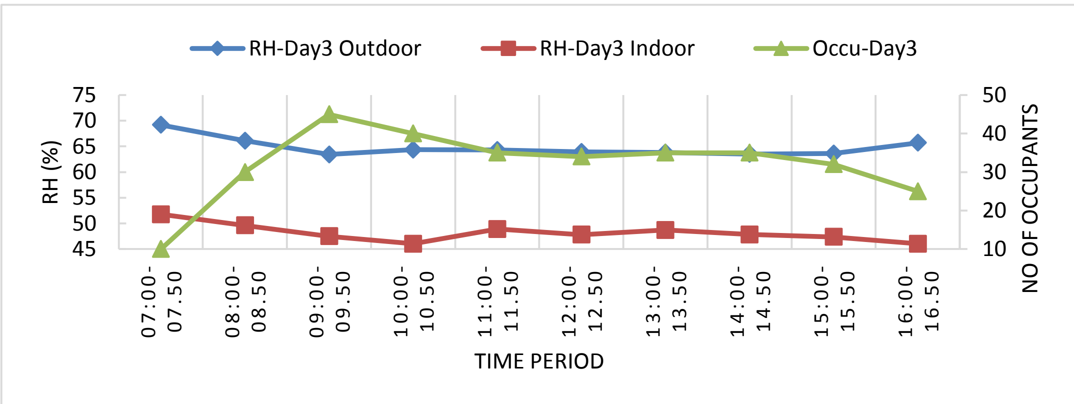
Appendix 6: Graphs of hourly average of RH with occupancy at AHU room of the Basement



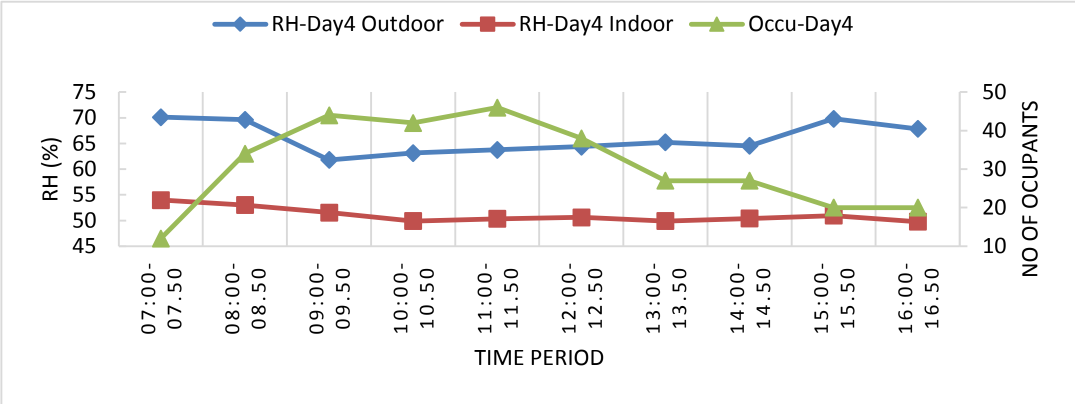
Hourly average of RH and occupancy at the Basement during day 1



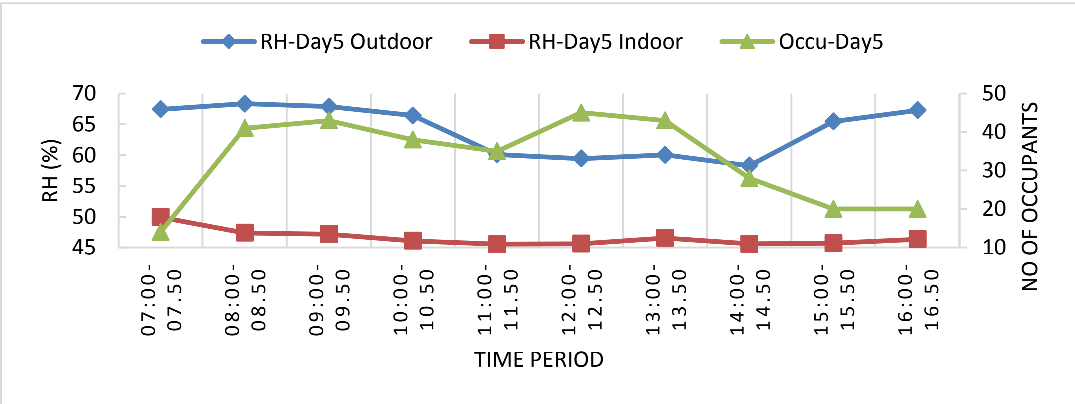
Hourly average of RH and occupancy at the Basement during day 2



