Evaluation of Indoor Environmental Quality in Green Low-Income Housing

by

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ABSTRACT

There is little empirical evidence in literature on the performance of green residential buildings, even more limited is the indoor environmental quality (IEQ) performance of green low-income residential buildings. This is particularly interesting because residents of low-income housing are exposed to higher levels of indoor pollutants. To address the lack of empirical evidence on the indoor environmental quality of green low-income housing, this study utilised a mixed-method approach to evaluate IEQ of 17 green low-income single attached family houses in Brandon, Manitoba, Canada. Snapshot physical measurements took place in 17 single family attached low-income housing clustered into four blocks over two seasons: the fall of 2016 and winter of 2017. The indoor physical environment was monitored with sensors in three sampling spaces per apartment; while a paper-based questionnaire was used to assess occupants' satisfaction with their indoor environment. Moreover, long-term evaluation of two selected apartments was carried out to elucidate the hourly variation of thermal comfort and indoor air quality. The long-term data showed that concentration levels peaked in the mornings and evenings during weekdays for the most pollutants. The comparison of the snapshot fall to winter data revealed that indoor air quality levels in the fall season were lower compared to the winter except particulate matter (PM). Same result was reported for the long-term evaluation. The Wilcoxon signed rank test showed that there were statistically significant differences in relative humidity (RH), temperature, carbon dioxide, carbon monoxide, particles smaller than 2.5 µm ($PM_{2.5}$), total volatile organic compound (TVOC) and background noise between the two seasons. Further, pertaining to the long-term evaluation, statistical significant differences were observed in concentration levels (i.e. CO, PM, and RH) between weekdays and weekend during the fall period. During the winter period, statistical significant difference existed in temperature levels. Further, occupants with higher snapshot satisfaction were generally exposed to relatively lower levels of indoor pollutants. A statistically significant difference was found in PM_{10} level only between the snapshot satisfied and snapshot dissatisfied groups of occupants. Moreover, for individual environmental parameters, significant differences were reported in RH, $PM_{2.5}$ and PM_{10} between reported acceptable IEQ and unacceptable IEQ group. Apparent sound transmission classes were below the standard reference value of 50, suggesting potential problems in noise attenuation within different spaces in a single apartment and between apartments. The findings of this study could help governments implement green principles for low-income housing and also renovate existing houses using the same principles.

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DEDICATION

For my Beloved Late Uncle Kwame Oduro with love and gratitude!

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LIST OF ACRONYMS AND ABBREVIATIONS

AER	Air Exchange Rate
ANOVA	Analysis of Variance
ASTC	Apparent Sound Transmission Class
BREEAM	Building Research Establishment Environmental Assessment Method
CO	Carbon Monoxide
CO_2	Carbon dioxide
CMHC	Canada Mortgage and Housing Corporation
DF	Daylight Factor
ETS	Environmental Tobacco Smoke
HVAC	Heating, Ventilation and Air-Conditioning
LEED	Leadership in Energy and Environment Design
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
NBCC	National Building Code of Canada
PH	Passive Housing
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter less than 2.5 µm aerodynamic diameter
PM_{10}	Particulate Matter less than 10 µm aerodynamic diameter
REL	Relative Exposure Level
RH	Relative Humidity
TVOC	Total Volatile Organic Compound

1 CHAPTER ONE

INTRODUCTION

1.1 Introduction

This chapter introduces the research by providing background information about this research, and the problem statement spurring this research. Also, the goal, objectives and scope are presented as well as the significance of the study.

1.2 Background Information

A major sign of failure of a nation's social welfare policy can be seen in dilapidated social housing that is overpopulated with poor families and individuals (Theodos, Popkin, Parilla, & Getsinger, 2012). This is because the provision of adequate social housing is perceived as an integral part of a country's social welfare policy that can counteract poverty and ensure a good quality of life (Suttor, 2014; Althawabteh, 2016). Social housing seeks fundamentally to address the provision of housing to low-income households and individuals (e.g. Ahn, Wang, Lee, & Jeon, 2014; Burgos, Ruiz, & Koifman, 2013; Theodos et al., 2012). In North America, in Canada and the United States in particular, the terms "social housing" or "public-housing" are predominantly used (see Theodos et al., 2012). However, these terms tend to refer to government-subsidized housing exclusively (Diaz Lozano Patino and Siegel (2018). This research uses the term "low-income housing" instead in order to include all low-income populations that do not necessarily live in public subsidized housing. Generally, on average, around 15% of people live in low-income households in developed countries (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007). According to Statistics Canada (2016), nearly 14% of Canadians lived in low-income households in 2012. This last century has seen a tremendous growth in low-income housing as a result of unprecedented levels of urbanization (Diaz Lozano Patino & Siegel, 2018).

Low-income housing tends to be associated with substandard housing and poor dwelling conditions such as extremely high or low temperatures, insufficient ventilation rates and poor insulation (Diaz Lozano Patino & Siegel, 2018; Santamouris et al., 2007). It also usually consists of smaller dwellings that suffer from overcrowding and from elevated concentrations of indoor pollutants such as carbon dioxide (CO_2). Other sources of indoor pollutants such as household chemicals (e.g. indoor sprays, detergents, and disinfectants) are also prevalent in low-income housing (Brown et al., 2015; Kolokotsa & Santamouris, 2015).

In general, low-income households tend to spend on average 30% or more of their total household income on shelter (Ahn et al., 2014). They also tend to spend at least 20% of their annual income on heating their homes and making meals (Fuhry & Wells, 2013). People in low-income housing are also more likely to be vulnerable due to factors such as age and socioeconomic status (Diaz Lozano Patino & Siegel, 2018). Approximately, 14 to 49% of them tend to be seniors. They are also more likely to smoke than other populations (Shrubsole et al. (2016).

A close relationship has been reported in the literature between high levels of indoor pollutants and poor health in low-income housing (e.g. Brown et al., 2015; Colton et al., 2014; Paravantis & Santamouris, 2016). This is because a significant amount of people's time (i.e. 15 hours per day) is spent at home (Wu, Jacobs, Mitchell, Miller, & Karol, 2007), leading them to interact considerably with their homes' indoor environment, increasing thereby their exposure to various indoor environmental quality (IEQ) parameters. Theodos et al. (2012) argued that occupants of low-income housing tend to be in poorer health on average than the general population. This is because they are more exposed to issues such as molds and moisture, environmental tobacco smoke (ETS), indoor air contaminants and inadequate ventilation (Doll, Davison, & Painting, 2016; Kolokotsa & Santamouris, 2015; Santamouris et al., 2007). Low-income household occupants also experience other IEQ problems such as thermal discomfort, visual discomfort and excessive noise levels (Krüger & Trombetta Zannin, 2007; Santamouris et al., 2007; Diaz Lozano Patino and Siegel (2018)). Moreover, these occupants tend to lack the proper knowledge on how to operate and control mechanical ventilation systems (McGill, Oyedele, & McAllister, 2015) and thus tend to manage their thermal comfort and indoor air quality through very basic means such as the opening and closing of windows (Colton et al., 2014).

Green housing has evolved out of a need to address these issues. Green homes have smaller carbon footprints that make them more environmentally friendly than conventional homes. They are designed to improve a home's energy efficiency, water efficiency, IEQ and to reduce waste (i.e. construction waste) and pollution (i.e. indoor pollution) (Colton et al., 2014; Coombs et al., 2016; Y. Xiong, U. Krogmann, G. Mainelis, L. A. Rodenburg, & C. J. Andrews, 2015). This is achieved through the use of strategies such as airtight, highly insulated building envelopes, energy and water efficient fixtures; recycled, reused or low-emission building materials and various construction waste management techniques. They offer higher quality indoor environments that can improve aspects such as respiratory problems (Jill Breysse et al., 2011), mental health (J. Breysse, Dixon, Jacobs, Lopez, & Weber, 2015), sick building syndrome (Colton et al., 2014) and productivity (Geng, Ji, Lin, & Zhu, 2017) and lower energy costs (Jaggs & Palmer, 2000). These potential benefits of green building reinforce the need to incorporate green features into low-income housing to mitigate the consequences of poor IEQ (Garland et al., 2013). This is because green low-income housing aims to combine the goals of low-income housing (i.e. low economic cost) and green building (i.e. improved IEQ and energy efficiency) (Ahn et al., 2014).

Social intervention programs that promote the use of green building principles in low-income housing have been implemented in a number of countries. In the US for example, a nationwide weatherization program was implemented in around 2009 to improve the IEQ (e.g. CO_2, carbon monoxide (CO), nitrite (NO_2), temperature, relative humidity (RH), $PM_{2.5}$, PM_{10}, formaldehyde) and energy performance of low-income dwellings (Doll et al., 2016). The program aimed to promote the use of proper building insulation to ensure an efficient building envelope that would optimize energy efficiency. Similar intervention programs are also found in Europe (e.g. United Kingdom and Austria). In Austria, for example, an intervention program was implemented in 2008 and 2009 to build social housing to passive housing (PH) concept (e.g. Rojas, Wagner, Suschek-Berger, Pfluger, & Feist, 2015a) in order to reduce their energy consumption and also improve their indoor environment. Also, in the United Kingdom (UK), social housing is being designed and built to comply with Code for Sustainable Homes Level 4 (Code level 4) (e.g. McGill et al., 2015). This code aims to ensure the design and construction of low-energy homes to cut down on energy bills and also carbon emissions. These programs have been shown to lead to positive results. Doll, Davison, and Painting (2016) for instance reported 90% compliance with established indoor air quality standards (i.e. CO_2, CO, Radon and NO_2) after weatherizing low-income single-family houses. Breysse et al. (2011) noted significant health improvements (i.e. asthma and non-asthma respiratory problems) among adult tenants following the renovation of low-income housing using green principles and other healthy housing features (e.g. low VOC-adhesives and paints, kitchen and bath exhaust fans). Rojas, Wagner, Suschek-Berger, Pfluger, and Feist (2015) reported increased occupant comfort in low-income PH in Austria. These preliminary results reinforce the need to study IEQ in these low-income homes and to study how greening them can affect their IEQ.

1.3 Problem Statement

A review of the literature reveals there's less research and thus less empirical evidence on the IEQ performance of residential buildings (e.g. houses) in comparison to other types of buildings such as commercial (e.g. offices) and institutional buildings (e.g. schools). There is in particular little empirical evidence on the IEQ performance of low-income housing despite this type of housing accommodating 15% of the population on average. There is a significant lack of IEQ research in green low-income housing in general; and Canada, in particular, published studies are nonexistent. Moreover, most of the literature appears to have focused on evaluating only one or two aspects of IEQ in low-income housing instead of the four main IEQ aspects of thermal comfort, indoor air quality, lighting and acoustics reinforcing the need to address these limitations in future research.

1.4 Research Goal, Objectives and Scope

The main goal of this research was to evaluate the IEQ performance of green low-income residential buildings. Specific objectives involved:

- Developing a methodology to evaluate the IEQ performance of green residential buildings
- Evaluating the physical objective IEQ performance of these buildings
- Determining the relationship between the physical objective IEQ performance of these buildings and their subjective performance
- Investigating the seasonal variation in the physical objective IEQ performance of these buildings between the fall and winter seasons
- Investigating the hourly variation in the physical objective IEQ performance of these buildings between the fall and winter seasons and between weekends and weekdays

The scope of the research was geographically and contextually limited because of time and resources constraints. Geographically, the study was limited to evaluating 17 green low-income apartments in Brandon, Manitoba (MB), Canada. These apartments were built to the

Leadership in Energy and Environmental Design (LEED) for Home green rating system administered by the Canada Green Building Council (CaGBC). Although all apartments were designed to LEED for Home Silver standards, only two of the investigated apartments actually underwent certification and consequently achieved a LEED for Home Gold Certification. The remaining 15 apartments did not undergo any formal certification process. Contextually, the study was limited to the measurement of a number of physical parameters (e.g. CO_2, CO, temperature, RH, $PM_{2.5}$, PM_{10}, TVOC, background noise, sound transmission loss and illuminance) in these homes and to the surveying of these homes' occupants. These physical measurements included short-term or snapshot measurements and long-term measurements of these parameters. The short-term measurements took place in the 17 apartments, while the long-term measurements were carried out in only two apartments because of the limited availability of long-term measurement equipment. The research also entailed observing the physical condition of these homes and interviewing the architects that were involved in the design of these homes and the facility managers that were involved in their operation and maintenance. The physical measurements were cross-referenced with occupants' opinions, with the results supported with the observation and interview data to interpret them further.

1.5 Significance of Study

The significance and originality of this research stem from it being one of the few in Canada to investigate the IEQ of low-income housing. This makes it of interest to policy makers, designers, contractors, facility managers, tenants and researchers involved in the design, construction, operation, maintenance, occupancy and evaluation of this type of housing. The research is also first to investigate the IEQ of green low-income housing in particular in Canada. This is to assess how green building principles affect indoor environmental conditions in these homes and benchmark these green homes' performance in comparison to that of conventional low-income housing. The research is also one of the few to evaluate all four main factors of IEQ in low-income housing: thermal comfort, indoor air quality, acoustics and lighting comfort. This is to enable a comprehensive thorough assessment of IEQ, of the relationships between the different IEQ factors and of how those factors affect occupant satisfaction.

The research also delivers a methodology to evaluate physical IEQ and occupant IEQ satisfaction in low-income housing that is based in part on adaptations of existing building post-occupancy evaluation methods. The methodology relies on the use of on-site physical measurements of IEQ in conjunction with occupant IEQ satisfaction surveys, on-site observations of the physical conditions of those homes and structured interviews with practitioners involved in the design, construction, operation and maintenance of those homes. The research also provides a dataset about the IEQ performance of low-income housing in Manitoba. This is a dataset that can grow considerably over time as more researchers investigate IEQ in low-income housing of various types and in different locations in Manitoba and across Canada. The methodology and dataset can be used to benchmark the performance of new and existing low-income housing in Manitoba. The resulting body of knowledge can be used specifically to design new low-income houses that offer improved IEQ to their occupants and improved occupant satisfaction. It can also be used to enhance the actual operation and maintenance of existing low-income houses in order to enhance their actual and future performance. This body of knowledge can be translated to evidence-based guidance that would inform the design and construction of new low-income houses and the operation and maintenance of existing ones.

Should the research show improved IEQ performance in green, low-income housing, it would be providing empirical evidence to support the decision of governments to regulate and mandate the delivery of new green low-income housing and the greening of existing low-income housing. If no difference is found in the IEQ performance of green certified versus green shadowed low-income homes, the results would also be making the case for green shadowing low-income housing instead of going through the more expensive and time-consuming route of certifying them.

2 CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter introduces the theoretical framework for the research. The chapter further discusses recent trends which have emerged as issues of concern for both academic and practitioners. These include low-income housing, various intervention programs to improve low-income housing quality, and adoption of green principles in low-income housing. A discussion of each of these recent trends follows.

2.2 Low-income housing

Low-income housing and households are defined in a number of ways. In North America for example, a household that spends 30% or more of their total household income on shelter can be classified as low-income (Ahn et al., 2014; Statistics Canada, 2016). The European Union and the UK government define low-income households are those that have incomes less than 60% of the national median (DCLG, 2013 cited in Shrubsole et al., 2016). In India, low-income housing is defined as “any housing that meets some form of affordability criterion, which could be income level of the family, size of the dwelling unit or affordability in terms of equated monthly installments size or ratio of house price to annual income” (High Level Task Force on Affordable Housing for All, December 2008, p. 7).

According to Statistics Canada (2016), about 13% of Canadian households representing 1.7 million households lived in low-income housing in 2016. Low-income housing is of a particular interest within the housing sector because of its social implications and because of the need to eradicate slums and provide safe and decent housing for low-income groups (Burgos et al., 2013; Mohamed, Mohammad Yusoff, Iman Pratama, & Raman, 2014; Peretti, Pasut, Emmi, & De Carli, 2015). It is also of interest because of rising poverty levels globally as evidenced by the increase in the number of low-income people in developed and developing countries because of the global economic crisis (Santamouris et al., 2007; Gopalan and Venkataraman, 2015). This type of housing aims to address the acute housing problems of these people (Suttor, 2014).

A major goal of low-income housing is affordability (Gopalan and Venkataraman, 2015). Because of this, when building low-income housing, the intent is usually only to meet minimum standard requirements (Mohamed et al., 2014). This leads to these houses often being built with inappropriate materials, which makes them susceptible to outdoor pollutant infiltration (Burgos et al., 2013). These houses are also often characterized by poor indoor environmental conditions such as extremely high and low temperatures (Santamouris et al., 2007), and insufficient ventilation rates (Doll et al., 2016). Moreover, low-income houses are often small in size, making them less ideal for larger families and leading to overcrowding which in turn exacerbates poor IEQ conditions (Mohamed et al., 2014). Coupled with these environmental problems are issues relating to the high operating (e.g., utility) cost of these houses relative to household income. In the United States for instance, the number of people seeking federal assistance to pay utility bills (i.e., heating and cooling) almost doubled from 2007 to 2010 (Fuhry & Wells, 2013). The ratio of residential energy expenses to household income, also known as the energy burden for low-income groups in the US also increased about 2% i.e. from 12.6% in 2001 to 14.6% in 2005 ((Nahmens, Joukar, & Cantrell, 2015). These levels were also quite higher than the average energy burden of 3.1% in 2001 and 3.2% in 2005. Moreover, about 20% of the income of low-income households in the US is spent on home energy costs (Fuhry & Wells, 2013).

2.3 Government Low-income Housing Programs

Low-income housing has not always been given priority by local governments as evidenced for example by the progressive cut-down on gross domestic product allocation (i.e. less than 1%) to low-income housing in some European economies (Copiello, 2015). As argued by Suttor (2014), low-income housing can be viewed by the public as a failed solution because of the mental image of poverty usually associated with it. Nevertheless, there is growing recognition of the importance of low-income housing because of their social implications. In Italy for example, national plans approved by Law 133/2008, s. 11 were drafted with the prime goal of providing housing for low-income households (Copiello, 2015). At the same time, a ministerial decree providing a legal definition of social housing came into effect in 2008 (Copiello, 2015). Similarly, in the United States, the federal government provides assistance to low-income households through various forms including low-income housing programs, subsidies for privately owned multifamily rental properties, and rental assistance to tenants (Wallace, 1995). Recently, the UK government unveiled a £2billion plan to boost social housing (Weaver, 2017). Although, the details are yet to be revealed, the pledge alone goes to demonstrate the importance that many governments are according to low-income housing.

This situation is similar in Canada. Affordable housing provision in Canada dates back to 1946 or the postwar era (Suttor, 2014). As in most developed countries, low-income housing came into existence in Canada following the failure of private housing developers to provide affordable housing to low and even middle-income households during the period of rapid urbanization in the mid-19th century (Althawabteh, 2016; Suttor, 2014). In its heydays (i.e., mid-1960s to mid-1990s), the Canadian social housing model housed a little more than one-third of low-income renters and also accounted for about 10% of total homes built. The development of low-income housing intensified during the post-second world war era in an attempt to house war veterans and low-income households. Soon, what became an internationally recognized housing model collapsed quickly and permanently in the mid-1990s (Suttor, 2014; Althawabteh, 2016). Althawabteh (2016) seems to offer an explanation on the possible reasons for this failure. Although the causes of this collapse are not entirely clear in the literature, Althawabteh (2016) attributed it to the perceived role of the state in housing provision remaining the same before and after the war and not changing to accommodate the changing political, economic and social landscape in the country. Nevertheless, this has started to change with current interventions focusing on providing emergency shelters, transitional housing, supportive housing, subsidized housing, market rental housing and market homeownership housing to struggling Canadians (Canada Mortgage and Housing Corporation, 2017). Today, the federal government invests $2 billion annually to improve access to sound and suitable low-income housing. Moreover, the government is committed through its 10-year, $40 billion National Housing Strategy to provide sustainable houses that are accessible to Canadians, particularly low-income ones. This growing investment in low-income housing reinforces the need to measure the impact of these various housing intervention programs, not least the quality of these houses' conditions on their occupants.

