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

Ediriweera Gamage Gayan Lankanath

(168413M)

Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Building Services Engineering

Department of Mechanical Engineering

University of Moratuwa

Sri Lanka

March 2022

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.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)".

…….

Signature of the candidate Date:

(Lankanath E.G.G)

The above candidate has carried out research for the Masters dissertation under my supervision.

……..

Signature of the supervisor Date:

(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.

ACKNOWLEDGEMENT

First and foremost, I want to express my heartfelt gratitude to Dr. Inoka Manthilake, who inspired and directed me during the process of conducting this research and writing the final dissertation.

I would like to thank Mr. H.D.S. Premasiri, Coordinator-Air Quality at the National Building Research Organization, for providing me with the equipment I need to test Indoor Air Quality.

I would also like to thank the Sri Lanka Air Force for assisting me with the Building Services Engineering course and relieving me of my duties so that I could pursue this education.

Finally, I want to express my gratitude and appreciation to my parents, family, and relatives for their support, encouragement, and patience.

TABLE OF CONTENTS

DECLARATION ii

ABSTRACT iii

ACKNOWLEDGEMENT iv

TABLE OF CONTENTS v

LIST OF FIGURES x

LIST OF TABLES xii

LIST OF ABBREVIATIONS xiii

LIST OF APPENDICES xiv

CHAPTER 01: INTRODUCTION 1

1.1 Background 1

1.1.1 Indoor air pollutants 1

1.1.2 Working environment 3

1.2 Problem formulation 3

1.3 Aim 4

1.4 Objectives 5

1.5 Methodology 5

1.6 Conceptual framework 6

CHAPTER 02: LITERATURE REVIEW 7

2.1 Indoor air pollutants 7

2.1.1 Carbon dioxide (CO_2) 7

2.1.2 Carbon monoxide (CO) 8

2.1.3 Particulate matter (PM) 9

2.1.4 Volatile organic compounds (VOCs) 11

a. Total volatile organic compound (TVOC) 13
2.2 Living environment of people 14
2.3 IAQ and human health 14
2.3.1 Building related illness (BRI) 15
2.3.2 Sick building syndrome (SBS) 15
2.3.3 Effect on performance 17
2.4 Factors affecting IAQ in office buildings 17
2.4.1 Thermal factors 18
a. Temperature 18
b. Humidity 18
c. Ventilation 18
2.4.2 Building related factors 20
a. Equipment 20
b. Activities 20
c. Location 21
d. Occupancy 21
2.5 Available guidelines for IAQ 21
2.5.1 ASHRAE IAQ guidelines 22
2.5.2 World health organization (WHO) IAQ guidelines 23
2.5.3 Hong kong IAQ objectives 23
2.5.4 Leadership in energy and environmental design (LEED) IAQ requirements 24
2.6 Research questions 27
CHAPTER 03: DATA COLLECTION 28
3.1 Design for data collection 28

3.1.1 Office space number 1 28
a. Air conditioning and ventilation of the office space no 01 29
3.1.2 Office space number 2 32
a. Air conditioning and ventilation of office space no 02 32
3.2 Data collection through in-situ measurements 33
3.2.1 In situ data collection approach 34
3.2.2 Arrangement of instrument for in situ measurement 35
3.2.3 Measurement at the office space number 1 36
3.2.4 Measurement at office space number 2 37
3.2.5 TVOC concentration with air fresheners and incense smoke 37
3.2.6 In situ measurement in the AHU room of the office space number 2 . 38
3.2.7 Summary of the data points collected during in situ measurements 39
CHAPTER 04: ANALYSIS AND RESULTS 40
4.1 Carbon Monoxide (CO) 40
4.2 Temperature (T) 40
4.3 Relative humidity (RH) 45
4.4 Carbon dioxide (CO_2) 48
4.5 Particulate matter ($PM_{2.5}$ and PM_{10}) 53
4.6 Total Volatile Organic Compound (TVOC) 58
4.6.1 TVOC with air fresheners 61
4.6.2 TVOC with incense smoke 61
CHAPTER 05: DISCUSSION 63
5.1 Carbon Monoxide (CO) 63
5.2 Temperature 63
5.3 Relative humidity (RH) 64

5.4 Carbon dioxide (CO_2) 65
5.5 Particulate matter ($PM_{2.5}$ and PM_{10}) 66
5.6 Total Volatile Organic Compounds (TVOC) 67
5.6.1 TVOC with dispersion of air freshener 68
5.6.2 TVOC with incense smoke 68
5.7 Outdoor air flow rate required for IT Lab 69
CHAPTER 06: CONCLUSION 70
6.1 Key findings 70
6.1.1 Location of the building 70
6.1.2 Occupancy related activities 70
6.1.3 Function of the space 71
6.1.4 Ventilation & air-conditioning system 72
6.2 Limitations 73
6.3 Recommendations 73
6.4 Future work 75
REFERENCES 76
APPENDICES 86
Appendix 1:Measured height from ground level to breathing zone of sedentary personnel of each office at the Basement 86
Appendix 2: Summary the data points collected for each of the parameters T, RH, $PM_{2.5}$, PM_{10}, and CO_2. 88
Appendix 3: Summary the data points collected for TVOC 89
Appendix 4 Summary the data points collected for CO 90
Appendix 5: Graphs of hourly average temperature variations with occupancy at AHU room of the Basement 91