Hourly average of RH and occupancy at the Basement during day 3

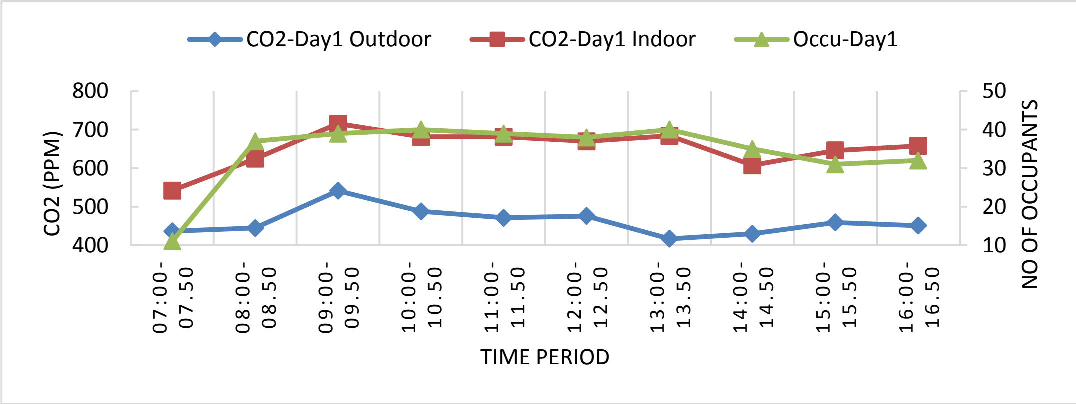


Hourly average of RH and occupancy at the Basement during day 4

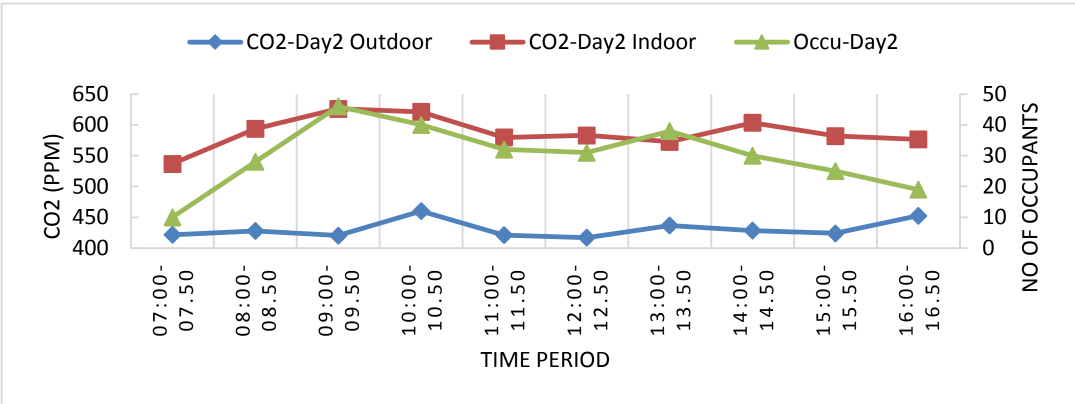


Hourly average of RH and occupancy at the Basement during day 5

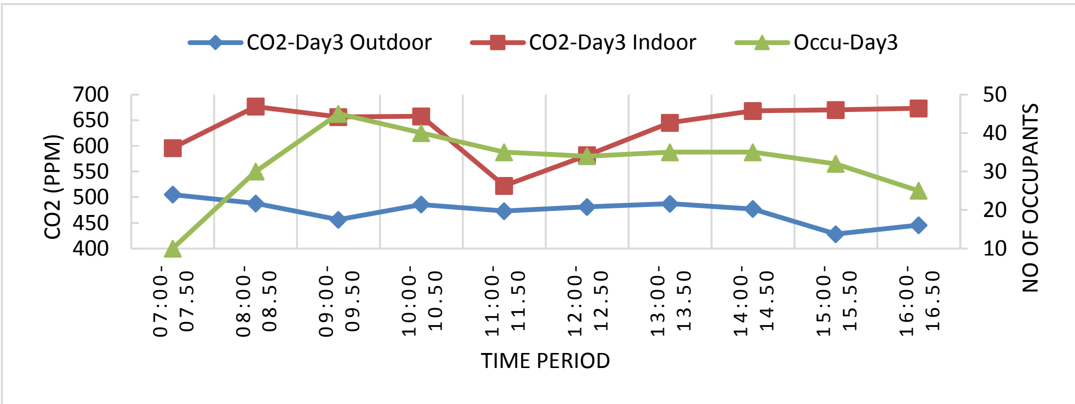
Appendix 7: Graphs of hourly average of CO_2 with occupancy at AHU room of the Basement



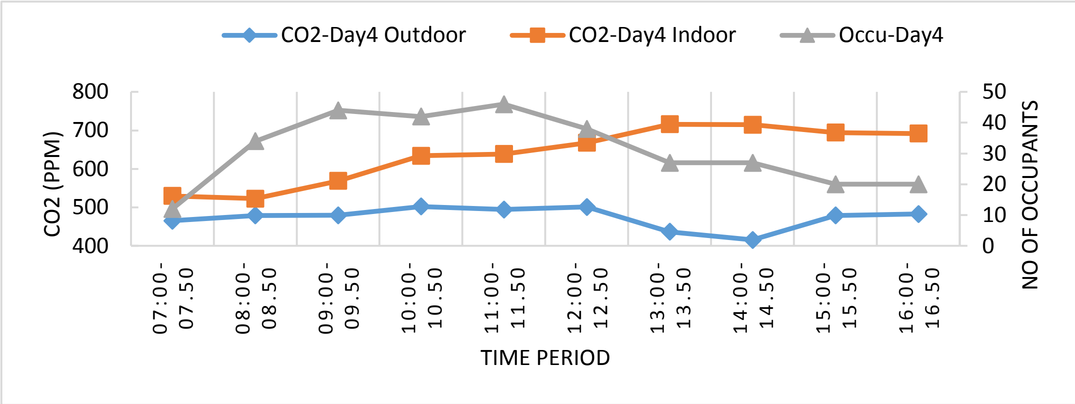
Hourly average of CO_2 and occupancy at the Basement during day 1