2.4 Greening low-income housing

Because of the potential for green buildings to reduce operating costs and improve IEQ, green building principles are starting to find their way in low-income housing (Ahn et al., 2014; Copiello, 2015; Fuhry & Wells, 2013). Green building emphasizes creating structures using environmentally responsible and resource-efficient building practices throughout these structures' lifecycles: from their design, all the way through their construction, occupancy, operation, maintenance and eventual disposal (Ahn et al., 2014; J. Breysse et al., 2015). While the origins of the concept are not entirely clear, the green building movement did not gain momentum until the early 1990s (Kats, 2003). The movement aimed to minimize the impact of the built environment on the natural environment and human health through the efficient use of natural resources and the reduction of waste and pollution (Ahn et al., 2014; Zalejska-Jonsson, 2014). This is because buildings and their construction are resource-intensive. They use about 50% of the world's energy consumption and contribute about 17% to greenhouse gas emissions (Altın, 2016; Nahmens et al., 2015). There is a need therefore to protect and preserve the environment through cutting down on these emissions and on the environmental harm associated with conventional building practices.

Green building emphasizes principles such as ensuring buildings' energy and water efficiency, using local materials and manpower, promoting indoor comfort and human health, and improving waste management techniques (Altın, 2016). These principles involve implementing measures such as increasing the air tightness and insulation of the building envelope as well as using high-efficiency windows, solar photovoltaics, green roofs and energy-efficient lighting and fixtures to improve buildings' energy efficiency. Other measures implemented to increase their water efficiency include using water-efficient fixtures and promoting the use of recycled and reused water using a number of water treatment technologies such as stormwater management. They also include relying on local renewable, reusable and recyclable materials with low or no emissions, improving passive heating, ventilation and using and air-conditioning systems (HVAC) and using more efficiency mechanical HVAC systems that improve indoor air quality and reduce airborne contaminants. Green buildings also emphasize reducing, recycling and reusing waste and relying on prefabrication whenever possible. These measures can have significant positive effects to them. For example, green roofs improve air quality and reduce urban temperature as a result of reducing the heat island effect (Y. Tan, Liu, Zhang, Shuai, & Shen, 2018). Photovoltaics also generate solar energy that can replace fossil fuel energy and reduce related energy dependence. Green materials such as low-VOC content paints are associated with less carcinogen and thus improved indoor air quality.

Several third-party rating systems exist for certifying green buildings. These include systems such as LEED, Green Globes, Green Star and the Building Research Establishment Environmental Assessment Method **(**BREEAM). These systems attempt to streamline the green building process to help achieve sustainability performance goals (Altın, 2016; Zalejska-Jonsson, 2014) . They do so by defining a number of broad categories and credits within each category that buildings would need to meet to be formally accredited as green. These categories typically align with green building principles and include ones such as: "energy efficiency", "water efficiency", "indoor environmental quality", and "location and site". Each category and credit are worth a number of points such that the higher the number of credits met, the higher the number of points achieved and the greener a building is. IEQ is usually one of the most important categories defined in these systems: one that can cover up to 20% of the total number of points that can be achieved by a green building, such as in the case of a LEED Platinum building for example. Table 2.1 shows the credits allocated to that category in the most popular green building rating systems used today, along with the maximum number of points allotted to each credit.

Despite the wide acceptance and adoption of green building practices in general, the implementation of these practices in low-income housing in particular has been slow for reasons not limited to cost alone(Fuhry & Wells, 2013). Many low-income housing developers might not have the organizational capacity to deal with the documentation and iterative planning required when building green (California Housing Partnership Corporation, 2017). Moreover, a decade ago, the application of green building principles to low-income housing was viewed with considerable skepticism because of the lack of documented success stories of building green low-income houses (Fuhry & Wells, 2013). This is because the evidence on the benefits, cost and value of these houses had been until then anecdotal rather than empirical.

Table 2.1: IEQ requirements in selected Certification Schemes

Program	IEQ categories	Credit Criteria	Points
BREEAM (70)	Indoor pollutants	Building product types, formaldehyde, TVOCs	10
	Temperature	Temperature analysis, foundation route, comprehensive route	20
	Ventilation	Ventilation air intakes, ventilation rates, maintenance and controls	12
	Daylight	Average daylight factor, View of sky	16
	Sound insulation	Between dwellings, between rooms	8
	Internal and external noise	Indoor and external noise levels	4
Green Globes (160)	Ventilation	Increased mechanical or natural ventilation	37
	Source control and measurement of indoor pollutants	Access to HVAC equipment, carbon monoxide monitoring, pest and contamination control	46
	Lighting design and systems	High quality lighting, daylight	30
	Thermal comfort	Thermal comfort	18
	Acoustic	Acoustical noise levels	29
Green Star (17)	Indoor air quality	Ventilation system attributes, provision of outdoor air, exhaust or elimination of pollutants	4
	Acoustic Comfort	Internal noise levels, reverberation, acoustic separation	3
	Lighting Comfort	Minimum lighting comfort, general illuminance and glare reduction, surface illuminance, localized lighting control	3
	Visual Comfort	Glare reduction, daylight, views	3
	Indoor Pollutants	Paints, adhesives, etc., engineered wood products	2
	Thermal Comfort	Thermal comfort, advanced thermal comfort	2
LEED (16)	Enhanced Ventilation	Enhanced local exhaust, enhanced whole-house ventilation	3
	Contaminant Control	Walk-off mats, shoe removal and storage, preoccupancy flush, air testing	2
	Balancing of Heating and Cooling Distribution Systems	Multiple zones, supply air-flow testing, pressure balancing, room-by-room controls	3
	Enhanced Compartmentalization	Enhanced compartmentalization	1
	Enhanced Combustion Venting	No fireplace or woodstove, enhanced combustion venting measures	2
	Enhanced Garage Pollutant Protection	Exhaust fan in garage, No garage, or detached garage, or carport	2
	Low-Emitting Products		3

This has started to change in recent times with the appearance of early empirical evidence on the potential benefits of these houses and that extend beyond energy efficiency (e.g. J. Breysse et al., 2015; Jill Breysse et al., 2011; Colton et al., 2014; Coombs et al., 2016). This is because green low-income housing is expected to combine the goals of affordable housing and green building in order to provide durable, cost-effective and energy-efficient housing with a healthy indoor environment (Ahn et al., 2014). These houses are designed to reduce energy consumption and costs through the use of energy-efficient lighting systems and fixtures: a necessity given that low-income households spend a considerable portion of their income on utilities and transportation (Fuhry & Wells, 2013; World Wide Fund for Nature, 2017). They are also designed to reduce transportation costs owing to the implementation of compact development strategies that aim to ensure these houses are accessible by public transportation and that their occupants do not fully rely on private car use (Arman, Zuo, Wilson, Zillante, & Pullen, 2009). The houses are also designed to use features such as low-VOC adhesives, paints and finishes, integrated pest management, high performance windows, efficient heating and cooling systems and heat recovery ventilators (HRV). Whether these potential benefits fully materialize remains to be seen in low-income housing. A review of the literature reveals there are very limited studies on the topic (e.g. J. Breysse et al., 2015; Jill Breysse et al., 2011). These studies tend to only investigate indoor air quality (IAQ) in those houses, reinforcing the need to evaluate the three other factors of IEQ in addition to IAQ. There is also a need to explore that performance in Canadian buildings in particular.

Financial incentives such as the Low Income Housing Tax Credit program in the U.S. have served as a driver for that change (Fuhry & Wells, 2013). The closest incentive in Canada is the seed funding program for low-income housing (Canada Mortgage and Housing Corporation, 2017). Created by the Canada Mortgage and Housing Corporation (CMHC), the program provides financial assistance for new affordable housing, in particular green low-income housing. Through the program, a housing project can obtain a maximum grant of $150,000 and about $350,000 in interest-free loans. In addition, the Affordable Housing Innovation Fund by the National Housing Strategy is committing $200,000,000 to innovative low-income housing. The fund which was launched in 2018 is expected to create 4,000 innovative affordable units over a five-year period.

2.5 Indoor Environmental Quality (IEQ)

The significance of the indoor environment stems from the fact that, on average, 90% of people's time is spent indoors (C. C. L. Tan et al., 2012; Wei, Ramalho, & Mandin, 2015). For a long time, the indoor environment, particularly that of residential buildings was considered to be made of only two aspects: thermal comfort and IAQ (Mitchell et al., 2007; Zhao, Chen, Guo, Peng, & Zhao, 2004). This was not surprising because the fundamental idea of shelter was to create an indoor environment that was more comfortable than the outdoor environment (Zhao et al., 2004). And comfort is essentially expressed in terms of the thermal climate, and subsequently grew to encapsulate IAQ owing to growing concerns that the indoor environment may be more polluted than the outdoor one (Mozaffarian, 2008). However, most recent studies (e.g., Du et al., 2015; Hui, Li, & Zheng, 2006; Lai, Mui, Wong, & Law, 2009; Q. Li, You, Chen, & Yang, 2013) perceive IEQ to embody four key factors: thermal comfort, IAQ, sound quality and lighting quality. This had led to defining IEQ in terms of those four factors because of their interrelatedness (Lai et al., 2009). A discussion of each of these four factors follows.

2.5.1 Thermal comfort

Thermal comfort research has existed since the 1920s as a result of introducing mechanical HVAC systems to control the thermal environment (Kim, 2012). However, it was not until the first energy crisis in the mid-70's that thermal comfort received largescale attention leading to extensive research on the topic (e.g., P. O. Fanger, 1972; P. O. Fanger, 1973; Gagge, Stolwijk,

& Nishi, 1971; Humphreys, 1974, 1976, 1978). This research aimed to investigate how the tightening of building envelopes that occurred as a response to that crisis affected occupant comfort, thus informing modern thermal comfort standards (Kim, 2012). Thermal comfort may be defined as the state of thermal equilibrium (Frontczak & Wargocki, 2011) that stimulates the condition of mind (American Society for Heating Refrigerating and Air Conditioning Engineers, 2013) to be satisfied with a number of environmental and physical parameters. Despite its wide application, this definition has practical problems. It over-relies on individual cognitive processes (Lin & Deng, 2008) and does not take into account the perceptions of a group of people in a room (Frontczak & Wargocki, 2011). The latter part of the problem seems to be addressed in ISO 7730 (1993) through indices that estimate the mean thermal sensation and satisfaction of a group of people with a building's thermal conditions.

Comfort is only possible when body temperature is within acceptable limits, when skin moisture is low, and when the physiological effort of thermal regulation is reduced (Lin & Deng, 2008). This implies the absence of local discomfort such as draught and extreme radiant temperature asymmetry amongst others (Frontczak & Wargocki, 2011). If the thermal environment is not comfortable, occupants sometimes also adapt by regulating the indoor environment. This approach is broadly termed the adaptive approach, and was first propounded by Humphreys (1976). It involves behavioural changes such as the altering of clothing, the relaxation of expectations and the opening of windows and is mostly used to improve occupant comfort (Frontczak & Wargocki, 2011; Lin & Deng, 2008). Thermal comfort is dependent on a number of factors such as: 1) air temperature (i.e., how cold or hot the air around our body is), 2) radiant temperature (i.e., the temperature of the surfaces around us), 3) relative humidity (i.e., the amount of water vapour in an air-water mixture), 4) air velocity (i.e., the rate at which air moves around and touches our skin). 5) metabolic rate (i.e., the amount of energy expended) and 6) clothing insulation (i.e., materials used to retain or remove body heat). The first four factors are referred to as environmental factors and the last two as personal factors (Ravindu, Rameezdeen, Zuo, Zhou, & Chandratilake, 2015).

2.5.2 Indoor Air Quality

Indoor air quality (IAQ) is defined as the “air, determined by cognizant authorities, not to contain known contaminants at harmful concentrations and which majority of the inhabitants (more than 80%) express satisfaction” (Hui et al., 2006). IAQ is affected by all components of the microenvironment such as odours and toxic materials and also by thermal comfort parameters such as temperature and relative humidity (Jokl, 2000). For a long time, air quality studies focused on ambient air monitoring in work environments due to emissions from automobiles and industrial processes. This was reflected in the bulky equipment that existed then to measure air quality and which could not be used indoors because of their size and the difficult of moving them within a space (Kim, 2012). It was also seen in the air quality standards that existed then and that focused exclusively on outdoor threshold levels (Kim, 2012). However, the recognition that indoor levels of pollutants can be several times higher than outdoor levels (Escobedo, Champion, Li, & Montoya, 2014) caused a shift in air quality research, with researchers changing their focus to IAQ instead. This change may have begun with the 1970 energy crisis when building envelopes were made tighter in order to reduce energy costs associated with building operation (Mozaffarian, 2008). These tighter buildings in addition to the simultaneous increase in the use of synthetic materials in interior finishes and of chemicals in cleaning supplies led to an increase in indoor airborne contaminants (e.g., VOCs) and other indoor air quality problems. These by extension led to indoor building occupants experiencing more health-related syptoms such as as sick building syndrome because of that deteriorating IAQ.

Only a few studies (e.g., Jo & Sohn, 2009; Jokl, 2000) investigated factors that may affect IAQ.

These studies expressed IAQ as a function of these influencing factors: 1) outdoor air quality, 2) emissions from indoor sources, 3) thermal factors (e.g., temperature and humidity), 4) building characteristics, and 5) occupant activity. The results of these studies on the relative importance of each of these factors have been hitherto inconsistent. Jo and Sohn (2009) found occupant activity including the duration of occupancy to be the most influencing factor. Other studies (e.g. Jiang, Li, Zhang, & Wang, 2013; Langer et al., 2016) argued that higher indoor concentration levels were mainly determined by emission sources which were influenced in some instances by occupant activity.

2.5.3 Acoustic Quality

There's plenty of evidence in the literature on the adverse effects of chronic noise exposure on the health of building occupants: from sleep disturbances, to psychological annoyance and cardiovascular diseases (S. H. Park, Lee, & Lee, 2017; C. Wang, Si, Abdul-Rahman, & Wood, 2015). Acoustics is the study of pressure fluctuation or disturbance sensed by the human ear (Matoski & Ribeiro, 2016). Acoustic comfort is achieved when occupants are satisfied with the level of disturbance or noise (Jeon, Ryu, & Lee, 2010; Jeon, You, & Chang, 2007). There's relatively less focus in the literature on acoustics in comparison to other IEQ factors (e.g., thermal comfort and IAQ). This may in part be due to the conventional practice of defining IEQ only in terms of thermal comfort and IAQ. Despite this being the case, acoustic comfort is noted to be the most important determinant of overall IEQ satisfaction (e.g. S. H. Cho, Lee, & Kim, 2011; Lai et al., 2009). As part of an effort to improve acoustic comfort, legislation that focuses specifically on environmental noise is being enacted (see Baker, 2015). For instance, the Swedish Government bill 1993/94:215 aims primarily to address road traffic noise (Pettersson, 1997). Also, in Europe, noise evaluations are being conducted to reduce public noise exposure. These evaluations have led to exterior façade renovations in building that reduce noise transmission (R. L. Neitzel, Heikkinen, Williams, Viet, & Dellarco, 2015). In Canada, the 2015 National Building Code of Canada (NBCC) has improved on the airborne sound transmission control from only direct paths mitigation to include both horizontal and vertical flanking paths.

In residential buildings, noise sources are typically categorized into two main groups: external and internal. External noise include nearby environmental noise sources (e.g., roads, rails, airport) and noise coming from neighbouring buildings (i.e., impact and airborne sound) (Hongisto, Mäkilä, & Suokas, 2015). Although outdoor noise, particularly environmental noise, represents the largest source of noise disturbance, internal or indoor sources are equally important in explaining the various health impacts of noise (R. L. Neitzel et al., 2015; S. H. Park et al., 2017). Within homes, these include airborne noise (e.g., speech, music system) as well as the noise coming from floors (e.g., footsteps, movement of objects) and ventilation systems and refrigerators (Matoski & Ribeiro, 2016; Ryu & Jeon, 2011). These noise levels tend to be more pronounced in low-income housing because of the smaller size of these houses, their higher occupancy rates and thus their higher density in comparison to other housing types (Mohamed et al., 2014). The small size of these houses and of the rooms in them also tended to worsen the perceive reflected sound because of multiple reverberations (Tajadura-Jiménez, Larsson, Väljamäe, Västfjäll, & Kleiner, 2010).

2.5.4 Lighting Comfort

There is a general lack of consensus on the role that some lighting variables play in IEQ and on definitions of the basic terminology related to lighting comfort (P. Xue, Mak, & Huang, 2016). This includes terms such as: “illuminance levels”, “illumination balance”, “satisfaction with visual balance”, and “reduction of glare problems”. This lack of consensus arises perhaps out of the attempt to represent lighting or visual comfort with these individual aspects of lighting comfort (P. Xue, Mak, & Huang, 2016). However, numerous studies (e.g., D. H. W. Li & Lam, 2001; D. H. W. Li, Wong, Tsang, & Cheung, 2006; Peng Xue, Mak, & Cheung, 2014) point to the fact that lighting comfort is influenced not only by the physical environment as conventional design thinking seems to suggest, but also by psychological and adaptive factors. Kaplan (2001), for instance, argued that there is enough documentation on the ability of occupants' adaptive factors such as nature-based activities to shape people's preferences and their overall well-being. Consequently, human behaviour and its relation to lighting is gaining considerable attention in lighting studies as the interaction between human behaviour and illuminance levels appears to determine lighting comfort (Peng Xue et al., 2014). From the foregoing, this study favours the definition of lighting comfort proposed by P. Xue, Mak, and Huang (2016) as occupants' satisfaction with indoor lighting (i.e. illuminance) levels. Lighting satisfaction or comfort in residential buildings broadly falls under two main categories: daylight and electric lighting. Lighting comfort studies place more emphasis on daylighting, not only because of its influence on energy but also because of its influence on human visual response (D. H. W. Li et al., 2006) and the circadian cycle. Daylight influences the biological clock of people determining their sleeping period so that people are awake during the day and sleep at night. Both the quantity and quality of daylighting in a building are influenced by internal (e.g., blinds or curtains) and external factors (e.g., solar shades, orientation of building, position of sun) (D. H. W. Li et al., 2006). However, with electric lighting, the choice of illumination levels is always task-related and depends mainly on the cost of energy (Lai et al. 2009).

2.6 IEQ Assessment Methods and Tools

If the results of an IEQ study are to be accurate and meaningful, the type of methods used to reach those results should be taken into account (Heinzerling, Schiavon, Webster, & Arens, 2013; Malmqvist, 2008). Evaluating IEQ involve the use of subjective methods (e.g., occupant surveys, interviews), objective methods (e.g., physical measurements of air temperature, PM) or both. Moreover, IEQ studies can be conducted as laboratory experiments or field investigations. Whereas laboratory experiments are conducted to investigate the influence of one or two variables on IEQ usually under a steady-state condition in a controlled environment, field investigations are carried out on site, in actual real-life environments to evaluate the IEQ of existing buildings. In practice, occupants' environments do not operate under a steady-state condition since variables are constantly changing, making it difficult for laboratory experiments to mimic the reality occupants find themselves in. Notwithstanding, the laboratory experiments sometimes serve as the basis for a further observation involving field investigations which occur on site in buildings.

2.6.1 Subjective Measurement Methods and Tools

IEQ investigations can clarify occupants' perceptions of their indoor environment and that of other stakeholders (e.g., designers, facility managers). Y. Xiong, U. Krogmann, G. Mainelis, L. A. Rodenburg, and C. J. Andrews (2015) argued that the majority of IEQ studies are based on the subjective responses of building stakeholders. Methods used to collect these subjective responses include interviews and surveys (i.e., face-to-face or online). Surveying is often the simplest and least expensive method for investigating these perceptions and can lead to identifying IEQ issues requiring corrective measures (Bonde & Ramirez, 2015; M. E. Cho, Kim, & Kim, 2015). Heinzerling et al. (2013) posit that occupant surveys take pre-eminence in IEQ studies because of the prime importance of occupant satisfaction to building owners and operators regardless of actual indoor conditions. Interviews, on the other hand, can help explain occupants' survey responses in more detail (Bonde & Ramirez, 2015; Rojas, Wagner, Suschek-Berger, Pfluger, & Feist, 2015b) though they are not employed as often as occupant surveys because occupant surveys are less-expensive. Further, because the attention of IEQ studies tends to turn to building occupants, the perspectives of designers and facilities managers are rarely captured despite the valuable information they may provide (Alborz & Berardi, 2015). Interviews with designers can help identify in particular the specific design features that went into the building (Ravindu et al., 2015) whereas facility managers can provide actual data (e.g. CO_2 levels, temperature) and also operational feedback (Alborz & Berardi, 2015).