Appendix 6: Graphs of hourly average of RH with occupancy at AHU room of the Basement 93

Appendix 7: Graphs of hourly average of CO_2 with occupancy at AHU room of the Basement 95

Appendix 8: Graphs of hourly average of CO_2 with occupancy at AHU room of the Basement 97

Appendix 9: Graphs of hourly average of PM_{10} with occupancy at AHU room of the Basement 99

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. 101

LIST OF FIGURES

Figure 1:Classification of air contaminants according to the state of matter..... 2

Figure 2: Conceptual framework of the study 6

Figure 3: Layout of the Basement and selected locations for measuring indoor air pollutants; measuring points S1 to S10..... 30

Figure 4: The arrangement of the IT Lab and its IAQ measuring point S11..... 33

Figure 5:Temperature variations in Colombo for February 2022, Source: [74]..... 38

Figure 6: Levels of temperature during the one-hour' period at the selected locations of the Basement on holiday..... 41

Figure 7: Levels of temperature during the one-hour' period at the selected locations of the Basement on working day..... 41

Figure 8: The temperature profile at location S10 for 8 hours' duration..... 42

Figure 9: Temperature profile of the IT Lab during 24 hours' period..... 43

Figure 10:The variations of outdoor and indoor temperatures 43

Figure 11: Hourly average of T and occupancy at the Basement during day 1..... 44

Figure 12: RH levels of the selected locations of the Basement during 1-hour' period on holiday..... 45

Figure 13: RH levels of the selected locations of the Basement during 1-hour' period on working day 46

Figure 14: RH profile of location S10 of the Basement for 8 hours' period on a working day 46

Figure 15: RH profile of the IT Lab during 24 hours' period..... 47

Figure 16:Hourly average of RH and occupancy at the Basement during day 1..... 48

Figure 17: CO_2 levels of the selected locations of the Basement for a 1 hour' period on holiday..... 49

Figure 18: CO_2 levels of the selected locations of the Basement for a 1 hour' period on working day 49

Figure 19: The average CO_2 levels for 1-hour period on holiday and working day at different locations of the Basement. 50

Figure 20: CO_2 profile for 8 hours' period at location S10 on a working day 51

Figure 21: 24 hours' CO_2 profile of the IT Lab 52

Figure 22:Hourly average of CO_2 and occupancy at the Basement during day 1 52

Figure 23: 1-hour' average PM2.5 levels at selected locations of the Basement on the holiday and the working day 54

Figure 24: 1-hour average PM_{10} levels at selected locations of the Basement on the holiday and the working day 54

Figure 25: $PM_{2.5}$ and PM_{10} profiles for 8 hours period at location S10..... 55

Figure 26: 24-hours concentration of $PM_{2.5}$ and PM_{10} at the IT Lab..... 56

Figure 27:Hourly average of $PM_{2.5}$ and occupancy at the Basement during day 1.... 56

Figure 28:Hourly average of PM_{10} and occupancy at the Basement during day 1 57

Figure 29: TVOC levels at the selected locations of the Basement on the holiday and working day 58

Figure 30: TVOC profile for 8-hours of period at location S10 of the Basement on the working day..... 59

Figure 31: 24 hour' TVOC profile at IT Lab on a working day 60

Figure 32: Hourly average of TVOC of the Basement during 5 days of period..... 60

Figure 33: Variations of TVOC concentration with dispersion of air fresheners inside the System Control Unit of the Basement..... 61

Figure 34:Variations of TVOC with incense smoke inside the Store..... 62

Figure 35:A mechanical ventilation system based on the concentration of CO_2 to improve the IAQ of confined office spaces like IT Lab 74

LIST OF TABLES

Table 1: WHO guidelines for indoor CO exposure 9

Table 2: The particle size fractions denoted by ISO/DIS 16890-1 standard 9

Table 3: WHO guidelines for particulate matter..... 11

Table 4: Classification of indoor organic pollutants..... 11

Table 5: Commonly available indoor volatile organic compounds 12

Table 6: Summary of WHO, ASHRAE, Hong Kong and LEED IAQ Guidelines.... 26

Table 7: Occupancy density and electronic equipment used in each office of the Basement..... 31

Table 8: Occupancy distribution and electronic equipment used in in IT Unit and IT Lab 33

Table 9: Measuring points of indoor air pollutants at the Basement 35

Table 10: Details of instruments used for IAQ measurements 36

Table 11:Total numbers of data points collected for all the IAQ parameters of the research 39

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

Appendix 1:Measured height from ground level to breathing zone of sedentary personnel of each office at the Basement..... 86

Appendix 2: Summary the data points collected for each of the parameters T, RH, $PM_{2.5}$, PM_{10}, and CO_2. 88

Appendix 3: Summary the data points collected for TVOC..... 89

Appendix 4 Summary the data points collected for CO 90

Appendix 5: Graphs of hourly average temperature variations with occupancy at AHU room of the Basement..... 91

Appendix 6: Graphs of hourly average of RH with occupancy at AHU room of the Basement..... 93

Appendix 7: Graphs of hourly average of CO_2 with occupancy at AHU room of the Basement..... 95

Appendix 8: Graphs of hourly average of CO_2 with occupancy at AHU room of the Basement..... 97

Appendix 9: Graphs of hourly average of PM_{10} with occupancy at AHU room of the Basement..... 99

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. 101