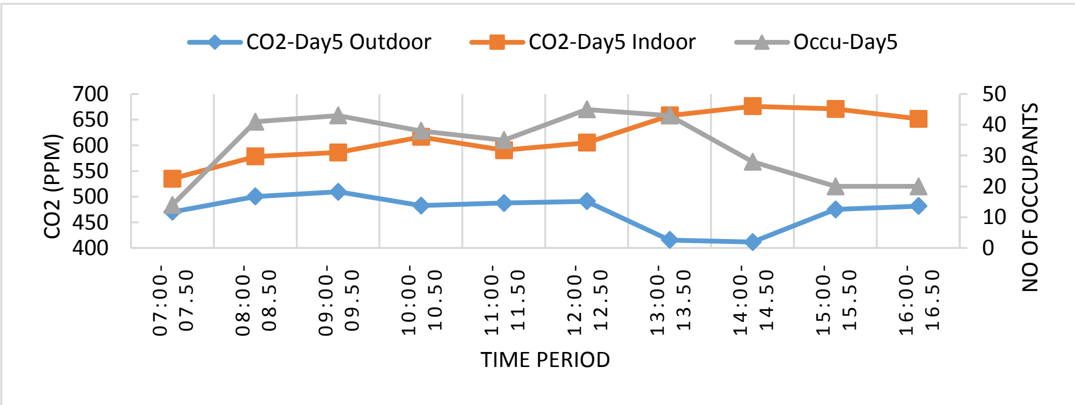
Hourly average of CO_2 and occupancy at the Basement during day 2