Despite the usefulness of subjective methods, the subjectivity of the responses they elicit needs to be taken into account. This is because occupants under the same environmental conditions can have different satisfaction levels (Frontczak & Wargocki, 2011) and therefore react differently to the same environmental conditions. Heinzerling et al. (2013) argued that subjective methods do not have a complete diagnostic capability as they cannot adequately capture how changing indoor environment conditions influence occupant comfort and vice-versa. Moreover, survey responses are likely to be influenced by current conditions, reinforcing the need to make a distinction between "right-now" questions that elicit responses about conditions at the moment, and "long-term" questions that enquire about perceptions over a period of time (e.g., a month, year) (Heinzerling et al., 2013). The framing or wording of the questions can also affect responses received, which can lead to biases and inaccuracies in the results. All of these concerns reinforce the need for a more objective method that addresses most of these issues.

Unlike IEQ studies in non-residential buildings that adopt one of the existing validated occupant surveys that are found in the literature for such buildings (e.g., the Centre for the Built Environment surveys (Centre for Built Environment, 2008)), there is a lack of validated occupant surveys to assess occupants' comfort in residential buildings in particular. This highlights the need to develop and validate such surveys.

2.6.2 Objective Measurement Methods

Objective methods such as onsite physical measurements are needed to confirm that indoor environmental conditions do not exceed levels set and recommended by third party certifications or regulations and are thus within acceptable levels (Alborz & Berardi, 2015). These physical measurements provide actual, objective empirical datAlborz & Berardi, 2015). These physical measurements provide actual, objective empirical data about the IEQ of a space that eliminates the inherent challenges associated with subjective methods. They involve the use of tools (i.e., equipment and instruments) to collect data on aspects such as indoor air conditions (e.g., carbon dioxide, carbon monoxide, total volatile organic compounds, radon, and particulate matter) and the thermal environment (e.g., air temperature, relative humidity). These tools are either simple or sophisticated (see R. Neitzel, Heikkinen, Williams, Viet, & Dellarco, 2016; D. Xie, Liao, & Kearfott, 2015; Youyou Xiong, Uta Krogmann, Gediminas Mainelis, Lisa A. Rodenburg, & Clinton J. Andrews, 2015), and can also be either handheld or custom built-cart or built-tripod (C. C. L. Tan et al., 2012). Simple equipment, as the name suggests, are very easy to operate and also collect fewer environmental parameters (i.e. usually, only one or two). They also sometimes lack the sensitivity required to detect low concentrations of pollutants (Kim, 2012). Sophisticated equipment, on the other hand, are state-of-the-art and allow complex data collection. Custom built-cart or built-tripod equipment incorporate several different sensors in one setup, making them suitable for larger studies involving many different buildings and parameters. Heinzerling et al. (2013) argued that using custom-built carts reduces the labour and cost involved in measuring multiple building parameters. Moreover, it makes the moving of multiple sensors within a space easier and maintains their stability during measurement. Finding inexpensive, easy-to-use, and accurate tools is usually a challenge in IEQ studies (Heinzerling et al., 2013). The cost of these tools including the cost of their calibration has been reported as a major barrier to the use of objective methods in IEQ studies

(Mui et al 2016). Compounding this prohibitive cost is the impracticality of analyzing the vast amount of data collected for all IEQ parameters (Heinzerling et al., 2013). This might explain their limited pplication in residential and non-residential IEQ studies. Only a few studies (e.g. Langer, Bekö, Bloom, Widheden, & Ekberg, 2015; Rojas et al., 2015b; Youyou Xiong et al., 2015) have used IEQ physical measurements in residential buildings in particular.

No matter the type of method used in IEQ studies, inherent challenges are inevitable when using either subjective or objective methods. Therefore, a mixed method approach that uses both methods and that capitalizes thus on the strengths of each may be the best approach.

2.7 IEQ in Low-Income Housing

In IEQ studies, achieving a good indoor environment (e.g., proper temperature levels, indoor air quality) and housing quality is sometimes associated with enhanced occupant IEQ satisfaction and improved quality of life (Diaz Lozano Patino & Siegel, 2018; Jacobs et al., 2014; Paravantis & Santamouris, 2016). This housing quality is determined by a number of factors such as building age, structural integrity (e.g. cracks), maintenance culture, income levels and others (Jafta, Barregard, Jeena, & Naidoo, 2017). Factors such as building age and poor maintenance may lead to worsened overall dwelling conditions within low-income housing (Diaz Lozano Patino & Siegel, 2018). There have also been other studies exploring the correlation between these indoor environmental conditions and income levels (e.g. Brown et al., 2015; Jafta et al., 2017; Paravantis & Santamouris, 2016). In all these studies, the evidence seemed to suggest that low-income housing had poor dwelling conditions and envelopes. For instance, in a literature review of IEQ by income levels, Santamouris et al. (2007) reported that only about 28% of low-income households lived in buildings with insulated envelopes compared to 70% of high-income households. Owing to this, IEQ studies on low-income housing is gaining attention as an area of research. Table 2.2 summarizes the findings from the reviewed studies on IEQ in low-income housing. From this table, it appears there is an evidence for the poor IEQ in low-income housing across the world. The problems range from extreme lower temperatures, higher levels of fine particulates and CO_2 concentrations, to poor acoustics. All these IEQ problems pervasive in low-income housing highlight the need for strategies that will improve the indoor environment of low-income housing. The succeeding section presents a review on the IEQ performance of low-income housing that have been built to green standards.

Table 2.2: Findings of IEQ in low-income housing

Study	Country of Origin	Research Design	Data Analysis	Results
Mohamed et al. (2014)	Malaysia	The study utilized site observation and questionnaire survey. Informal discussions with occupants were carried along side. 45 occupants responded to the questions.	Descriptive Statistics	Majority of the respondents (92%) expressed satisfaction with the layout of the space. Occupants expressed dissatisfaction with room size. Only 30% of respondents expressed satisfaction with room size. Wide windows provided adequate ventilation leading to a large number of occupants (>70%) being satisfied with or at least neutral to ventilation. Similar results were reported for temperature. The only IEQ factor of major concern was noise. Only 26% of respondents were satisfied with noise disturbance. Traffic noise appeared to be the major cause of this disturbance.
Paravantis and Santamouris (2016)	Greece	Indoor temperature was recorded in 50 low-income dwellings.	Descriptive statistics and cluster analysis	Indoor temperatures were found to be below acceptable standards reaching sometimes below 5^{o}C.
McGill et al. (2015)	UK	28 residents in social housing (four mechanically-ventilated homes and four naturally-ventilated homes) filled out survey questionnaires along with a face-to-face interview to ascertain more details about the physical characteristics of the building, perception about thermal comfort and IAQ. Snapshot physical	Descriptive statistics	The Bedrooms recorded higher CO_2 levels relatively than the living rooms. In some rooms they were peaked at 4173 ppm in summer, and >2000 ppm in winter for both MVH and NVH. In summer, formaldehydes level peaked above the recommended i.e. >0.08 ppm for both types of building. Overheating was reported during the summer in two NVH and all four MVH, with

		measurements were taken to measure IAQ and thermal comfort. The study also made use of diary to take notes of daily activities.		measurements recording peak temperatures above 27^{0}C in one NVH and two MVH dwellings.
Escobedo et al. (2014)	USA	Physical measurement of selected indoor air quality (i.e. $PM_{2.5}$, carbon, proteins) were conducted in 30 homes. Participants were also administered survey questions including questions on health. 29 households completed the questionnaire.		40% of the homes was considered overcrowding i.e. they had more than 2 people per bedroom. The highest $PM_{2.5}$ concentration (28 µg/m^3) was recorded in the home that indicated indoor-cigarette smoking in the survey two weeks before the measurements. The study showed the presence of indoor sources of fine particulates (with average indoor/outdoor $PM_{2.5}$ ratio of 2.0). Similarly, indoor organic carbon concentration (average = 6.8 µg/m^3) was higher than outdoor (average = 14.8 µg/m^3) indicating indoor sources, probably as a result of human activities.
Burgos et al. (2013)	Chile	A cross-sectional study of 98 relocated families and 71 still living in slums was carried out, obtaining indoor and outdoor samples by a Personal Environmental Monitor. Home characteristics, including indoor air pollution sources were collected through questionnaires.	Descriptive statistics and multivariate regression	Indoor $PM_{2.5}$ concentrations were higher in slums (77.8 µg/m^3, SD = 35.7 µg/m^3) than in public housing (55.7 µg/m3, SD = 34.6 µg/m^3, $p < 0.001$). Differences between indoor and outdoor $PM_{2.5}$ were significant only in the slum houses. Outdoor $PM_{2.5}$ was the main predictor of indoor $PM_{2.5}$. Other significant factors were water heating fuels and indoor smoking.
Peretti et al. (2015)	Italy	Six apartments were monitored for indoor temperature and relative humidity (RH) using electronic	Descriptive statistics and tests of	Air temperature was different between apartments with mechanical ventilation (MV) and apartments without. Same results

		sensors installed in the living rooms. 25 occupants were surveyed before and after the measurement period to collect their perceptions about the environmental parameters.	statistical significance	were reported for the levels of relative humidity. Apartments with MV exceeded 50% RH in only one case, while for apartments without MV sometimes reached 80%. Occupants in apartments without MV opened windows more frequently improving their indoor air quality.
Mahdavi, Haaland, and Siegel (2016)	Canada	75 apartments across seven social housing buildings were physically monitored for particulate matter	Descriptive statistics and graphs	Particle concentrations showed large variations within and between units. Smoking significantly elevated concentration ($p<0.05$, Wilcoxon signed-rank). Other high concentrations were also due to other sources (e.g., cooking), transfer of particles from other units or infiltration from outdoor air.
Haaland, Tzekova, Purcell, and Siegel (2016)	Canada	70 units across seven social housing buildings were monitored for temperature, relative humidity and mean radiant temperature. Occupant thermal comfort was monitored using psychrometric charts.	Descriptive statistics and correlational analysis	Overheating (> 25^0C) was reported as the major source of occupant discomfort occurring over 50% of the time.

2.8 IEQ performance of Green Low-Income Housing

Studies investigating the impact of green features on the IEQ performance of residential buildings in general are limited in the literature. However, significant evidence exists even among that limited literature on how greening a building may improve its IEQ. It may translate into lower levels of VOCs, allergens, particulate matter (MacNaughton et al., 2017). Table 2.3 provides a snapshot of IEQ studies on green residential buildings.

Similar studies investigating IEQ in green low-income housing are significantly lacking despite the reported elevated levels of environmental exposure among low-income households (Brown et al., 2015; Colton et al., 2014; Escobedo et al., 2014; Paravantis & Santamouris, 2016). This is perhaps because the initial higher cost premium associated with green buildings is a major obstacle to the greening of low-income housing. Notwithstanding attempts are being made to greening low-income housing and the evidence is encouraging. Pertaining to interventions that limit environmental exposure, lead abatement, integrated pest management; weatherization (Doll et al., 2016) have successfully reduced environmental exposure in affordable housing (Colton et al., 2014). Doll et al. (2016) investigated the impact of weatherization on IEQ in low-income single-family homes. Data were collected at three North Carolina locations in the United States for selected IEQ parameters (i.e. CO_2, CO, nitrogen dioxide NO_2, temperature, RH, formaldehyde, radon, $PM_{2.5}$, PM_{10}, particle counts, household characteristics, and weather) in 69 homes, before (PRE) and after (POST) weatherization. The aggregate POST results were lower than the PRE and were within the compliance limit. CO_2 reduced from 799 ppm to 690 ppm after the weatherization. Similarly, CO decreased from 0.38 ppm to 0.21 ppm. The same is reported for $PM_{2.5}$ and PM_{10}. These reduced exposure levels translated into improved occupant self-reported health (e.g. mental health, asthma and non-asthma respiratory problems and overall health) as found in the few studies that explored these relationships in low-income housing (J. Breysse et al., 2015; Jill Breysse et al., 2011; Garland et al., 2013).

Table 2.3: Findings of IEQ in green residential buildings

Study	Country	Research Design	Data Analysis	Results
Zalejska-Jonsson (2014)	Sweden	Occupants filled questionnaires to rate their satisfaction with air quality, thermal comfort, sound quality and daylighting; controlling strategies and perceived problems in two periods – spring and autumn. Responses were analyzed based on the status of residents – owners or renters. Seven (7) green, and seven (7) non-green. Occupants (n=1200, RR=40%)	Descriptive statistics, Mann-Whitney tests, ordered logistic regression	No statistically significant difference between occupants' satisfaction with IEQ in green and non-green apartments for either renters or owners. Owners of green apartments were less satisfied with thermal environment than renters of non-green apartments. Renters of green apartments were less satisfied with thermal environment than owners of non-green apartments. Owners of green apartments were more satisfied with IAQ than renters of non-green apartments. Renters of green apartments were less satisfied with IAQ than owners of non-green apartments
Bonde and Ramirez (2015)	USA	Semi-structured interview involving six residents to obtain a general sense of the buildings' operation. Residents filled online surveys to rate their satisfaction with and problems of temperature, air quality and lighting. One (1) green (LEED) and one (1) non-LEED. Students (n=1130, RR=7%)	Chi square	83.78% and 81.08% of all green building respondents were satisfied with indoor temperature in spring and fall seasons respectively versus 60.86% and 51.06% of non-green building respondents. Air quality satisfaction followed same trend as thermal comfort, however, there were no significant differences between artificial and daylighting satisfaction

Rojas et al. (2015b)	Austria	Continuously logged selected parameters such as indoor temperature, relative humidity, CO_2 and VOCs. Occupants were interviewed and also filled questionnaires to rate their satisfaction with the indoor environment. 12 passive certified with mechanical ventilation, and six (6) non-passive certified houses. (n=354, RR=17%)	Descriptive statistics	Around 70% of the respondents stated they were satisfied with the preset temperatures, 18% would prefer it even warmer. Overall mean temperature was 23.5^{o}C and 21.6^{o}C for passive houses and non-passive respectively. Relative humidity for passive houses ranged from 20 – 40% and was generally below 30% for non-passive. Non-passive houses had 25% of bedrooms and 35% of living rooms exceeding 1000 ppm of CO2 concentrations versus 2% of bedrooms and 15% of living rooms for passive houses
Langer et al. (2015)	Sweden	Physically measured both outdoor and indoor parameters over a 2-week period during each of the four seasons between 2012 and 2014. Analysis was carried out based on the differences between the two types of homes – passive and conventional. 20 green (passive), and 21 non-green	Two-sample t-test, two-sample Wilcoxon Mann-Whitney rank-sum test.	Majority of the indoor parameters (e.g. relative humidity, AER, ozone) varied with seasons. For most part of the thermal environment and indoor air parameters (air temperature, RH, NO_2) there was no statistically significant difference between green and non-green homes. CO_2 levels exceeded the national guideline (1000ppm) in both homes. However, for 20% of the measured time green homes appeared to perform better than non-green homes. Significant differences were observed in RH, Formaldehyde and TVOC between green and non-green houses

Holopainen, Salmi, Kähkönen, Pasanen, and Reijula (2015)	Finland	Interviews and questionnaire survey involving occupants to assess perceived IEQ. Environmental problems were elicited from the past 3 months and occasionally every week during winter and autumn of 2013. 5 green (low energy) and 5 non-green	Descriptive statistics	Occupants in green houses perceived their indoor environment better than in non-green houses. Insufficient illuminance levels, insufficient ventilation, and too high varying temperatures were the commonly reported IEQ problems in non-green houses
Zalejska-Jonsson (2012)	Sweden	Occupants rated their perceived satisfaction and indoor comfort through questionnaire. The questions covered reasons for choice of buildings, their general perception of indoor climate, behavioral practices and occupants' background. 3 green (low-energy) and 3 non-green (RR= 50% and 42% for green and non-green respectively)	Descriptive statistics, Mann-Whitney tests, ordered logistic regression	Generally, there was no significant difference in satisfaction with building quality between both occupants. However, building location, gender and age impacted on occupants' satisfaction (at 0.01 significance level). Occupants in non-green houses were more satisfied with indoor temperature in winter than in green houses and so employed supplementary heating devices. 69% of occupants in green houses found sound insulation to be 'very good' compared to 51% in non-green houses. Negative correlation was found between occupants satisfaction and additional heating, but sound quality and additional cooling have no statistical significance on general satisfaction

This is because with reduced pollutants and pest lead to less home water or dampness issues and decreased insecticide usage (J. Breysse et al., 2015).

To contextualize the health outcomes of green renovation of low-income housing, a useful reference is a study conducted by Jill Breysse et al. (2011), who investigated association between health outcomes and green renovation of a 60-unit apartment building in the United States. They investigated occupant health and IEQ performance outcome at baseline and one year after the renovation of low-income housing using Enterprise Green Communities green specifications, which improve ventilation; reduce moisture, mold, pests, and radon. The study combined questionnaire survey and physical measurement on ventilation, carbon dioxide and radon. Thirty-one (31) of the 54 occupied units were involved in the study. They reported that majority of the homes had significantly fewer mild dew odour/musty smell ($p = 0.020$) or evidence of water dampness ($p = 0.083$) after renovation. Also, the use of insecticides by residents significantly improved ($p = 0.059$) after renovation. 62 percent reported that adult health was very good/excellent at renovation compared with 33% at the baseline. The percentage of adults reporting several specific health problems significantly improved from baseline to renovation for asthma ($p= 0.046$) and non-asthma respiratory problems ($p= 0.030$).

Colton et al. (2014) also compared the performance of IAQ in green and conventional multifamily low-income housing. The study involved conducting environmental sampling, home inspections, and health questionnaires with families in green and conventional (control) apartments in two low-income housing developments. A subset of participants was followed as they moved from conventional to green or conventional to conventional housing. They measured $PM_{2.5}$, formaldehyde, NO_2, nicotine, CO_2, and AER over a seven-day sampling period coincident with survey administration. In their multivariate models, they observed 57%, 65%, and 93% lower concentrations of $PM_{2.5}$, NO_2, and nicotine (respectively) in green versus control homes ($p = 0.032$, $p < 0.001$, $p = 0.003$, respectively), as well as fewer reports of mold, pests, inadequate ventilation, and stuffiness. However, differences in formaldehyde and CO_2 were not statistically significant. Moreover, participants in green homes experienced 47% fewer sick building syndrome symptoms ($p < 0.010$).

These interventions in low-income houses have generally focused on addressing IAQ problems, with limited emphases on the other factors of IEQ. However, it has been suggested in many studies (Alborz & Berardi, 2015; Heinzerling et al., 2013; Mohamed et al., 2014) that a comprehensive IEQ improvement (i.e. all four main IEQ factors and occupant feedback) is necessary to significantly improve the indoor environment in low-income housing.

3 CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter describes the data gathering and analysis process employed in this study. For convenience in discussion, this chapter has been sectionalized into the following headings: Study Design, Data Collection, and Data Analysis. Each of these is further described below.

3.2 Study Design

Nenty (2009) believes that research design involves identifying the procedures that researchers will use to analyze relationships among different variables and consequently to argue the preference of particular procedures over others. Thus, research design can be thought of as a master plan that shows how the research is to be conducted. In the literature, there are two main types of research design: descriptive and analytical (i.e., explanatory) research. Descriptive research is designed to depict participants or situations accurately (Ayyash *et al*. 2011). Analytical or explanatory research, on the other hand, examines trends over time or compares situations. This research uses a partly descriptive and partly analytical research design to capture occupants' interaction and satisfaction with their indoor environment, and the physical performance of the indoor environment respectively. The descriptive took the form of an occupant survey, whereas the analytical involved physical measurements of a sample of homes and observation of their surroundings. The mixed method research is used because of its proven ability to provide a better description or explanation of the quality of indoor spaces compared to subjective or objective only method in IEQ studies (e.g., Alborz & Berardi, 2015; Brown et al., 2015; Rojas et al., 2015a) The detailed study design is outlined below.

3.2.1 Population, sampling technique and sample size

In research, the term "population" refers to a collection of elements from which inferences can be made (Lepkowski, 2008). In this study, the population was considered to be all low-income green residential homes in Brandon. Davidson (2006) argued that sampling is required because of the impossibility of involving the whole population in the research owing to time or financial constraints. In this study, a sample of low-income houses comprising four blocks of rental townhouses and one rental bungalow was analyzed. These rental homes were in Brandon, the second-largest city in the province of Manitoba in Canada with a population of approximately 48,859 (Statistics Canada, 2017). According to Statistics Canada (2017), the population density is 631.2 per square kilometre. Manitoba has a temperate climate, with monthly precipitation averages of 19 mm in January and 48 mm in September. The average monthly maximum and minimum temperatures in September and January are 19 ^oC and 5 ^oC and -13 ^oC and -24 ^oC, respectively (Climate-Data.org). The buildings were occupied in 2010 and were all two-storey high wood framed. The apartments making up those rental homes all had the same floor plan consisting of three bedrooms, a living room, a kitchen, and a basement, with a footprint of 1,520 ft^2.

The buildings incorporated a number of green features during their design and construction. These features are summarized in Table 3.1. The apartments, except for the bathrooms, were finished with linoleum. The bathrooms and storage or laundry floors were finished with sheet vinyl. The wood framed walls were covered with gypsum wall boards and finished with low-VOC paint. To maintain continuity of thermal protection to building elements and spaces and also excessive air leakage, insulation was installed within the walls. The overall window-wall ratio (WWR) of the building was approximately 0.18. The north side of the apartments has larger window sizes compared to the south to allow for sufficient daylight with maximum heat gain in winter (see Figure 3.1 & 3.2) and thus optimal balance between energy and daylight.

Table 3.1 Green features incorporated in the studied homes

Green housing feature	Action
IEQ	• Enhanced combustion venting measures – carbon monoxide detectors installed in each apartment, no unvented combustion appliances • Moisture control – Central HVAC system equipped with additional dehumidification mode • Enhanced outdoor air ventilation and third-party performance testing • Enhanced local exhaust (automatic timer tied to switch) and third-party performance testing • Best air filters (MERV 8) • Indoor air contaminant control • Preoccupancy flush • Radon-resistant construction – active ventilation • ENERGY STAR with indoor air package including low-VOC paints, adhesives and sealants, heat recovery ventilators (HRV) • Smoke free policy
Energy and Atmosphere	• Advanced lighting package – no ceiling fans, 80% of lamps are ENERGY STAR CFL • High-Efficiency appliances – ENERGY STAR labelled • Use no refrigerants
Materials and Resources	• Applied Framing efficiency techniques to reduce lumber cuts • Environmentally preferable products with Forestry Stewardship Council certification e.g. linoleum, 90% hard flooring • Waste diversion

Fig. 3.1. Elevations of Blocks

Of the five blocks of studied buildings (i.e. A, B, C, D, and E), block B represented the LEED gold certified block, while block D was excluded from the study because of occupants' unwillingness to participate for reasons related to personal factors in the study and because it was a bungalow and the others were townhouses which limits a direct performance comparison. This is because of the differences in physical factors such as size of space, size of openings. In this study, six out of eight apartments two out of four, all four, and five out of six in blocks A, B, C and E respectively were investigated. In this study, attempt was made to analyze the apartments individually despite similar physical building characteristics such as same materials and building plans because of the possible impact of outdoor environmental factors (road traffic, factory buildings) on the indoor environment; and also the possible influence of likely differences in occupants' characteristics (pet keeping, hours spent at home) on the indoor environment. The buildings were oriented as follow: block A (east-west), block B (east-west), block C (north-south) and block E (north/west-south/east) as showed in Figure 3.2.

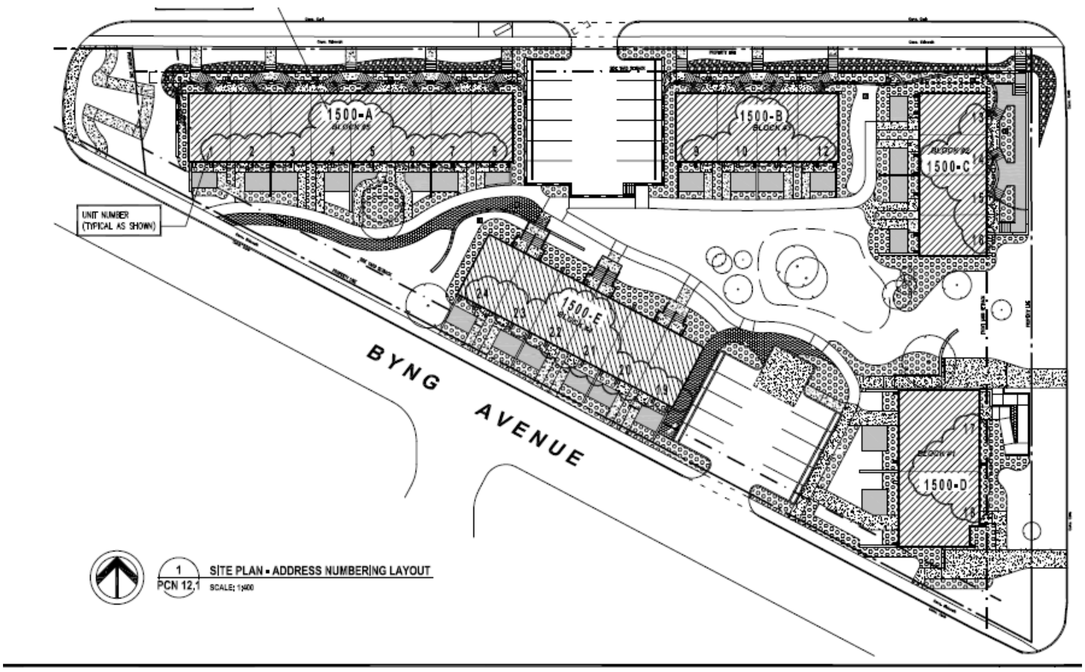

Fig. 3.2. Layout of blocks

This study complied with ethical standard set out in University of Manitoba. Thus, the study obtained an ethics approval from the University of Manitoba Tri-Council Research Ethics Board. The study protocol was reviewed and approved by the University of Manitoba Ethics Review Board. Occupants were subsequently contacted through Manitoba Housing, the agency responsible for the management of the buildings. This involved sending written notices about the project inviting occupants to participate in the study. Recruiting participants through the housing manager was necessary for two reasons. Primarily, from ethics point of view, it prevented any undue influence that may have arisen from the direct contact of the researcher with the occupants. Second, since the occupants are most likely to be familiar with the housing manager they might be more receptive to participate in the study. After obtaining permission from the occupants to participate in the study, they were briefed about the details of the project (for instance, their respective roles and the risks they were likely to assume). Additionally, this project was in two phases. The first phase occurred in fall season specifically September-October 2016), and the second phase was done in January 2017. Occupants signed an informed consent form to participate in this study and were given a $15.00 gift card when they completed the first phase in to encourage participation in January 2017. Only occupants above 18 years of age were recruited to participate in occupants' IEQ satisfaction survey. Participation in the study was voluntary; and out of the 24 households, 19 households consented to participate in the fall and 17 in the winter. However, to enable a pairwise comparison of homes across the two seasons to understand the influence of seasonal variations on the IEQ performance, apartments must be involved in both phases. If apartments were involved in only one of the phases, they were excluded from the analysis altogether. Consequently, two apartments in fall season were excluded from the study.

3.3 Data Collection

Data collection took place in two seasons. For the snapshot measurement, data was collected in September-October 2016 (fall) and January 2017 (winter), while the long-term measurement data was collected from only two apartments. The long-term data collection involved only physical measurement. All long-term measurement occurred from September to November 2016 and December to February 2017 for the fall and winter seasons respectively. The long-term measurement involved the use of inexpensive and simple electronic sensors (i.e. Foobot) that enabled real time monitoring over the internet. Snapshot measurement is a sampling method conducted at a single point in time at a couple of specific places usually within a reasonable short-time (e.g. any period less than 24 hours). On the other hand, long-term measurement involves continuously monitoring a space allowing for real-time and in-depth reporting on IEQ. Snapshot measurements help identify potential problems of IEQ and transient comfort if the problems or case happened during the measurement period. But such a situation may rarely happen, and that is why long-term continuous measurement is becoming popular and a choice-option in evaluating IEQ. The study surveyed households within each block based on their volunteer to participate in the survey (provided they were adults i.e. 18

years and above, who comprehended English or Spanish). I translated the English questionnaire survey into Spanish to enable easy comprehension for Spanish-speaking occupants. As part of the ethical concerns their confidentiality was ensured by aggregating individual responses and anonymizing the apartments. Hence, their responses were consequently anonymized. Each of the instruments is explained in detail.

3.3.1 Instruments design

The data collection instruments (i.e. questionnaire survey, interview survey, and measurement protocol) were developed and validated in a pilot study. The whole intent of the pilot study was to test these research instruments to verify their suitability for the study. Two apartments (one in block B and one in block C) were selected in the pilot phase. The developed IEQ measurement protocol and occupants' questionnaire survey were applied in these apartments in November 2015. Overall, four occupants participated in the questionnaire survey. The instruments were the product of an extensive review of publications on IEQ in residential buildings, as well as other relevant buildings (non-residential) and scenarios such as peculiarities of low-income housing. The review showed the inconsistencies and gaps in the methods of the various studies. For instance, there was no standardized questionnaire survey instrument for residential buildings to assess occupants' satisfaction with IEQ unlike non-residential buildings (offices). This formed the basis for the development of the various data collection instruments. The selection of the various instruments and their components was based on the research needs and the number of occurrence in widely adopted scientific studies and papers; and partly on optimum reliable usage and performance of the tools in the post occupancy phase. Generally, IEQ methods vary between subjective and objective techniques. The methodology used for this study is a combination of subjective and objective data collection instruments that solicits different perspectives from various participants (including facilities managers and occupants). Subjective data collection methods included face-to-face interviews and surveys with many stakeholders (i.e. designers, facilities managers, and occupants). The study included interviewing the design team members who were involved on this project and as such had extensive knowledge on the design of these homes. These were the architect and his assistant. Appendix V (3) details the questions used to interview the design team. Subjective methods provide valuable information on the operational feedback through occupants' survey and interviews with facility managers; and calculation assumptions and the design features incorporated through interviews with the design team. This helped to ascertain whether the homes met the design intent since becoming operational. Physical measurements, meter readings are some of the key objective data collection methods (Alborz & Berardi, 2015). Physical measurements provided information on the pollutant level to ensure occupants were within exposure limits as set out by organisations and agencies. Also, since occupants respond differently to the same indoor environment, it was necessary to compliment the responses from the surveys and interviews with objective data to explain the nuances in their responses. Therefore, a holistic IEQ methodology should thus not only capture users' attitudes and occupants' perception, but also objective assessment of the indoor environment. The various instruments are subsequently discussed.

3.3.1.1 Physical measurement

Sampling position

A comprehensive instrumentation cart and tripod was used to collect IEQ-factors including thermal comfort, IAQ, acoustics and lighting. To construct the instrumentation, previous studies and standards were reviewed to identify the instruments that had been used to measure corresponding metrics. This involved equipment availability on the market, power consumption, sensitivity, calibration and cost information to assess the appropriate sensors. Tables A1-A4 in the appendix show a summary of the measurement protocol and the parameters measured. Tables A1, A2, A3 and A4 show the parameters measured under the thermal environment, indoor air quality, acoustic and lighting environments, respectively. Moreover, the equipment types and their sensitivity range, unit of measurement, and sampling location are included in the protocol. Figures 3.3 to 3.5 shows selected images of equipment setup. For thermal comfort and IAQ, the mounting height adapted was 1.10 m. The measurement involved a snapshot monitoring with averaging time of fifteen (15) minutes. Further, measurements were logged every one minute for the entire sampling period i.e. the duration of the sampling. Sampling position was in the middle of the space. Participants' availability determined actual measurement times. The three locations (living room, bedrooms 1 and 2) were deemed representative of the IEQ conditions of the studied apartments (see Colton et al., 2014; Lai, Mui, Wong, & Law, 2009). For the long-term measurement, two Foobots were placed in the living rooms and basements of the two apartments that were investigated. The equipment logged every five minutes during the measurement period. Also, I monitored the real time measurement over the internet. The details of the sampling parameters and procedure are described next.

Sampling parameters

CO_2, CO, TVOCs, $PM_{2.5}$ and PM_{10}, and radon were the IAQ parameters measured. The parameters were selected on the basis of the most frequent pollutants commonly studied in residential homes in scientific literature and also in consultation with industry partners. Only the radon was sampled for a 24-hour period because of the level of sophistication of the equipment which did not permit a 15-minute snapshot measurement. Radon was measured using commercially available continuous radon monitors (Professional Continuous Radon Monitor, Model 1028, Sun Nuclear Corporation, Melbourne, FL, USA) in the basement and living rooms. D. Xie et al. (2015) argued that radon gas is more pronounced at the basement and the ground floors. In this study the living room was located on the ground floor. CO_2, CO, TVOC, $PM_{2.5}$ and PM_{10} were measured using GrayWolf IQ-610 and GrayWolf PC-3016A, respectively. These pollutants were measured simultaneously for fifteen (15) minutes at every sampling space (i.e. bedrooms and living room). However, the first three minutes of the sampling period, based on the results of the pilot study, were discarded because of sometimes extreme fluctuations in values due to issues such as lagging response of sensors. The Foobot sensor measured only CO_2, $PM_{2.5}$, and TVOC. However, the TVOC was based on algorithm that is closely related to CO_2. That is to say the TVOC was extrapolated from the CO_2 results.

The monitored thermal comfort parameters are the parameters that affect energy loss from the body and they include: air temperature, radiant temperature, RH and air velocity. The study monitored parameters such as air temperature and radiant temperature using a Campbell Scientific 109-L and Campbell Scientific black globe L, respectively. RH and air velocity were monitored using GrayWolf data logger (IQ 610 and AS-201). The long-term sensors also measured air temperature and RH. Regarding acoustic quality parameters, ATL, background noise and reverberation time were measured. Background noise was measured in all the measurement spaces aforementioned. However, ATL of partition walls was only measured between two adjacent bedrooms. Availability of households limited the measurement of partition walls between apartments (which would have been the ideal situation) since occupants are usually less tolerant to noise from other apartments.

Figure 3.3. Thermal comfort and air quality setup

Figure 3.4 Acoustic comfort setup

Figure 3.5 Data collection with thermal comfort and air quality equipment

3.3.1.2 Questionnaire survey

Subjective IEQ performance of the building took the form of a self-administered paper-based IEQ assessment questionnaire survey designed from the occupant IEQ survey of the Centre for the Built Environment (CBE), University of California, scientific studies in literature (e.g. Peng Xue et al., 2014; Zalejska-Jonsson, 2014) and input from industry practitioners. The CBE questionnaire was adapted because of the long-standing credibility of the study and its direct relevance to this study. For instance, the questions on adaptive control behaviours, occupancy were adapted from the CBE survey. The other studies in literature investigated green residential apartments with sections of the questionnaire with direct application in this study. For instance, the IEQ problems section of the questionnaire was adapted from (Zalejska-Jonsson, 2014). The questionnaire was divided into three parts. Part 1 enquired about demographic information (e.g. age, weight, years of stay). Part 2 asked questions about occupancy patterns (e.g. number of occupants, time spent indoors and occupancy activities). Lastly, part 3 asked about occupants' perception of IEQ (e.g. adaptive control behaviours, satisfaction with IEQ, perceived problems with the indoor environment). The results of the pilot study led to modifications of the research instruments for the main study. Comments from the occupants and the size of the space led to the modification of portions of the survey and measurement protocol, respectively. Portions modified included sections about demographics (e.g. certification type, weight of occupants); occupancy (number of occupants, percentage of time spent on activities); and IEQ (snapshot or current feeling). Also, from the pilot study and initial interaction with the occupants it became apparent that majority were immigrants from a Spanish-speaking country. So, the survey questions were translated into Spanish to make it easier for the Spanish-speaking occupants.

For each IEQ topic area, occupants were asked to rate the sources of discomfort using a 5-point discomfort scale (1-always, 3-neutral, 5-Never) followed by long term occupant's satisfaction evaluation on a 7-point satisfaction scale (1 – very dissatisfied, 4 – neutral, 7 – very satisfied); and transient or 'right now' occupant satisfaction was evaluated using a 5-point satisfaction scale (1 –very uncomfortable/poor/dissatisfied, 3-neutral, 5-very comfortable/satisfied/good). Questionnaires were either in English or Spanish to cover the two major languages participants spoke. Questionnaires were filled by occupants during the measurement period and it took about 20 minutes. The term transient or 'right now' satisfaction, as used in this study, referred to their satisfaction with environmental parameters at the time of the IEQ physical measurements, while "long term satisfaction" went beyond the physical measurements to enquire about their satisfaction with IEQ in general over a longer time period. Transient occupant satisfaction was subsequently converted into an artificial dichotomous variable (i.e. 1 – uncomfortable/dissatisfied/poor for ratings of 1 or 2, or 2 – comfortable/satisfied/good for ratings of 4 and 5) using 3.0 as the reference point. Long-term satisfaction, on the other hand, was subsequently converted into two satisfaction groups (i.e. acceptable and unacceptable groups) with 4.0 as the reference point to enable comparisons between subjective and objective measurements. The goal of this was to enable a detail assessment of environmental levels across the two various groups and also to determine if occupants' subjective satisfaction is influenced by these levels. Occupants of block B did not participate in the questionnaire survey and were thus excluded during the perceived IEQ satisfaction assessment in subsection 4.4. A total of 27 questionnaires were distributed to the occupants of the studied apartments and were all retrieved. Out of the 27, only 22 completed significant portion of the questionnaire. Detailed questionnaire is found at the appendix VII (3).

3.3.1.3 Field observation

The observation sheet (see Appendix III) captured conditions or factors that have a tendency to influence IEQ. They included both indoor and outdoor conditions or factors that can be physically observed. Conditions were identified essentially for each of the four main IEQ factors including position of ventilation outlets, type of windows, proximity to local sources of pollutants, and outdoor weather conditions. A walkthrough of the site and in the apartment provided the necessary answers, and also formed the basis for following up on how some of the conditions affect their IEQ. For instance, whether proximity to noise sources e.g. roads, factories affected their acoustic satisfaction. Some physical conditions existed in the apartments and around the apartment (building envelope). The observation sheet was completed by the principal investigator during the physical measurement of the apartment. This augmented the results obtained from physical measurements and survey responses.

3.3.1.4 Interviews

The interviews (see Appendix V including responses) enabled a broader perspective to the issue of IEQ, and also helped treat IEQ as an iterative process rather than limited to only the post-occupancy phase. An interview with the designers helped the researchers to establish the design goals, challenges and the specific design features or technologies (e.g. building automation control systems) incorporated into the building to enhance IEQ. The interviews were conducted before the full-development of the questionnaire survey and subsequent field investigation. The interview involved two members of the design team and they were conducted in person. On the average, the interviews lasted for about 30-45 minutes per session.

Further, an interview with the facility manager (see Appendix VI including responses) provided operational perspective of the facilities. The interview followed after the interview with the designers. Because of unavailability of the facility manager in person, electronic copy was sent, and written response received via email. This interview coupled with the visits to the site, designers' responses and review of documents enabled the researchers to establish very clearly the specific design features.

3.4 Data Analysis

The study utilized Statistical Package for the Social Sciences version 23.0 to analyze the data. Questionnaire data were analyzed for descriptive statistics (frequency distributions, means). Similar descriptive statistics was calculated for individual environmental parameters (such as temperature, CO_2).

3.4.1 Reliability and validity checks

It is a common practice to use Shapiro-Wilk test to assess the normality of data with less than 50 sample size (Laerd Statistics, 2015). Hence, Shapiro-Wilk test for normality was used to test the normality assumptions of the continuous data (i.e. physical measurements) and visual inspection of box-plots was used to identify outliers, particularly in the physical measurements and survey responses. Values higher than the upper quartile plus three times the interquartile range were deemed outliers. However, outliers identified in the continuous data were subsequently retained in the dataset for reasons identified in the observation sheet that seemed to support the rationally higher levels. For the most part, the data failed the normality distribution test, except the background noise measurements. In consequence, non-parametric tests analyses were used for the data that failed the normality test. Cronbach's alpha coefficient was used to test the reliability and internal consistency of the questionnaire survey responses. The underlying objective of the reliability test was to test whether the items on the thermal comfort, air quality, lighting, and acoustics quality scale respectively were measuring the same underlying dimension. The alpha values for thermal comfort, air quality, lighting quality and acoustic quality were 0.617, 0.690, 0.753 and 0.814, respectively. Within the IEQ literature, the acceptable value of alpha ranges from 0.60 to 0.95 (Peng Xue et al., 2014). In this research, all the coefficients were above 0.60 indicating a good reliability of the scales.