Hourly average of CO_2 and occupancy at the Basement during day 3

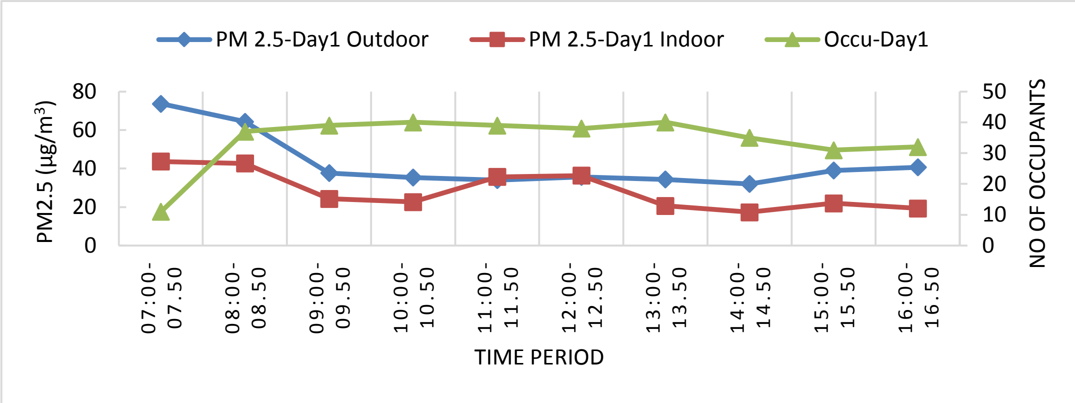


Hourly average of CO_2 and occupancy at the Basement during day 4

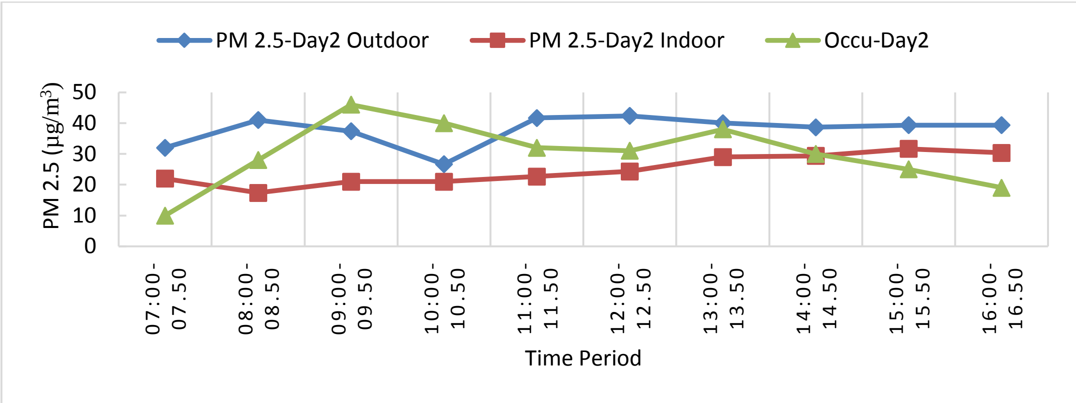


Hourly average of CO_2 and occupancy at the Basement during day 5

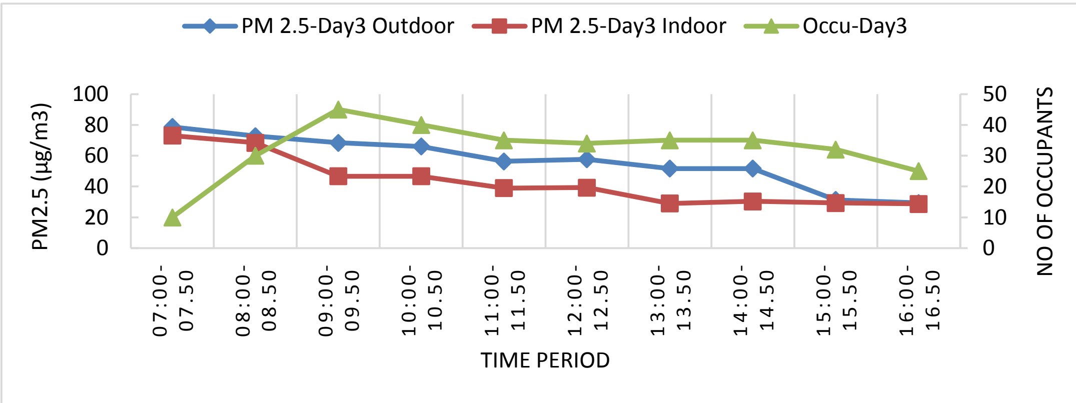