3.4.2 Test of differences

A one-way analysis of variance (ANOVA) was used to test the difference between the mean sound levels of the three sampled spaces (bedrooms 1, 2 and living rooms) in the measured apartments in the fall season because of the different possible sources of noise. ANOVA test examines association of continuous or ordinal (rank) data with more than two independent groups (Choi, Loftness, & Aziz, 2012; Gauthier, 2016). This tool is considered appropriate for this analysis because of the equal sample size of the groups (bedroom 1, bedroom 2 and living room); and in particular the data is assumed to follow a normal distribution (Laerd Statistics, 2015). Subsequently, a post hoc test was run to test the differences among the specific groups in all possible pairwise comparisons (Gauthier, 2016). Specifically, Tukey-Kramer post hoc was deemed appropriate because of the equal number of group sizes (Laerd Statistics, 2015). Statistical significance was defined as $p < .05$. Thus, a p-value less than 0.05 indicated significant differences among the various groups.

Box plots were constructed showing the magnitude and variability of environmental parameters in the survey response (i.e. snapshot or right now satisfaction with the environmental factors). The use of box plots is consistent with IEQ research practice particularly in demonstrating distribution over satisfaction scores (see Du et al., 2015; Frontczak, Andersen, & Wargocki, 2012; Q. Li et al., 2013). The significant differences between these two groups were examined using Mann-Whitney U-test. This was also performed with a predefined significance level of 0.05. This made it possible to establish if occupants in the groups responded differently to the measurement levels. Additionally, the Mann-Whitney test was also used to assess differences between groups of long term satisfaction (i.e. acceptable and unacceptable) of IEQ following the example of Zalejska-Jonsson (2012). Also, a Mann-Whitney U-test was run to determine differences in the objective measurements between the groups of temporary satisfaction.

Further, following examples in literature (e.g. Du et al., 2015; Peng Xue et al., 2014), the Wilcoxon signed Rank test was used to test for differences within blocks for fall and winter. Furthermore, the measured apartments were further categorized into smoking and non-smoking apartments based on whether occupants smoked or allowed smoking indoors to explain the possible association with CO.

For the long term IAQ, to examine the weekly variation of the measured air quality, concentrations were grouped into two main categories: (a) weekdays and (b) weekend, to account for the different home living scenarios. Mean concentrations were averaged over the entire sampling period (i.e. two months) and the concentration measurements were conducted both in fall and in winter. Independent t-test was used to determine differences in the measured parameters between weekend and weekdays; and also between fall and winter seasons. Statistical significance was defined as $p < .05$. Thus, a p-value less than 0.05 indicated significant differences among the various groups

3.4.3 Correlations

Correlations are among the widely adopted statistical tools in IEQ research to evaluate any relationships among environmental parameters, satisfaction levels, and other related factors (see Du et al., 2015; Q. Li et al., 2013; P. Xue, Mak, & Ai, 2016; Peng Xue et al., 2014). Similarly, Spearman rank coefficient was calculated to investigate the relationship between environmental parameter feeling and IEQ satisfaction level. In this study, the environmental parameter feeling was occupants' responses with their environmental condition particularly during the measurement period. Further, relationship between environmental parameters and household characteristics (such as pet-keeping, number of occupants) was also tested using Spearman rank coefficient (see Pirie, 2004). Pearson correlation was used to test relationships between individual environmental parameters (e.g. temperature, RH) during the long-term measurement to understand how the parameters affect each other.

4 CHAPTER FOUR

ANAYLSIS AND DISCUSSION OF RESULTS OF SNAPSHOT EVALUATION

4.1 Introduction

This chapter presents the results of the data analysis analysis and a subsequent discussion of results obtained from the snapshot evaluations. Demographic data was analysed using descriptive statistics, while the dependent variables were analysed using descriptive statistics, correlations and tests of differences. The first section deals with the profile of the respondents, household characteristics, and building characteristics and their influence on the overall goal of research. Paper-based questionnaires were administered to only adults (i.e. occupants above 18 years of old). In all, twenty-two (22) participants completed the questionnaires with at least one person per household and 17 apartments were recruited in this study. The analyses of the results are based on these number of questionnaires retrieved and apartments environmentally monitored. Consequently, these formed the basis of the findings of this research.

4.2 Analysis of Demographic data

Block level characteristics of participants are summarised in Tables 4.1. The participants were predominantly female (14). The age range of the 22 participants was 18-50 years. Furthermore, in block A, most of the participants spent more than five hours per day at home and in block C the majority spent less than five hours per day at home. In block E, however, the participants spent more than 5-10 hours per day of their time at home. Despite these varying hours spent indoors in each block, the participants generally seem to spend reasonable (i.e. more than 10 hours) amount of time at home and thus interact with the indoor environment. Hence, their responses were deemed to be adequate representation of their indoor environment.

Table 4.1 Demographic Information

Item Description	Category	Block		
		A	C	E
Occupant characteristics				
Gender	Male	3	1	4
	Female	7	4	3
Age	18-30	5	3	4
	31-50	5	2	3
Average hours spent indoors at home	≤ 5 hrs	3	3	
	5-10 hrs	1	1	3
	10-15 hrs	3	1	3
	15-20	2		
	> 20 hrs	1		1
Housing characteristics				
Years of occupancy	< 1 year	2	1	1
	1-2 years	2	1	-
	3-5 years	1	1	4
Pet keeping	Yes	2	1	-
	No	3	2	5
Number of occupants	Minimum	2	3	2
	Maximum	6	7	8

The information on housing characteristics, reported by the head of each of the participated households, shows that in block A, C and E, occupants have stayed on average 1.6 years, 2 years and 3.3 years in their apartments, respectively. This meant that most of the occupants have experienced each season at least once making their value judgment of the indoor environment across the two seasons relevant. Consistent with the original intent of low-income housing (i.e. to make it affordable for low-income households), most of the households rented their apartment because of price affordability. In terms of activity, the dominant activities included sedentary (i.e. playing games, watching television) and low-intensity (such as cooking). Moreover, the average number of occupants in the studied apartments in blocks A, C and E was 4.25, 4.40 and 5.85 persons respectively. The maximum number of occupants in blocks C and block E were seven (7) and eight (8) per apartment. About three apartments had people per bedroom (PPB) to be more than two and these were found in blocks C and E. The average number of PPB in those apartments was 2.67. These were considered overcrowded. A room was considered overcrowded if it had a PPB of greater than 2 (Escobedo et al., 2014). There was overcrowding in some of the apartments since the average number of persons per the apartment was higher (> 1.5 times) than the initial design assumption of four persons per apartment as explained during the interview with the designers. The relative high number of occupants in some apartments could increase indoor CO_2 levels and contribute to elevated levels of airborne pollutants (Escobedo et al., 2014), particularly particulate matter (PM).

4.3 Evaluation of Indoor Environmental Quality

4.3.1 Indoor Air Quality

Carbon dioxide and carbon monoxide

The range of CO_2 concentrations in the measured apartments ranged from 533.54 ppm to 1409.11 ppm during the monitoring period in fall season. As showed in Figure 4.1, most households had mean range levels between 600-970 ppm; 800-1008 ppm; and 620-818 ppm in bedrooms one, two and living rooms respectively. The range of winter levels in bedrooms one, two and living rooms of most households were 600-970 ppm; 808-1008 ppm; and 620-818 ppm, respectively. During the measurement period, the number of people in the living room was about three more than the other locations as a result of the presence of the researcher and assistant, which was expected to increase the concentration of CO_2 in the living rooms. It seems more probable, therefore, that the lower levels in the living rooms were due to their large size relative (i.e. about 15 m^2 more than) to the bedrooms and also the frequent opening of the living rooms' windows and control of heat recovery ventilators (HRV) which displace indoor air with outdoor air. This is consistent with earlier results (e.g. Q. Li et al., 2013) on the influence of any mechanism like window opening that increases ventilation rate which in turn reduces CO_2 concentration indoors. Concentration of CO_2 is mostly used as an indicator of ventilation and IAQ.

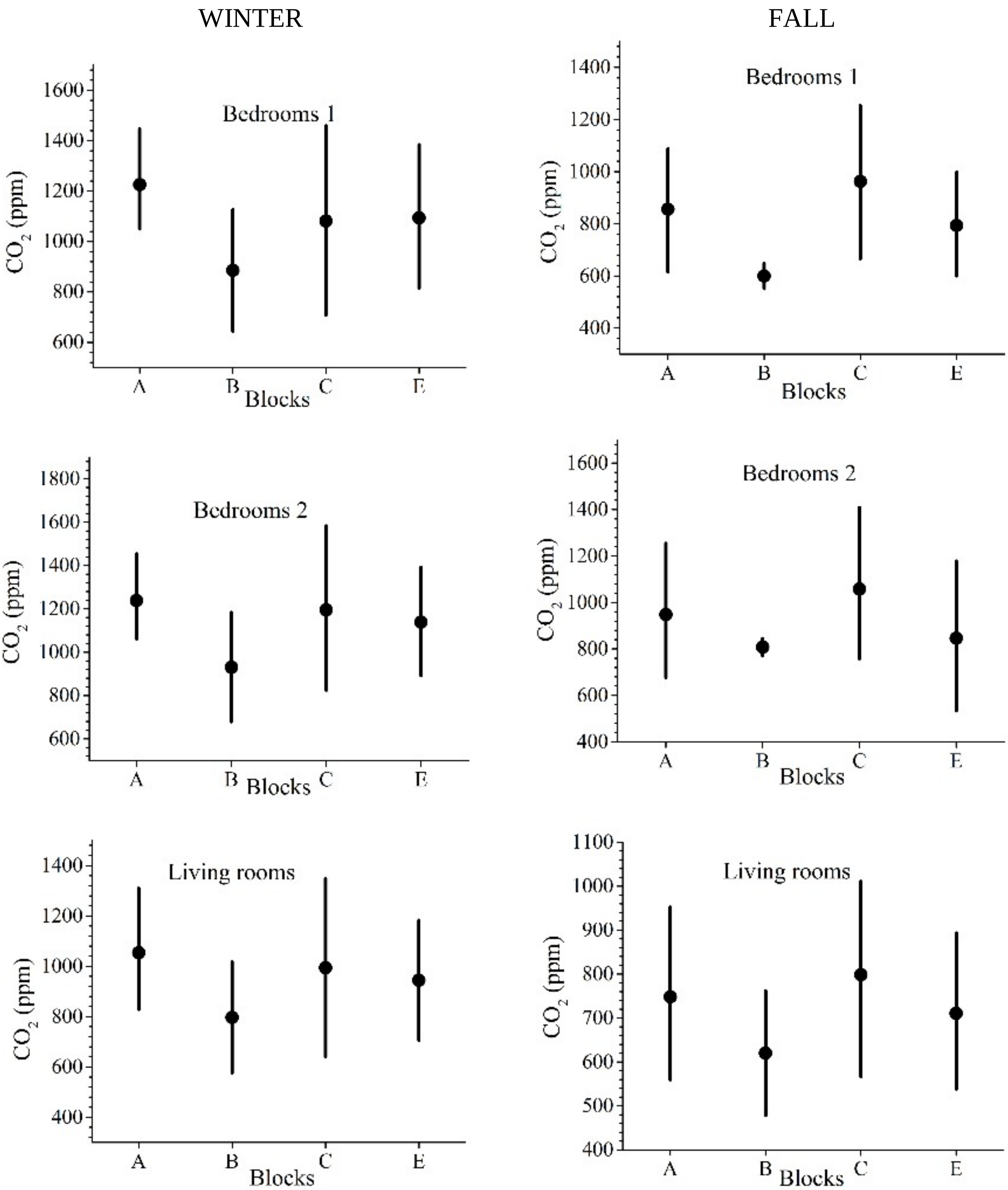

Fig. 4.1. Distributions of CO_2 in bedrooms 1 and 2 and living room during fall and winter seasons.

Furthermore, the results on seasonal differences in IAQ parameters among the blocks are presented Table 4.3. From the table, all the blocks except in block B showed a statistically significant ($p = 0.00$) mean increase in CO_2 in winter season compared to fall season. Block A showed a statistically mean difference of approximately 300 ppm (i.e. 1135 ppm – 836 ppm), $t = 4.53$, $p <.000$. In all the statistically significant blocks (i.e. A, C and E), the mean levels were above 1000 ppm in winter suggesting perhaps a problem with ventilation in winter. This is because, in scientific literature, CO_2 level above 1000 ppm remains the practical guideline value indicating good ventilation (McGill et al., 2015; Rojas et al., 2015a). This further suggests a somewhat poorer indoor environment during the winter as measured by conventional metrics using CO_2. Notwithstanding, these results are consistent with findings in literature (e.g. McGill et al., 2015; Rojas et al., 2015a) on the seasonal variation of indoor pollutant levels, particularly CO_2. More so, the winter results are also similar to a previous study in green residential building in Sweden by Langer et al. (2015) that also reported concentration above 1000 ppm for most of the investigated buildings. Typically, occupants and cooking represent the main sources of indoor CO_2 (Noris et al., 2013). In this current study, the differences in levels between the seasons can be possibly explained by occupancy pattern (i.e. high amount of time spent indoors) and window opening behaviour. During the fall as recorded on the observation sheet during the measurement period, windows were fully or partially opened to introduce fresh air. Also, the number of people present during the winter measurement period was higher (about 3 persons more) compared to the number of people in the apartments in fall season. All these perhaps accounted for the increase in levels during winter. Although block B also recorded almost 200 ppm increase in CO_2 in winter levels compared to fall levels, the result was not statistically significant. This may be because of the smaller number (in terms of sample) of apartments in block B (i.e. 2 apartments). Fall CO_2 levels in block C was about 100 ppm more than the other blocks. The probable explanation might be as a result of the cooking during the measurement period in two households in block C during the fall season compared to the other blocks; and overcrowding as earlier highlighted. Contrary to expectation that blocks with higher occupants will translate into higher concentration of CO_2, block A with less average number of occupants (i.e. 4 persons) recorded highest average levels of CO_2 particularly in winter (1135 ppm). More so, the number of people present during the measurement period might have also accounted for this. During the fall, the number of persons was at least six (about two more than in other blocks), therefore adding to the CO_2 levels. Although at these levels CO_2 is not noted to pose any serious health risks, it is a major indicator of adequacy of ventilation.

Concerning CO, mean winter levels were for the most part marginally higher than levels in the fall in all spaces of all households. All blocks except for block B recorded levels above 1.00 ppm in the winter and for most of the fall. Regarding to spatial levels, the range of mean levels in the fall in bedrooms one, bedrooms two and the living rooms with corresponding winter levels in parentheses were 0.72-1.17 ppm (0.96-1.59 ppm), 0.87-1.15 ppm (0.69-1.38 ppm) and 0.80-1.15 ppm (0.84-1.94 ppm), respectively. This is also showed in Figure 4.2. Peak levels throughout the measurement period were less than the recommended national indoor concentration level of 28.6 $\mu g/m^3$ (25 ppm) for 1-hour averaging time. Considering that indoor CO was collected for only 15 minutes, all readings were well below 28.6 $\mu g/m^3$. This result is particularly not surprising as there were no obvious possible indoor sources of CO. However, previous studies have attributed levels of CO usually to indoor smoking (Q. Li et al., 2013). The mean values were .84 ppm and 1.02 ppm in apartments with smokers and apartments without smokers, respectively. To corroborate this result, a Mann-Whitney U-test was run to determine differences between these categories of apartments. The results revealed no statistically significant difference in CO levels between these apartments. This indicates that indoor smoking was not perhaps the leading source of CO in these measured apartments. The result is not particularly surprising since indoor smoking is not allowed indoors. The only probable source may be outdoor – automobile exhaust from very close medium traffic road, railway and industrial buildings.

Table 4.3. Wilcoxon-signed rank test of indoor air quality environmental parameters

		A				B				C				E			
		Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p
TVOC ($\mu g/m^3$)	Winter	954	329	1.50	.15	918	112	1.53	.19	847	93	-1.77	.10	1047	300	3.42	.00
	Fall	810	298			715	235			1399	1113			866	234		
CO_2 (ppm)	Winter	1135	168			871	268			1083	293	5.77		1052	210		
	Fall	836	193	4.53	.00	676	142	1.95	.11	931	242		.00	797	184	3.42	.00
$PM_{2.5}$ ($\mu g/m^3$)	Winter	3.03	1.53			4.34	0.94			1.72	0.86			2.63	2.74		
	Fall	7.28	5.61	-3.58	.00	5.45	1.98	- 1.27	.26	3.42	1.36	-3.19	.01	4.51	1.83	-1.70	.04
CO (ppm)	Winter	1.59	0.52	2.46	.03	0.83	0.25	.26	.81	1.61	0.67	2.78	.02	1.43	0.41	3.07	.01
	Fall	1.15	0.42			0.80	0.10			0.97	0.20			1.08	0.40		
PM_{10} ($\mu g/m^3$)	Winter	12.73	5.50			15.07	7.04			10.96	8.78			14.98	14.20		
	Fall	21.20	21.43	-1.54	.14	17.11	7.25	-.67	.54	17.14	8.04	-1.48	.17	16.62	10.04	-.29	.78

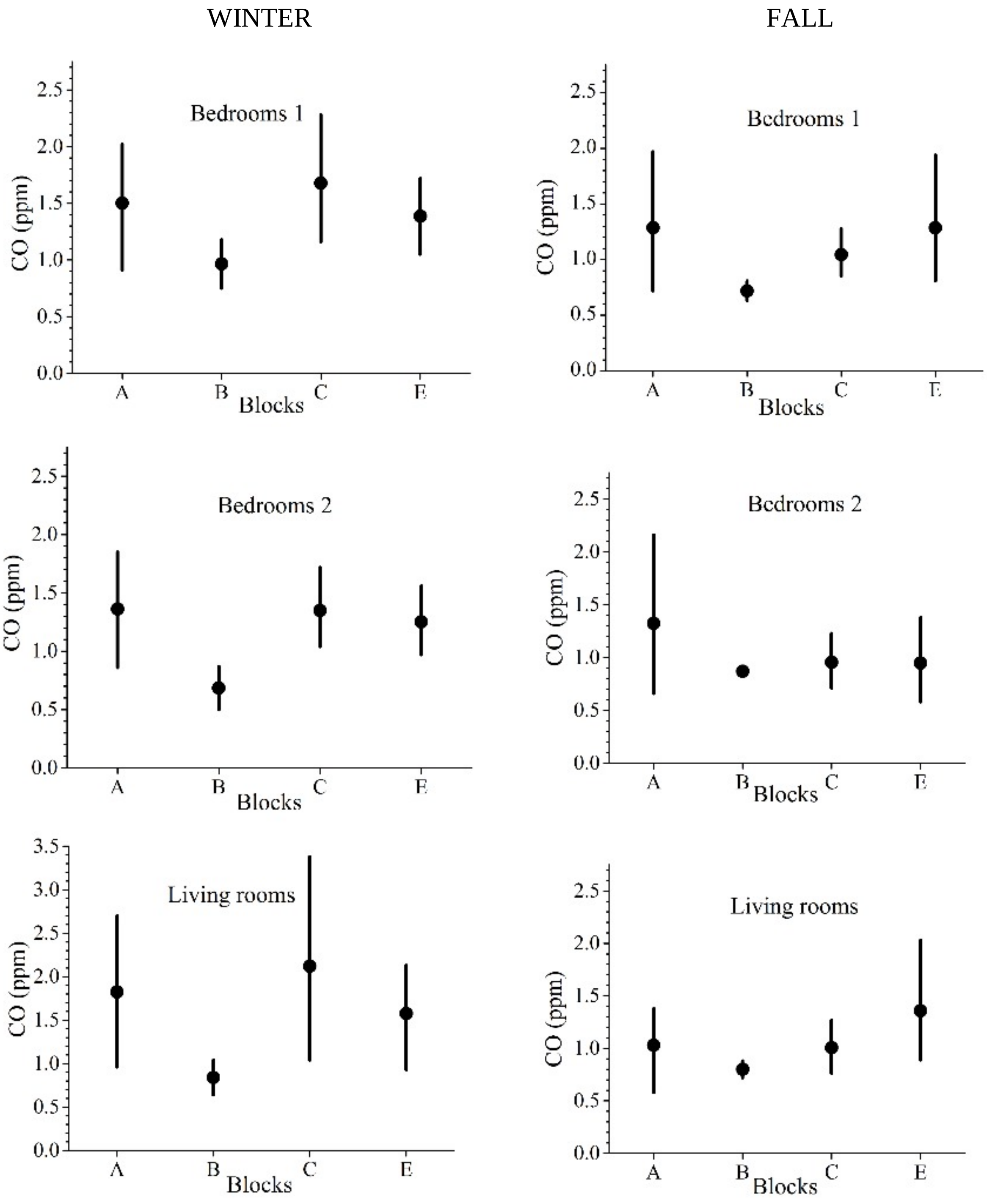

Fig. 4.2. Distributions of CO in bedrooms 1 and 2 and living room during fall and winter seasons.

The statistically significant differences in winter and fall levels of CO followed a similar pattern to CO_2. All blocks except for block B showed a statistically significant mean increase in winter levels compared to fall levels (Table 4.3). Of particular interest is block C, which recorded a mean increase more than the other blocks. In block C, there was a mean increase (0.63 ppm) in CO, when there was a change in season from fall (0.97 ppm) to winter (1.61 ppm), $t = 2.78$, $p < .02$. Further, as showed in the Table 4.3, the winter (0.83 ppm) and fall levels (0.80 ppm) were very close in block B, with almost no noticeable change. The findings of this study are similar to existing studies in literature on seasonal variation of CO (Chaloulakou & Mavroidis, 2002; Ni et al., 2016). Ni et al. (2016), for instance, found higher levels of CO in winter (1.33 ppm) than in summer (0.8 ppm). The significant differences between the seasonal concentrations and especially the marginal higher level in winter can probably be ascribed to the following reasons: 1) increase in commuting vehicles since harsh winter in Manitoba favours the use of vehicles, 2) to the different engine operating conditions, due to the lower winter temperatures (Chaloulakou & Mavroidis, 2002), and 3) meteorological conditions in winter that favour accumulation of pollutants.

Radon

The mean radon levels in measured apartments A1, A2, A3, A5, and A10 were 163.9 bq/m^3, 30.9 bq/m^3 (171.9 bq/m^3), 66.5 bq/m^3 (102.7 bq/m^3), 37.8 bq/m^3 (122.4 bq/m^3) and 31.4 bq/m^3 respectively. The values in parenthesis are corresponding winter levels. It is evident that winter levels are higher than fall levels. Only apartments A1 and A2 were found to have a slightly higher mean radon level than the reference exposure level of 148.0 bq/m^3 set by the New York State department of environmental conservation (2017). However, Health Canada (2014) indicates no remediation action is required for radon levels less than 200.0 bq/m^3. Given that the major source of radon is infiltration from the soil, it’s not clear why those differences in radon levels exist between the different apartments. This is because the houses are exposed to the same soil and weather conditions and use the same passive ventilation strategies. They are also of the same age, were built by the same contractor using the same methods; therefore, one house is unlikely to have considerably more cracks than others. Although physical observation of the measured apartments revealed no visible cracks in the basement, invisible cracks may explain the higher radon levels in apartment A1. Other environmental parameters (e.g. RH, indoor-outdoor temperature difference) may have also contributed to those higher radon levels; however, none of them were measured in the basement.

Total volatile organic compound (TVOC)

Similar trends to the ones observed with CO_2 concentration were also found with TVOC. TVOC was used as an indicator for indoor air VOCs because of the lack of consensus on the VOC to be sampled and the methods of sampling and analysis (Y. Xiong et al., 2015). Mean TVOC concentrations in the winter were marginally higher than in the fall (see Figure 4.3 and Table 4.3). During the winter season, TVOC concentrations ranged from 845 to 1047 $\mu g/m^3$, 805 to 960 $\mu g/m^3$, and 892 to 1134 $\mu g/m^3$ in bedrooms one, two and living rooms respectively. In the fall, the concentration levels were below 1000 $\mu g/m^3$ in most apartments. The maximum levels recorded in the living room, bedroom one and bedroom two of one of the apartments in block C were 3955.93 $\mu g/m^3$, 3055.64 $\mu g/m^3$ and 2460.07 $\mu g/m^3$ respectively. This incident could perhaps be explained by a strong presence of local sources (e.g. cleaning agents, fragrance) in fall as observed. Also, from the results in Table 4.3 what stood out was the concentrations in block C during the fall season which exceeded the corresponding winter levels by at least 200 $\mu g/m^3$. Consequently, block C reported a substantial decrease in TVOC concentration levels of 552 $\mu g/m^3$. Conversely, blocks A, B and E showed an increase in winter indoor TVOC levels from fall level of 144 $\mu g/m^3$, 203 $\mu g/m^3$, and 181 $\mu g/m^3$ respectively.

Aside the unusual seasonal levels in block C, the higher levels in winter is consistent with previous studies (Jiang et al., 2013; Langer et al., 2016). This seasonal pattern could be explained by two probable reasons. First, increased ventilation because of window opening in fall helps reduce indoor concentration of TVOC or perhaps due to inadequate local ventilation (Hormigos-Jimenez, Padilla-Marcos, Meiss, Gonzalez-Lezcano, & Feijó-Muñoz, 2017) in the apartments during winter. Second, outdoor sources such as mobile and industrial sources, the strengths of which are higher in winter can be a major contributor (Jiang et al., 2013). Additionally, although air exchange rate (AER) was not recorded in this study, the extreme low levels of air velocity and the ventilation commission values (< 2.5 ACH @50 pascals) implied tighter envelopes of the studied apartments and lower ventilation especially in the winter. This could lead to an increase in accumulation of pollutants primarily from indoor sources such as household and consumer products (e.g. cleaning agents, fragrance and nail polish). This in turn could be an explanation for a higher indoor TVOC from specific indoor sources being primarily active because of heating. This supports the assertion by Colton et al. (2014) that reduced AER increase air pollutants with indoor sources such as VOCs. In green homes like the ones reported in this study where paints, adhesives and other sealants are low VOC, the major indoor sources are most likely to be emitted from cleaning products and air fresheners (see Y. Xiong et al., 2015). The general relative low levels of TVOC, aside the unexpected level in one of the apartments in block C, may be ascribed to building materials such as sealants, paints, etc. that were low-emitting. Additionally, the levels reported in this were still within the Health Canada (2016) recommended benchmark of 200 to 30,000 μg/m^3 for a 15-min sampling time. Despite these seemingly differences, differences between the seasons proved statistically insignificant in all blocks, except block E. Block E recorded a mean increase (181 μg/m^3) in TVOC, when there was a change in season from fall (866 μg/m^3) to winter (1046 μg/m^3), $t = 3.415$, $p < .00$.

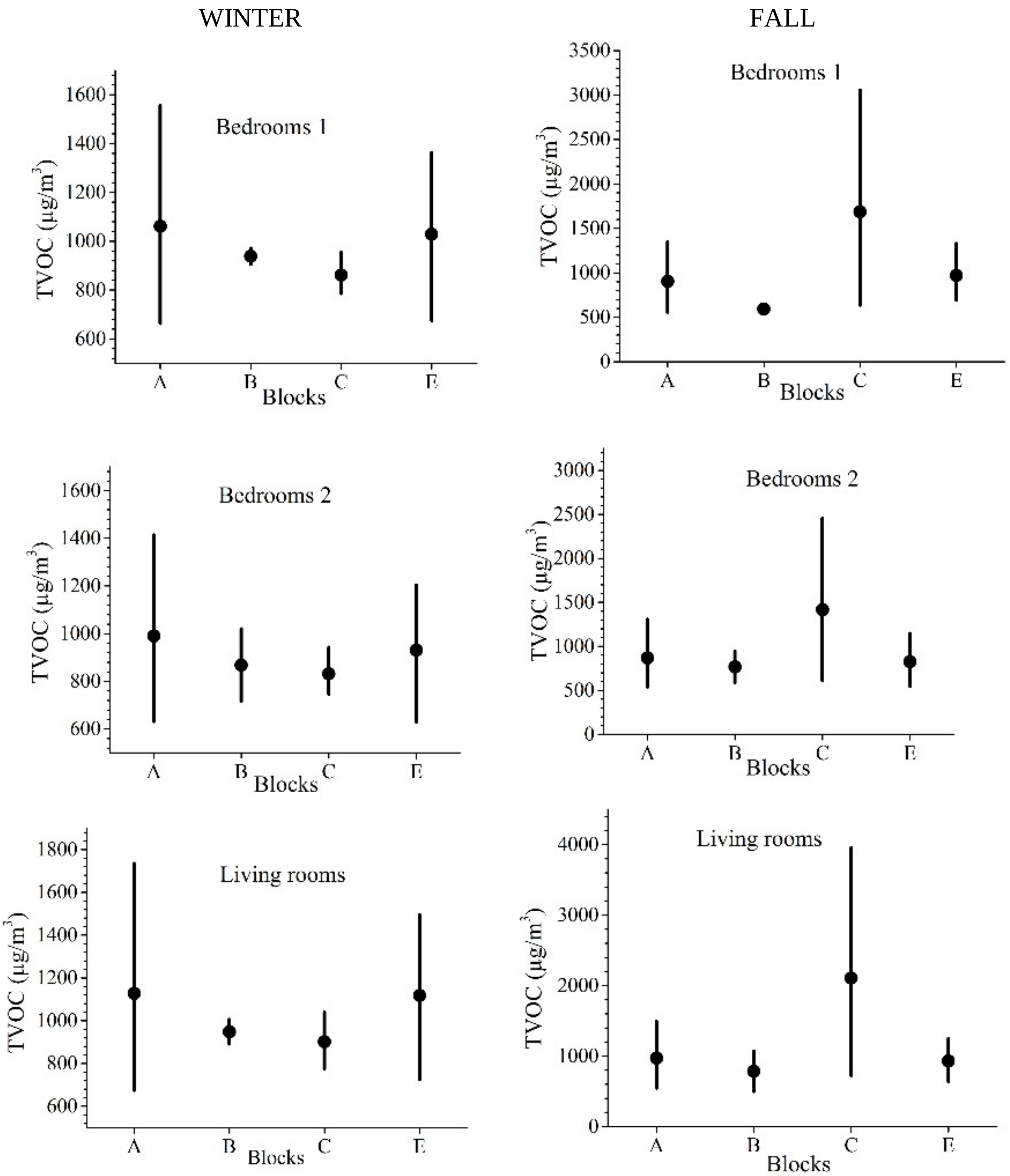

Fig. 4.3. Distributions of TVOC in bedrooms 1 and 2 and living room during fall and winter seasons.

PM_{10} and $PM_{2.5}$

The mean indoor $PM_{2.5}$ and PM_{10} concentrations measured throughout the study are shown in Figures 4.4 and 4.5 respectively Generally, maximum PM_{10} concentrations were marginally lower in the winter season (56 µg/m^3) compared to the fall season (84 µg/m^3). Similar results were observed in $PM_{2.5}$ except for bedrooms 2 in block A. During the fall, the mean levels of PM_{10} in bedrooms one, two and living rooms were 21.32 µg/m^3, 17.50 µg/m^3 and 18.64 µg/m^3, respectively. The maximum PM_{10} concentrations in the fall were 86.37, 56.18 and 30.09 µg/m^3 in bedrooms one, two and living rooms respectively. For $PM_{2.5}$, maximum concentration increased from bedroom 1 to living room. The levels of $PM_{2.5}$ were in bedrooms 1 (i.e. 12.321 µg/m^3), 2 (i.e. 16.272 µg/m^3) and the living rooms (i.e. 23.146 µg/m^3). Differences in PM_{10} observed within spaces of the same apartment (about 15 µg/m^3) were marginally lower than differences between different apartments (40 µg/m^3). On the contrary, there was less variation in $PM_{2.5}$ within different spaces of the same apartment and also between different apartments (refer to Fig 4.4). The differences in PM_{10} between apartments could be explained by two probable reasons, partly because of socio-economic variation such as occupant density, human activities; and partly because of the technical performance of ventilation systems. For instance, the elevated levels of PM_{10} (86.37 µg/m^3) in one of the apartments in block A could be due to the temporal shut down of ventilation system since the apartment was uninhabited during the monitoring period. It is noteworthy to indicate the possibility of potential outdoor sources (such as medium traffic roads, nearby industrial buildings) of PM_{10}; however, outdoor concentrations were not measured. More so, in the survey, occupants indicated more than one IAQ problem that bothered them during the physical measurement. Common to all the IAQ problems in all the apartments as showed in occupants's response (i.e. 72%) was dust. Notwithstanding, the measured levels of PM were within recommended levels required by standards and levels recorded in previous studies in literature for green houses (Colton et al., 2014) and conventional houses (Brown et al., 2015; Du et al., 2015; Escobedo et al., 2014).

In both $PM_{2.5}$ and PM_{10} concentrations, mean levels in winter decreased compared to fall levels (see Table 4.3). The decrease in levels was as high as 4.25 $\mu g/m^3$ and 8.47 $\mu g/m^3$ in $PM_{2.5}$ and PM_{10}, respectively; and as low as 1.10 $\mu g/m^3$ and 1.64 $\mu g/m^3$. Also, whereas statistically significant differences in levels of $PM_{2.5}$ between seasons were reported in three blocks (i.e. A, C and E), differences in PM_{10} showed no statistical significance. In block A, for instance, there was a mean decrease (-4.25 $\mu g/m^3$) in $PM_{2.5}$ when there was a change in season from fall (7.28 $\mu g/m^3$) to winter (3.03 $\mu g/m^3$), $t= -3.58$, $p <.000$. The result on seasonal variation of particulate in this study is contrary to some studies (e.g. Carter et al., 2016; Langer et al., 2016; Ni et al., 2016) that document higher levels of particulates in the heating season compared to other seasons. For example, in China, Carter et al. (2016) found significantly higher levels of particle content during the winter season, with winter elevated levels as twice as summer levels. Also, Langer et al. (2016) reported higher levels of particulates in French dwellings during the heating season. Although outdoor sources were not measured but they appeared to have influenced the relative higher levels of PM in fall season compared to winter. This result supports previous knowledge on the impact of outdoor air pollution on personal indoor exposure (Coombs et al., 2016). In this study, the results seem to suggest outdoor sources predominantly had influence on indoor levels. This is consistent with (Burgos et al., 2013; Ni et al., 2016) who found outdoor sources to be a major predictor of indoor $PM_{2.5}$. Window and door openings are likely to be the major routes of particle transportation to indoor. This behaviour is most common in the non-heating seasons such as fall making likely outdoor particulate infiltration more pronounced during the season. Also, major roadways were less than 500 m from the apartments making transportation of particles from roadways and vehicles a possible explanation for the slight decrease in winter levels since study participants closed their windows and doors.

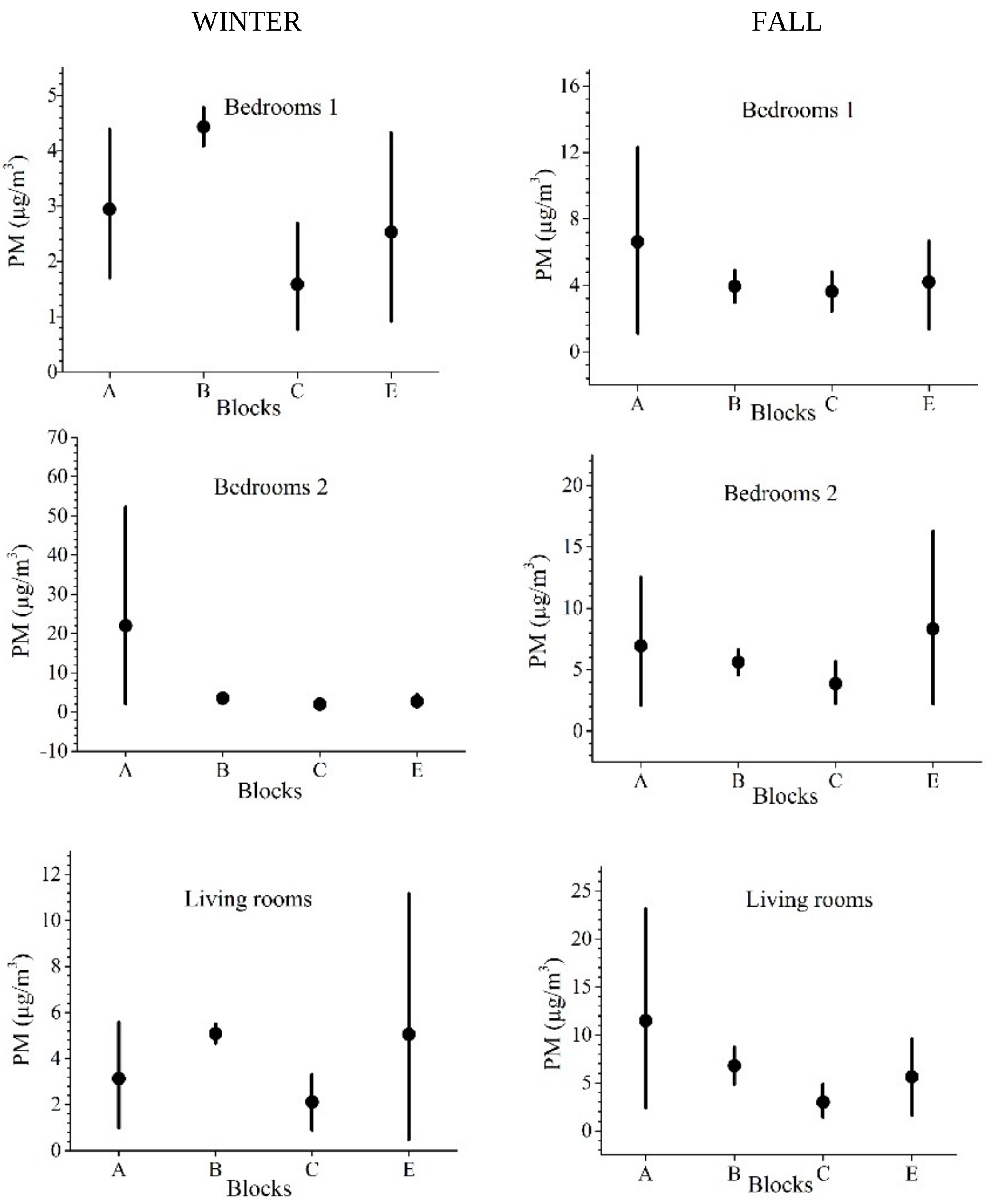

Fig. 4.4. Distributions of $PM_{2.5}$ in bedrooms one and two and living room during fall and winter seasons.

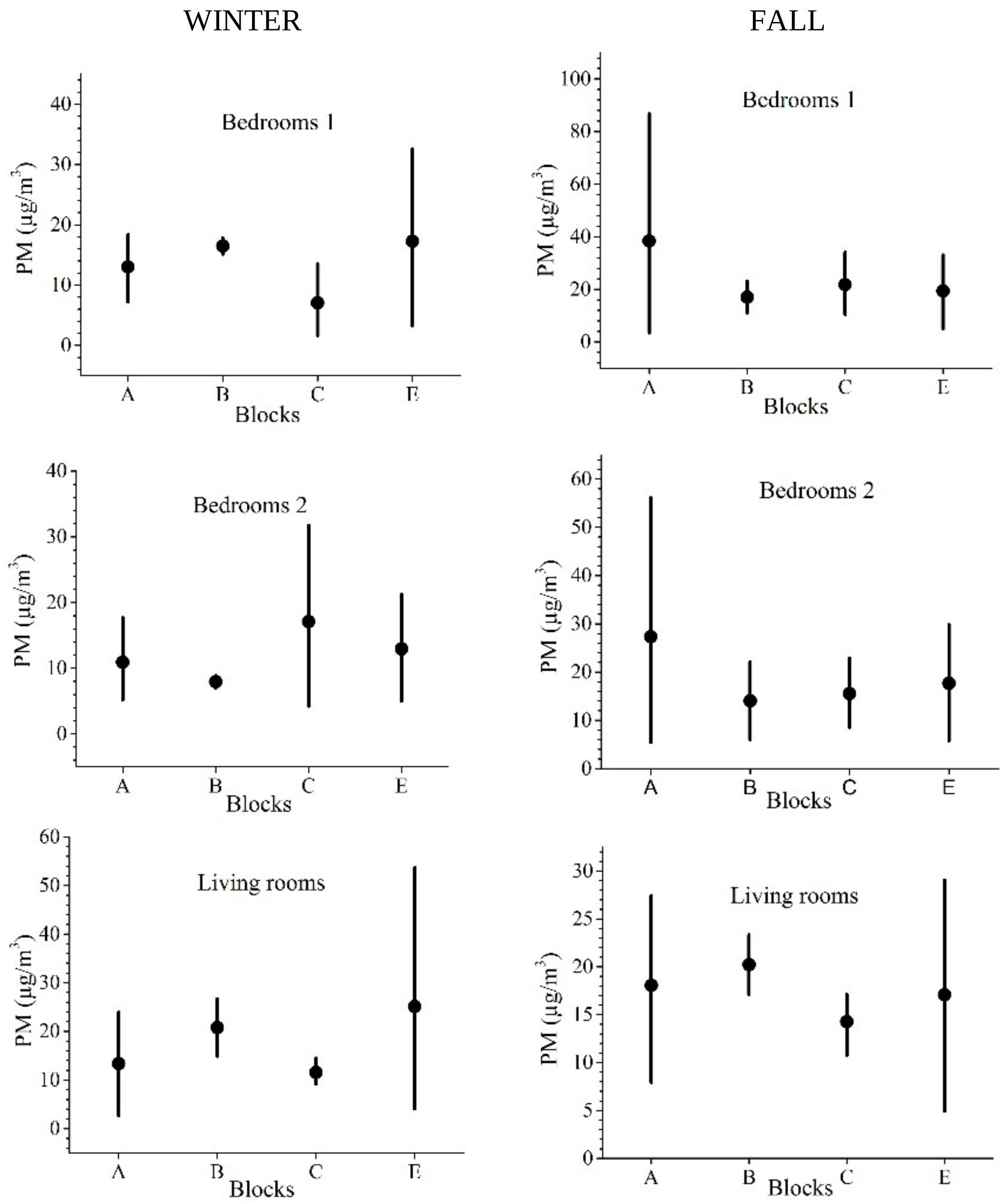

Fig. 4.5. Distributions of PM_{10} in bedrooms one and two and living room during fall and winter seasons.