Appendix 8: Graphs of hourly average of CO_2 with occupancy at AHU room of the Basement



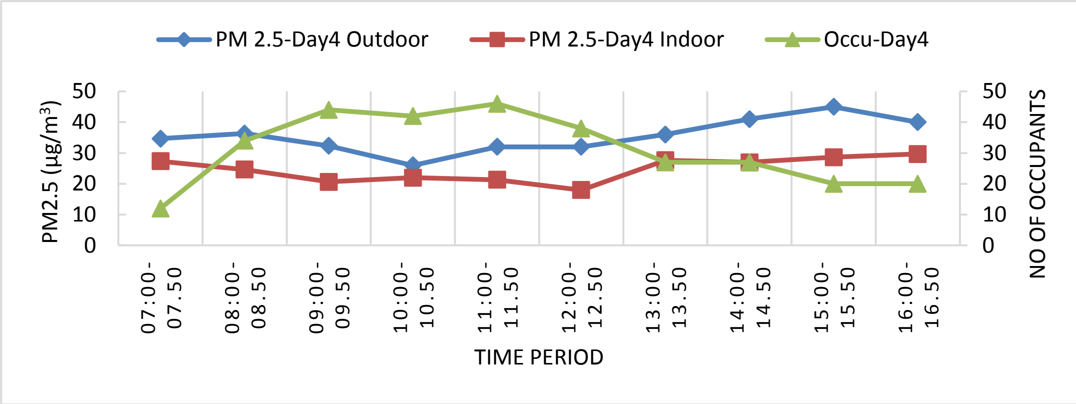
Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 1



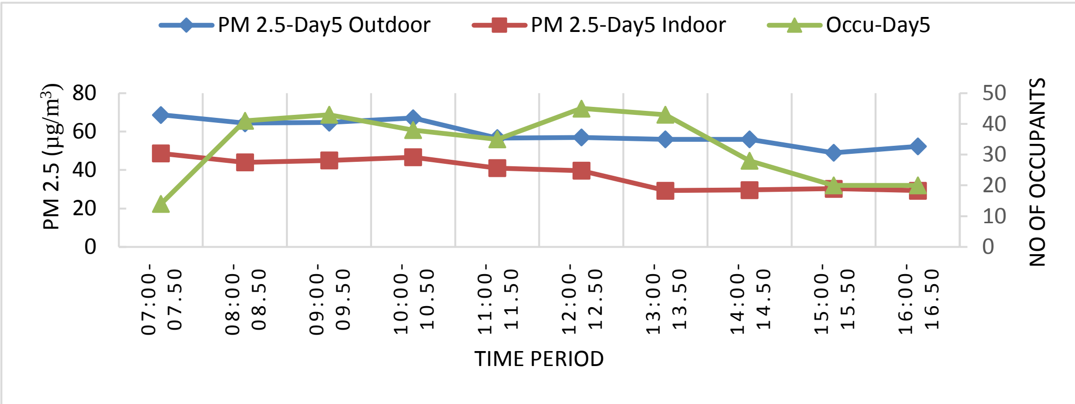
Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 2



Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 3

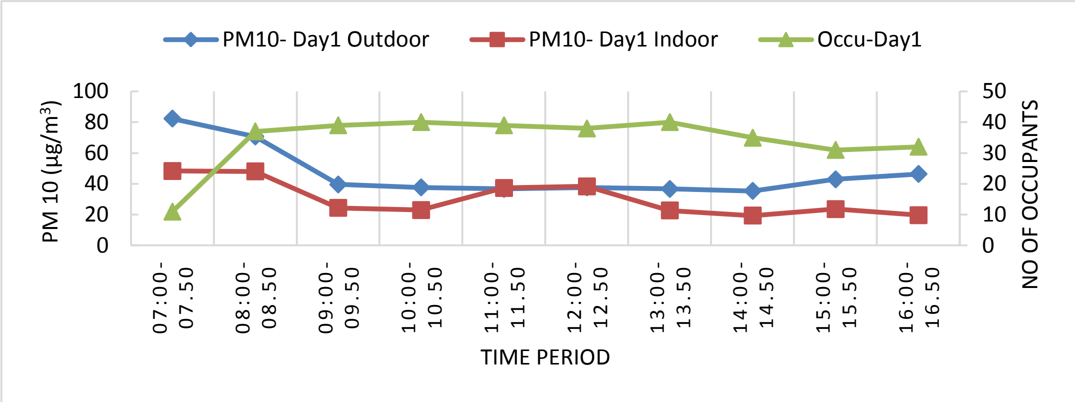


Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 4

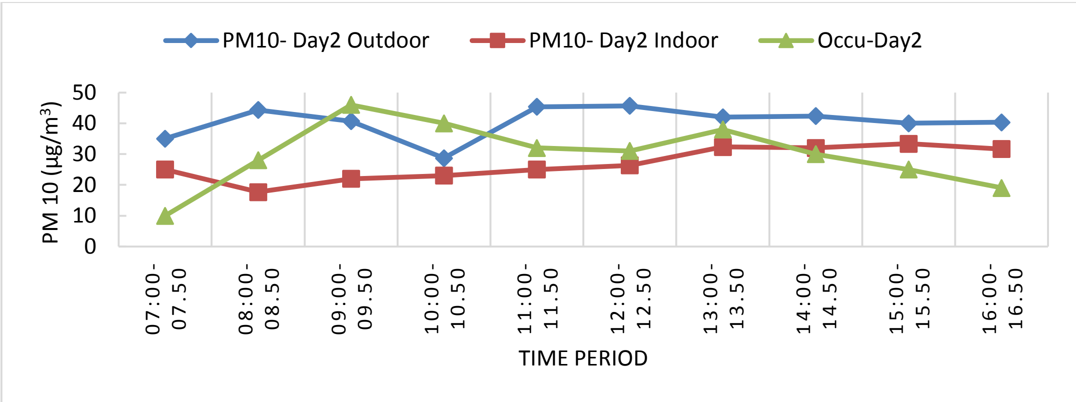


Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 5

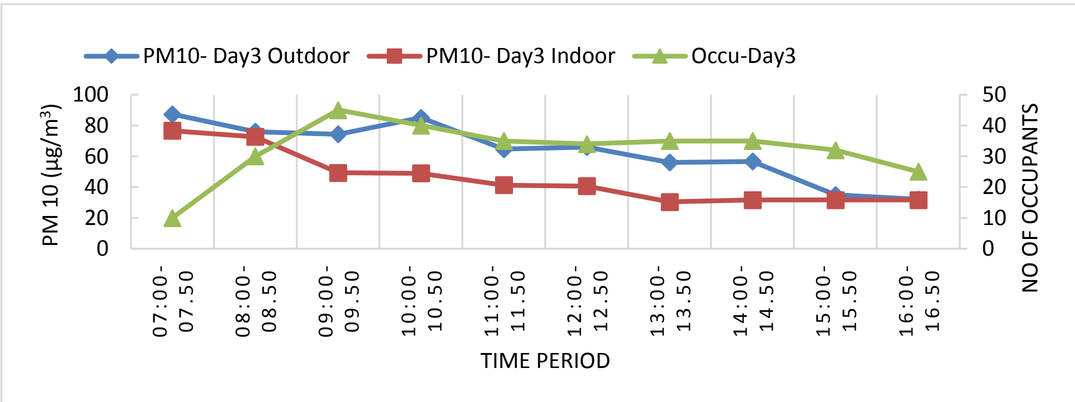