4.3.2 Thermal Comfort

Temperature

As showed in Figure 4.6, average fall temperatures ranged from 22^{o}C-23^{o}C, 22^{o}C-23^{o}C and 22^{o}C-24 ^{o}C in bedrooms one, two and the living rooms respectively. Mean winter temperatures ranged from 22 ^{o}C-23 ^{o}C; 21 ^{o}C-22 ^{o}C; and 21 ^{o}C-22 ^{o}C in bedrooms one, two and the living rooms respectively. Peak fall indoor temperature was observed to be above 25 ^{o}C in one of the apartments in block C, whereas the minimum winter temperature was below 18 ^{o}C in one of the apartments in block A. These results reported in this current study were superior to the indoor environment of investigated green and conventional low-income buildings reported in literature (Haaland et al., 2016; McGill et al., 2015; Paravantis & Santamouris, 2016). These studies reported over-heating in non-heating seasons and some homes recorded lower temperatures. For example, Paravantis and Santamouris (2016) reported temperature as low as 5 ^{o}C in their study. Generally, measured indoor temperatures in the winter in bedrooms one of block A were marginally higher than in the fall; but for the remaining blocks, the mean levels in the fall season were higher. It is also important to note that outside temperature in the fall and winter ranged from 8 to 20^{o}C and 1 ^{o}C to -40 ^{o}C (including wind-chill), respectively during the investigation period. It is recognised that outside temperature also influenced the indoor thermal parameters. Indeed, Du et al. (2015) argued that in snapshot measurement like this study, the interpretation of indoor thermal parameters must be done in tandem with the outdoor thermal conditions such as prevailing temperature, humidity, and solar loads which are the basis of a building’s indoor temperature.

Other factors unrelated to building characteristics such as personal preferences, activity level also influence thermal environment (Frontczak et al., 2012), particularly the operation of thermostatic device and control of indoor micro climate. Typically, in residential buildings, thermal comfort requirements may change based on the level of activities in the different rooms which is influenced by the varying uses of the individual spaces e.g. cooking. Despite these varying thermal requirements, indoor thermal parameters were similar across different spaces (i.e. bedrooms and living room) in this study perhaps because of the operational mechanism of the thermostat that centrally regulates indoor temperature of the apartment from a single location.

Moreover, measured temperatures in about 95% of the apartments were within the recommended levels (i.e. 18.0-24.0 ^{o}C) (McGill et al., 2015) for a satisfactory thermal environment. However, an unexpected high temperature (i.e. about 26^{o}C) was recorded in one of the apartments of block C, which is suspected of some individual preferences or a lack of understanding on thermostat controls. This is confirmed by the record on the observation sheet. The thermostat set-point (or heating set-point) was higher (i.e. about 26 ^{o}C) in one of the apartments in Block C maybe because of occupants' preference of a relatively warmer environment especially in the living room where significant amount of their time was spent. Although the majority of occupants indicated sufficient knowledge in usability of controls, limited knowledge in their ability to control their indoor environment using thermostat control cannot be ruled out as a probable cause of this extreme temperature since subsequent interaction revealed that only the husband knew how to effectively operate the thermostat. The observed higher temperature existed for only the fall season, which means occupants had a limited knowledge on the thermostat controls. Also, a consistent thermal problem in most IEQ studies in green residential buildings is cold floors and cold indoor environment particularly in winter (Alborz & Berardi, 2015; Zalejska-Jonsson, 2012, 2014). These studies in literature reported typical indoor temperature between 16 ^{o}C and 20 ^{o}C, while in this study the mean indoor temperature level in winter was 22 ^{o}C indicating an efficient building envelope. It was therefore not surprising that complaints about cold floor and cold indoor environment did not seem to be a major cause of thermal discomfort in this study. On average, the survey occupants did not have serious problem (i.e. thermal discomfort) with their thermal environment. The mean frequency of the sources of problem were all above 3.5 indicating rare occurrences. Nonetheless, occupants' feedback through survey indicated there were complaints about drafts through underside of living room doors in about two of the apartments during the winter.

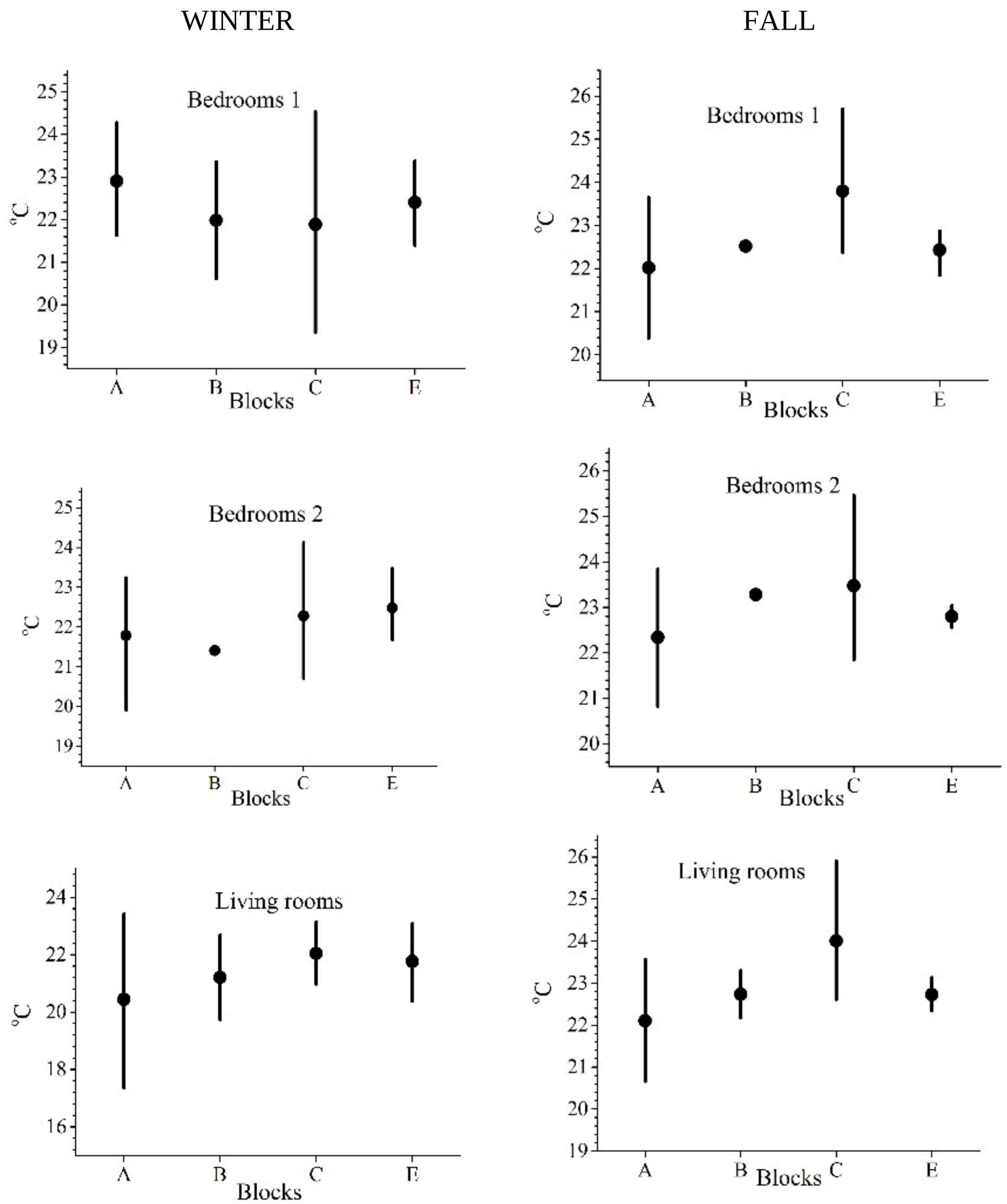

Fig. 4.6. Distributions of temperature in bedrooms one and two and living room during fall and winter seasons.

Table 4.4 shows the observed differences in thermal environmental parameters between the fall and winter seasons across the four blocks. A statistically significant mean decrease in temperature (-1.31 ^{o}C) in block B in the winter season (21.54 ^{o}C) compared to the fall season (22.85 ^{o}C), t= -2.720, p < .05 was observed. Similarly, in block C the decrease in temperature between the winter and fall seasons was -1.67 ^{o}C, t= -5.989, p < .000. The other blocks showed no statistically significant differences in temperature between the seasons. Occupant characteristics (e.g. personal preferences and behavioural patterns) and obvious differences in outdoor conditions such as temperature, RH (Liu, Wu, Li, Cheng, & Yao, 2017) may explain these differences between the two seasons. For example, outdoor temperature during the measurement of most of the apartments in blocks C and E occurred between period of very low temperatures (i.e. about -38^{o}C plus wind chill) which certainly had influence on indoor temperature. Also, apartments appeared to receive different levels of solar loads because of their orientation and the shading devices used in them, which may explain the seemingly subtle inconsistent thermal environment in the winter and fall. Block C, oriented north-south appeared to receive high solar load at the north facing walls (location of windows) in the winter; whereas solar intensity was more pronounce in the east and west facades of blocks A, B and C during the fall season. Furthermore, windows are also located in the east façade of block B allowing transfer of heat within the space. This perhaps explains the significant differences between seasons in these two blocks. Further, nominal infiltration of cold wind (i.e. draft) through the underside of living rooms observed during the measurement period in the winter could also influence these differences. Additionally, the thermal conditions in each apartment seemed to vary in response to occupancy factors such as HRV and thermostats and the level of control over the indoor micro climate (cooling and heating patterns). This is consistent with studies in literature (e.g. Peretti et al., 2015) that assert indoor temperature is related to thermostat setpoint influenced by individual preferences. For instance, the thermostat set-point was higher in some of the apartments in Block C because of occupants' preference of a relatively warmer environment especially in the living rooms where significant amount of time was spent. In most low-income housing, thermostat set-points is usually a trade-off between comfort and cost (Peretti et al., 2015). In this study, it was purely because of comfort since occupants were not responsible for heating and cooling bills. Beside occupants having direct control over their indoor environment, another consistent observation throughout most apartments in this study was the presence of portable fans to provide additional comfort perhaps during the cooling season.

Table 4.4. Wilcoxon-signed rank test of thermal environmental parameters

		A				B				C				E			
		Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p
RH (%)	Winter	24.25	4.34	-16.37	.00	20.33	7.58	-7.89	.01	24.24	7.91	-6.83	.00	23.07	4.22	-26.38	.00
	Fall	49.94	5.89			41.46	1.31			40.97	5.90			44.50	6.43		
AV (m/s)	Winter	0.00	0.01	-0.21	.83	0.01	0.01	1.58	.18	0.02	0.05	1.40	.19	0.03	0.10	1.209	.25
	Fall	0.00	0.01			0.00	0.00			0.00	0.00			0.01	0.02		
Temperature (^oC)	Winter	21.86	1.77	-.66	.52	21.54	1.33	-2.72	.04	21.93	1.70	-5.99	.00	22.19	1.03	-1.84	.10
	Fall	22.15	1.12			22.85	0.50			23.60	1.57			22.87	0.16		

Relative Humidity

Indoor RH varied largely between the two seasons. Indoor mean RH in bedrooms one, two and living rooms during the fall season ranged from 40% to 49%, 40% to 48%, and 41% to 53% respectively (refer Figure 4.7). Conversely, mean winter RH ranged from 20% to 23%, 20% to 24%, 21% to 27% in bedrooms one, two and the living rooms successively. Block B had the minimum winter RH of 13% whereas minimum RH in the fall was observed in block C. The results were comparable to a similar green social housing by Rojas et al. (2015a) . In their study they reported similarly lower levels of RH (between 20% and 40%) in the winter period in all the investigated apartments. RH levels in block A were around the acceptable range for occupant comfort (i.e. 50%) in the fall season. Generally, 30%-60% is the recommended RH range (Y. Xiong et al., 2015). RH below 30% may lead to increased occupant discomfort such as stuffy nose, eye irritation, and drying of skin, while high RH levels imply saturation which may promote mould and fungi growth and also sweating and thus also cause discomfort (Langer et al., 2015). In winter, RH levels were below 30% for almost all measured apartments. In Canada, specifically cold provinces such as Manitoba, it is not surprising to have RH adjustments to levels below 30% partly because of issues related to condensation and mold growth. Air velocity results are not reported due to the recorded low values (.0 to .1 m/s).

Unlike temperature, the four blocks reported a statistically significant difference in the fall and winter RH levels (see Table 4.3). The differences in RH between the two seasons supported the findings on seasonal variations by McGill et al. (2015) and Rojas et al. (2015a). The widest difference was observed in block A, whereas the lowest difference was observed in block C. There appears to be similarity in RH levels across the various blocks of apartment. In block A, there was a mean decrease (-25.7%) in RH, when there was a change in season from fall (49.94%) to winter (24.25%), $t = -16.73$, $p < .000$. The probable reason is because occupants set their thermostat-set point at “cool” in many investigated apartments in block A and outdoor precipitation level, as recorded on the field observation sheet, was about 1 mm during investigation of one of the apartments and probably influenced indoor RH.

WINTER FALL

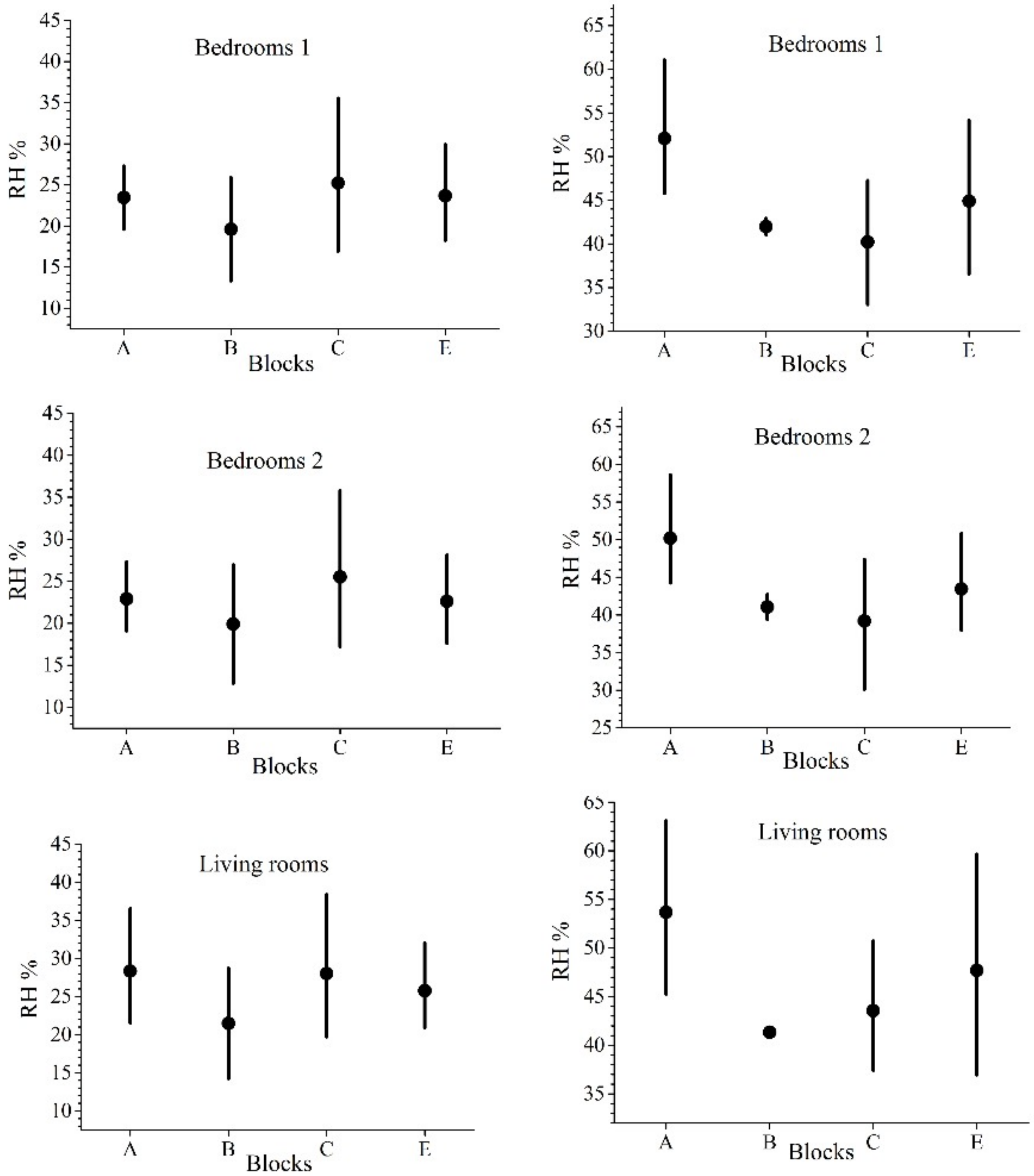

Fig. 4.7. Distributions of RH in bedrooms one and two and living room during fall and winter seasons.

4.3.3 Lighting Comfort

Mean daylight factors (DF) for bedrooms one, two and the living rooms in the fall season ranged from 2.03% to 5.14%, 1.29% to 6.61%, and 2.28% to 7.08% respectively. Similarly, the corresponding mean winter DF ranged from 1.05% to 9.53%, 0.94% to 4.18%, and 3.34% to 8.74% in bedrooms one, two and the living rooms respectively. Generally, daylight levels in fall were lower (about 30-100 lux) than in winter despite no statistically significant differences. However, as can be seen in the Table 4.5, the standard deviation (SD) were higher than or close to mean values indicating variation in lighting levels between apartments for reasons related to time of the day the measurement took place. Additionally, the levels of daylight differed among blocks and among the different spaces, particularly in winter season. However, in general the average daylight levels appeared adequate i.e. within the 150 lux recommended by Li et al. (2016) for residential buildings except for block C in both seasons. Moreover, the mean of daylight illuminance levels of blocks A, B, C, and E in the fall ranged from 148 to 410 lux, 148 to 260 lux, 146 to 210 lux, and 120 to 200 lux respectively. In the winter, mean daylight levels reported were relatively lower except for bedroom two of block A, which was 1107 lux, perhaps because of factors such as outdoor illuminance, lack of obstruction and orientation. Mean levels ranged from 70.84 to 1107.7 lux, 144.58 to 599.87 lux, 66.67 to 112.75 lux, and 71.77 to 158.51 lux for blocks A, B, C and E respectively in winter. Relative high electric illuminance levels were observed in block A in fall season, with highest value in bedroom two i.e. 2734 lux. This is more related to the time of the day since most of these apartments the measurement took place at sundown when occupants had turned on their electric lights.