Appendix 9: Graphs of hourly average of PM_{10} with occupancy at AHU room of the Basement



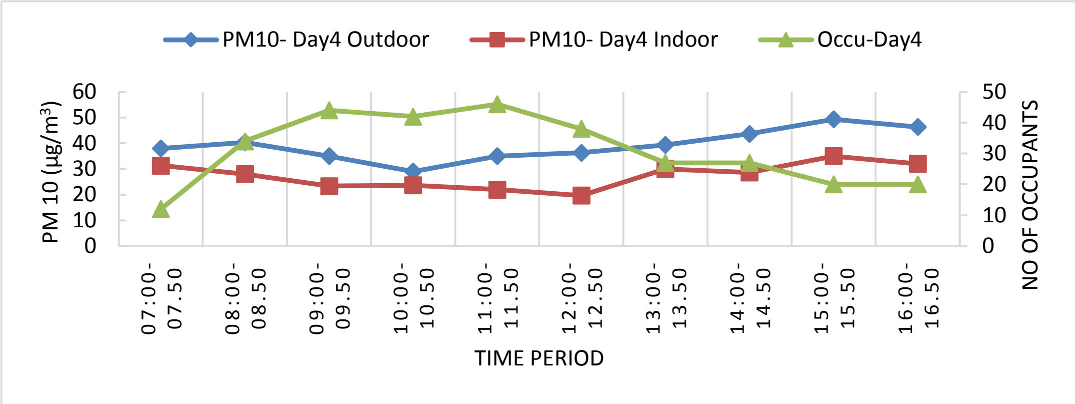
Hourly average of PM_{10} and occupancy at the Basement during day 1



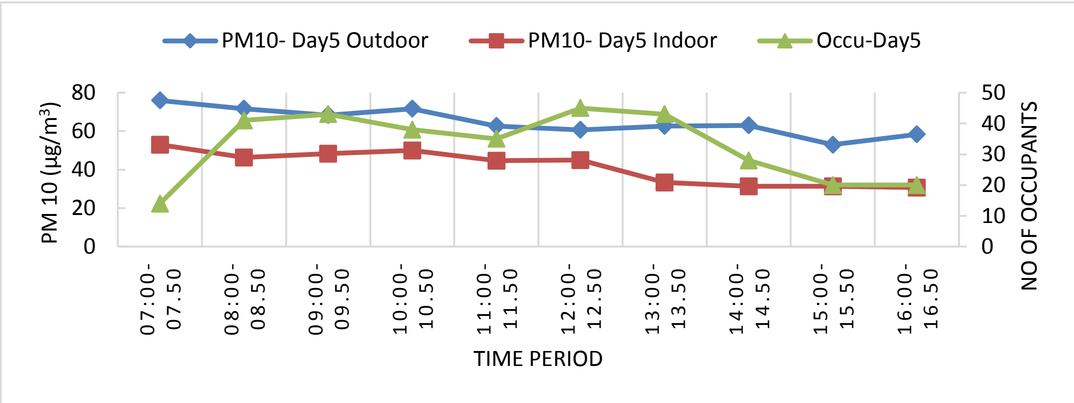
Hourly average of PM_{10} and occupancy at the Basement during day 2



Hourly average of PM_{10} and occupancy at the Basement during day 3



Hourly average of PM_{10} and occupancy at the Basement during day 4



Hourly average of PM_{10} and occupancy at the Basement during day 5

Appendix 10: Calculations to determine the additional energy cost due to the heat gained of the return air to the AHU room at the ceiling plenum.

a. Finding the rate of heat gained by the return air to the AHU room at the ceiling plenum.

$\dot{q} = \dot{m}C_p\Delta T$ (Equation 2)

Where;

$\dot{q}$ - Rate of heat transfer (W)

$\dot{m}$ - Mass flow rate (kg/s)

C_p - Specific heat (J/kg.K)

ΔT - Temperature difference (K)

Temperature of the return air to the AHU - 31.03 ^{0}C

Indoor air temperature - 26 ^{0}C

ΔT = 5.03 ^{0}C

Air mass flowrate; $\dot{m}$ = 3.94 kg/s

Specific heat of air; C_p = 1007 J/kg.K

From Equation 2;

$\dot{q} = 3.94 \times 1007 \times (31.03 - 26) = 19{,}956.93 \text{ W} = 19.96 \text{ kW}$

Heat gained by the return air to the AHU room at the ceiling plenum = 19.96 kW

b. Finding output power of the chiller

Temperature of the chilled water entering the chiller - 8 ^{0}C

Temperature of the chilled water leaving the chiller - 5 ^{0}C

ΔT = 3 ^{0}C

Chilled water flowrate; $\dot{m}$ = 50 kg/s

Specific heat of water; C_p = 4205 J/kg.K

From Equation 2;

$\dot{q} = 50 \times 4205 \times (8 - 5) = 630{,}750 \text{ W} = 630.75 \text{ kW}$

output power of the chiller = 630.75 kW

c. Finding power input to the chiller

$P = \sqrt{3}\, V\, I\, \cos\emptyset$

Where;

P - Power (W)

V - Voltage = 410 V

I - Current = 300 A

$cos\emptyset$ - Power Factor = 0.8

$$\mathrm{P} = \sqrt{3} \times 410 \times 300 \times 0.8 = 170{,}428.8\ \mathrm{W} = 170.43\ \mathrm{kW}$$

Power input to the chiller = $170.43\ \mathrm{kW}$

d. Finding coefficient of performance (COP) of the chiller.

$$COP = \frac{\text{output power of the chiller (kW)}}{\text{Power input to the chiller (kW)}} = \frac{630.75}{170.43} = 3.7$$

e. Finding additional energy cost due to the heat gained of the return air to the AHU room at the ceiling plenum.

$$\text{Additional energy} = \frac{\text{Heat gained by the return air (kW)}}{\text{COP}} = \frac{19.96}{3.7} = 5.395\ \mathrm{kW}$$

Electricity consumption for 10 hours = $5.395 \times 10 = 53.59\ \mathrm{kWh}$

Electricity tariff = Rs. 20.70 per kWh

Cost of electricity per day = $53.59 \times 20.70 = \mathrm{Rs.}\,1{,}116.68$

Cost of electricity per month = $1{,}116.68 \times 30 = \mathrm{Rs.}\,33{,}500.43$

The annual cost for electricity = $33500.43 \times 12 = \mathrm{Rs.}\,402{,}005.19$