The most obvious finding to emerge from the analysis is that illuminance levels for both daylight and electric light are different within blocks and between measurement periods. Time of measurement, shading or obstruction and prevailing weather condition influenced to a greater degree illuminance level in measured blocks (D. H. W. Li et al., 2006; Peng Xue et al., 2014). At the same time, orientation of the measured blocks also influenced the penetration of daylight illuminance. For instance, block A with no sky or external obstruction on the indoor daylighting level appeared to have higher levels of illuminance (winter = 446 lux; fall = 161 lux). Other blocks experience more sky obstruction (i.e. trees, presence of obstruction blocks) than block A. Without external obstructions these blocks will enjoy a certain amount of daylight. Also, some apartments in block C and E were investigated almost around sundown also accounting for relative lower levels of daylight. For instance, the weather was foggy and partly cloudy when conducting the physical measurements in apartment A14 (one of the apartments in block C), which may explain its low mean daylight values in the living room (i.e. 12.32 lux), bedroom 1 (i.e. 98.6 lux) and bedroom 2 (i.e. 14.21 lux). However, the measure of illumination as based on mean DFs shows adequacy of the amount of lighting in space. Recommended levels of DFs in homes are at least 1% and 1.5% in bedrooms and living rooms respectively (D. H. W. Li et al., 2006). At these levels, occupants will not have to rely on electric lighting for most part of the cooling season. The highest daylight level in the living rooms may be due to the size and number of windows allowing more light into the space, resulting very high DF in the living rooms. Bedrooms one and two are at level above external obstruction to be able to receive much daylight. However, the location of the windows of bedrooms one was north side of blocks A and B resulting in the lowest levels of daylight (less than 200 lux). It is worth noting that measured apartments (about 2 number in block E) with low electric illuminance level (i.e. mean 134 lux) somewhat had fixtures with low intensity or no fixtures in some of the measured spaces (e.g. bedroom one and living rooms) during fall season. Notwithstanding, these results were in general similar to the few IEQ studies that have reported on lighting in the literature (D. H. W. Li et al., 2006; Q. Li et al., 2013).

Table 4.5. Wilcoxon-signed rank test of lighting environmental parameters

		A				B				C				E			
		Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p
Electric (lux)	Winter	365	857	0.72	.48	173	113	-.78	.47	159	75	.10	.92	162	185	.45	.66
	Fall	311	647			231	127			154	126			134	100		
Daylight (lux)	Winter	446	1420	.86	.40	311	333	.52	.62	89	81	-.57	.58	105	168	.16	.88
	Fall	161	271			219	145			117	146			95	103		

Table 4.6. Wilcoxon-signed rank test of acoustic environmental parameters

		A				B				C				E			
		Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p	Mean	SD	t	p
Background noise (dBA)	Winter	43	9	1.18	.02	34	8	-1.68	.25	34	8	-2.81	.00	35	5	-3.22	.00
	Fall	39	10			40	6			41	6			42	12		

4.3.4 Acoustic comfort

Background noise

As shown in Figure 4.8, the mean ranges of A-weighted background noise levels in fall were from 32.06 dB to 44.20 dB, 34.60 dB to 45.00 dB, and 41.50 dB to 58.67 dB in bedrooms one, two and the living rooms respectively. Similarly, during winter, the mean ranges of A-weighted background noise level were from 27.95 dB to 45.73 dB, 29.65 dB to 45.13 dB, and 41.65 dB to 48.10 dB in bedrooms one, two and the living rooms respectively. Generally, the background noise levels were below levels that will make people sick i.e. 55 dBA (H. Xie, Baizhan, & Jie, 2006). However, the results showed that background noise in the various spaces appeared to be unacceptable and the mean values were slightly above recommended levels for residential buildings (i.e. 30-35 dBA) (Engineering ToolBox, 2004a). The implication is that the apartments do not appear to provide the adequate noise environment conducive for residential buildings. Although these levels appeared not acceptable, it is significant to highlight that the levels recorded in this study were lower than existing studies in literature on low-income housing and other type of housing (e.g. Lai et al., 2009; S. H. Park et al., 2017; Ribeiro, Kortchmar, & Slama, 2001). Lai et al. (2009) reported average 67 – 78 dBA equivalent sound pressure level (SPL). Similarly, Ribeiro et al. (2001) reported indoor noise levels range 54.5 – 56.6 dBA. Additionally, a consistent observation in both the winter and fall seasons is elevated levels of background noise in the living rooms. For most part, it was about 4.0 dBA higher than the bedrooms perhaps because of reasons related to noise from refrigerators since they were not switched off during the measurement period and also the impact of traffic noise was also more pronounced in living rooms because of the large windows. This finding is consistent with a previous study that showed that refrigerator noise were more pronounced in a living room area compared to other spaces in an apartment (Jeon et al., 2007).

The present study also reported that the disturbing noise sources from the survey results were ‘vehicle noise from street including snowplough’ (2.75), and ‘speech, laughter, TV or music from neighbour’ (3.00). This finding is in agreement with previous studies on green residential buildings (Zalejska-Jonsson, 2014) and conventional residential buildings (Lai et al., 2009; Y. S. Wang, Guo, Feng, Ju, & Wang, 2017). This is particularly not surprising for attached dwellings or apartments where neighbourhood noise is predominant. Lai et al. (2009) found traffic noise and noises from neighbourhood activities as typical sources of unsatisfactory indoor acoustic environmental quality. In this study, the highly rated disturbance level from traffic sources and neighbourhood activities is probably because of the intrinsic characteristics of the building, mainly due to the sound attenuation properties of the walls, which is explored in the next section. Noise from plumbing HVAC and fans sources was considered slightly neutrally disturbing (i.e. mean = 3.5). This finding is inconsistent with studies on green residential that identified noise from HVAC and fans as a major acoustic problem in green residential houses (Zalejska-Jonsson, 2012, 2014). This could be due to the dwellings in this study having small size ventilation systems that generate low noise levels. Pertaining to noise from plumbing systems, some of the occupants expressed concerns that sound easily travels from toilets or flushing toilets generated loud disturbing noise. This is coincident with a previous study that noted occupants’ perception of flushing toilets as annoying (C. Wang et al., 2015).

Aside block A, all other blocks reported a reduction (about 6 dBA) in A-weighted BN levels in winter compared to fall (see Table 4.6). Blocks A, C and E showed statistically significant differences in background noise levels between winter and fall levels. The Wilcoxon signed-rank test determined that there was a statistically significant mean increase in BN level (4 dBA) in block A in winter season (43 dBA) compared to fall season (39 dBA), $t = 1.18$, $p < .02$. The only probable explanation to this converse result in block A compared to the other blocks may be because of the closeness to the highway compared to the other blocks.

Apparent transmission loss and Apparent sound transmission class

Sound insulation properties of the partition wall between the bedrooms were tested using apparent transmission loss (ATL). The mean apparent sound transmission classes (ASTC) of the investigated blocks in the fall and winter were 35 (35), 36 (29), 34 (32) and 34 (34) for A, B, C and E respectively. The values in parentheses represent the winter ASTC. Further, ASTC of the partition between the bedrooms of the individual apartments were determined to be between 26 and 41. No individual deficiency in any frequency band was more than 8 dB below the reference contour and the sum of the deficiencies was also less than 32 dB. More so, a significant proportion of the apartments were above ASTC 35; hence, which implies that loud speech will be heard but not understood (Engineering ToolBox, 2004a). Given the range of the ASTC in this study, traffic noise and home music systems would still be a potential problem. Moreover, the assigned noise criterion (i.e. N.C) for the apartments was NC-40. This suggests the inconvenient acoustic problem of these apartment buildings since the recommended NC level for apartment houses is 25-35 (Engineering ToolBox, 2004b).

Single-number ratings such as ASTC could be predictors of subjective ratings of acoustic quality including loudness, disturbance and others (Hongisto et al., 2015; H. K. Park & Bradley, 2009). The performance of internal partition walls in this study appeared to perform somewhat poorer, especially at lower frequencies. The internal partition assesmbly of the apartments failed to meet the minimum requirement for partition between units in the both international and national building codes i.e. International Building Code for new construction (ASTC = 50) and the 2015 National Building Code of Canada (ASTC = 47) (Hoeller, Mahn, Quirt, Schoenwald, & Zeitler, 2017). This is consistent with studies that highlight the difficulty in attenuating lower frequency sounds in residential buildings because of mass-air-mass resonance (Hongisto et al., 2015). Here, ASTC of the partition wall was used as a surrogate of partition walls between apartments. To measure the ASTC of partition walls between apartments was practically impossible because of occupants' availability.

However, ASTC sometimes reveals a little about the sound absorption properties of the walls and thus the acoustic environment since ASTC mostly disregards lower frequencies which is a major issue in acoustic quality. So a closer look at the ATL at frequency band is important. This revealed marginal differences (i.e. about 5 dBA) in sound attenuation at lower frequencies, whereas at higher frequencies (i.e. within 800 to 4000 hertz) the blocks attenuated similar amount of noise. This partly explains why human speech, which occurs at higher frequencies, appeared not to be a major noise problem as indicated in the occupant survey. Occupants expressed low levels of satisfaction with acoustics compared to thermal comfort, air quality, and lighting; the general acoustic feeling was at least slightly noisy. Occupant satisfaction with acoustic quality was slightly above the neutral point (i.e. scale point: 4), but below the satisfied point (i.e. 5.0). The mean and standard deviation (S.D.) of occupants' satisfaction with acoustics were 4.76 and 1.77 respectively. The S.D. showed less variation in the occupants' reported satisfaction levels. Detailed examination revealed that majority of the occupants assigned low assessment scores indicating perhaps low satisfaction with acoustic quality in the rooms. For example, about 48 per cent of the occupants described their acoustic environment as poor. This result is consistent with findings of other studies on green residential buildings (Alborz & Berardi, 2015; Zalejska-Jonsson, 2014). Green residential houses generally have poor acoustic quality because of the inadequate attention to acoustics in majority of the rating schemes. Indeed, till now, the LEED version 4 has not changed much in terms of acoustics. It is important to note that LEED for Homes does not place any premium on acoustic quality and as such it's not a prerequisite, although in other schemes such as LEED v4 for healthcare facilities and schools this condition has greatly improved. The acoustic requirements include sound transmission class (STC) with a possible 1 credit point. Per the LEED version 4, the threshold is 50. This is despite acoustic performance and noise protection been considered as an important part of social sustainability aspects of buildings.

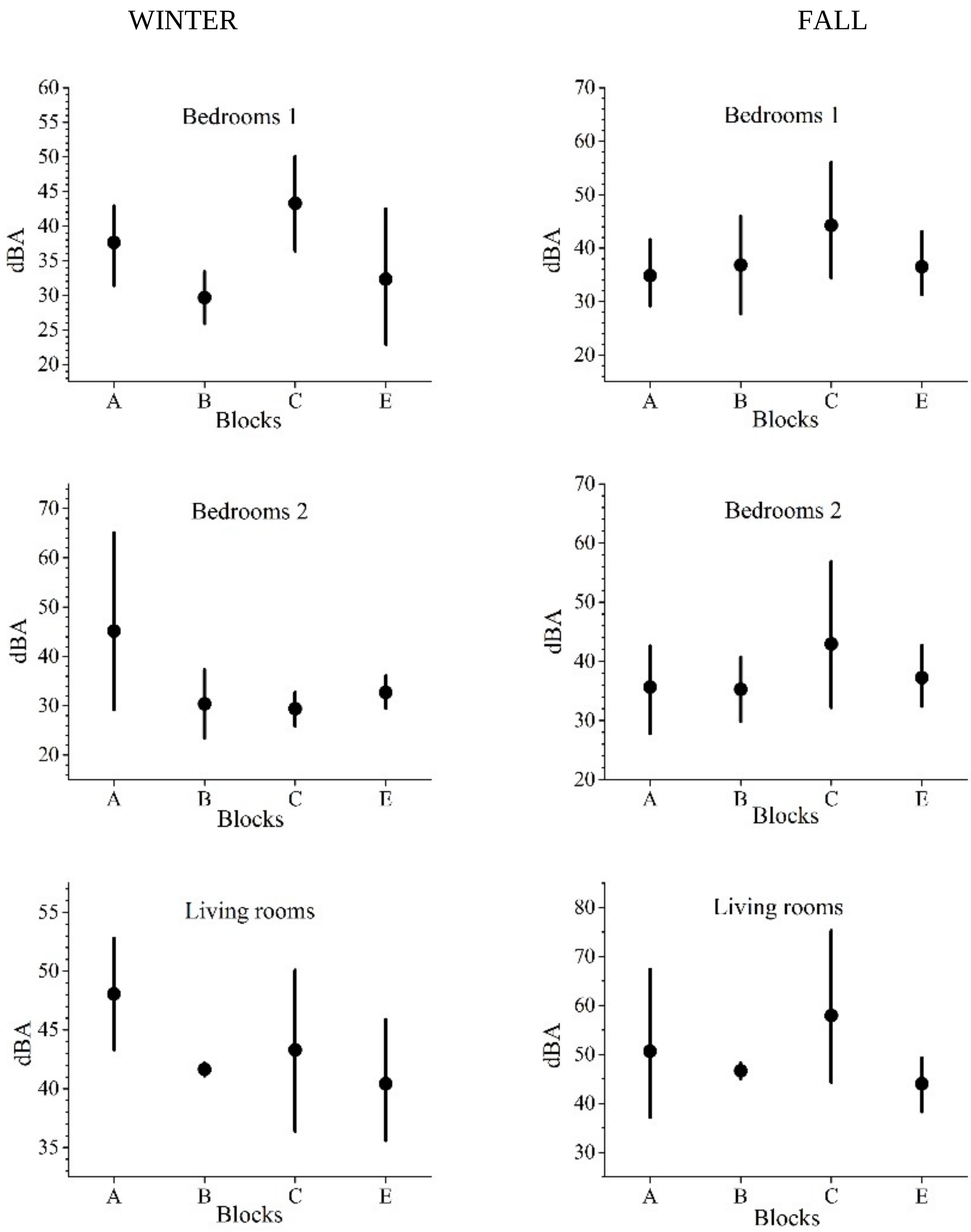

Fig. 4.8. Distributions of background noise in bedrooms one and two and living room during fall and winter seasons.

4.4 Differences between LEED-certified and non-LEED-certified (LEED shadowed) blocks

Tables 4.7 & 4.8 show the differences in IEQ parameters between LEED-certified and non-LEED-certified residential blocks of apartments during the winter and fall seasons. During the fall season, the mean levels of parameters for the most part were higher in non-LEED-certified homes compared to the LEED-certified homes. Similar observation was made during the winter season, except for parameters such as $PM_{2.5}$ and PM_{10} which recorded higher levels in the LEED-certified homes. Furthermore, the standard deviation (SD) of the levels of parameters in the non-LEED-certified homes appeared to be higher indicating variation in individual home levels more than the LEED-certified homes. For instance, the levels of TVOC in the non-LEED-certified homes fluctuated at higher levels within the individual homes (i.e. max = 1735.68 $\mu g/m^3$; min = 629.04 $\mu g/m^3$) compared to LEED-certified (i.e. max = 1020 $\mu g/m^3$; min = 715.88 $\mu g/m^3$). This even appears to be more pronounced during the fall season for reasons related to influence of local outdoor sources of contaminants. The mean CO_2 levels recorded in the LEED-certified homes were lower in both seasons compared to the non-LEED-certified homes. Interestingly, the mean CO_2 winter levels of non-LEED-certified homes exceeded (i.e. about 93 ppm) the recommended threshold (i.e. 1000 ppm), whereas the LEED-certified homes recorded levels lower (i.e. about 150 ppm below the recommended threshold) in the same period.

The mean CO levels in non-LEED-certified homes (i.e. 1.54 ppm) were about twice the levels recorded in the LEED-certified homes (0.83 ppm) in the winter season. Although the source of the higher levels in non-LEED-certified homes is unclear, an investigation of the surrounding conditions revealed that non-LEED-certified homes were closer to outdoor sources of CO i.e. highway, rail station and factory. Moreover, there were many smokers in the non-LEED-certified homes compared to the LEED-certified. However, it is unsure if that contributed to the higher levels of CO in the non-LEED-certified homes since indoor smoking is not allowed within the homes. More so, $PM_{2.5}$ concentrations in LEED-certified and non-LEED-certified apartments were similar in fall season but appeared different in winter. LEED-certified apartments recorded levels higher in the winter (mean = 4.34 µg/m^3) compared to the non-LEED-certified apartments (mean = 3.68 µg/m^3). The most likely explanation may be that the occupants in the LEED-certified apartments engaged in activities that caused the suspension of particles or dust perhaps before the measurement period. However, a careful consideration of the SD seems to suggest huge variability in the levels of $PM_{2.5}$ between non-LEED-certified apartments. It is also worth pointing out that the maximum level in non-LEED-certified apartments (52.25 µg/m^3) was almost twice the levels in LEED-certified homes (28.72 µg/m^3) during the winter period. Conversely, the mean level in non-LEED-certified homes (5.58 µg/m^3) was slightly higher in the fall period compared to LEED-certified homes (5.45 µg/m^3).

Mean daylight levels in LEED-certified homes were higher than non-LEED-certified homes during both seasons. LEED-certified homes appeared to receive daylight levels sufficiently higher in winter (more than 300 lux). For the fall season, both homes appeared to have insufficient lighting (i.e. less than 300 lux). It is worth pointing out the variability (i.e. SD greater than mean) in daylight levels between apartments in the non-LEED-certified building. Again, this highlights the inconvenient problem of taking measurements at different times of the day and under different weather conditions.

Table 4.7 Differences in IEQ parameters between LEED-certified and non-LEED-certified during winter season

	Parameter									
Winter season	TVOC	CO2	CO	RH	PM2.5	PM10	Temp	Electric	Daylight	BN
LEED-certified (N=2)										
Mean	918.45	871.01	.83	20.33	4.34	15.07	21.54	173.21	311.18	33.90
SD	112.02	268.20	.25	7.58	.94	7.04	1.23	112.96	332.51	7.83
Minimum	715.88	576.48	.50	12.84	2.68	6.97	19.73	71.16	75.32	23.40
Maximum	1020.36	1183.25	1.18	28.72	28.72	26.76	23.36	332.60	966.60	42.20
Non-LEED-certified (N=15)										
Mean	956.42	1093.32	1.54	23.85	3.68	12.92	21.96	242.55	237.35	37.68
SD	280.84	218.34	.52	5.38	7.64	9.62	1.56	553.34	905.46	8.60
Minimum	629.04	640.76	.86	16.92	.48	1.66	17.35	.42	0.00	24.80
Maximum	1735.68	1583.00	3.38	38.39	52.25	53.71	24.54	3748.00	6117.00	65.10

Table 4.8 Differences in IEQ parameters between LEED-certified and non-LEED-certified during fall season

	Parameter									
Fall season	TVOC	CO2	CO	RH	PM2.5	PM10	Temp	Electric	Daylight	BN
LEED-certified (N=2)										
Mean	715.01	675.95	.80	41.46	5.45	17.11	22.85	231.26	219.13	40.47
SD	235.33	141.76	.10	1.31	1.98	7.25	.50	126.53	144.83	6.20
Minimum	498.00	478.40	.63	39.38	2.99	5.93	22.17	75.22	54.97	29.20
Maximum	1071.80	845.96	.91	42.94	8.73	23.35	23.34	426.60	454.20	48.20
Non-LEED-certified (N=15)										
Mean	977.21	844.08	1.08	45.39	5.58	19.23	22.62	206.00	129.96	40.73
SD	614.72	206.32	.35	6.72	4.18	14.45	1.07	398.76	186.27	9.57
Minimum	536.29	533.54	.58	30.12	1.12	3.44	20.38	1.17	1.54	27.70
Maximum	3955.93	1409.11	2.16	63.10	23.15	86.74	25.91	2734.00	1038.00	75.30

N = Number of apartments

4.5 Objective measurement distribution over transient or 'right now' satisfaction

This subsection presents the results and discussions of the relationship between the subjective 'right now' or transient satisfaction with the individual factors and their respective objective measurements. The results is only for the fall season.

4.5.1 Thermal comfort

The results on the transient or 'right now' satisfaction of thermal envionment were similar indicating no statistically significant difference. The comfortable group experienced mean temperature of 22.50 ^{o}C slightly above the uncomfortable group (with a temperature mean of 22.0 ^{o}C). Furthermore, the mean level of air velocity for uncomfortable and comfortable groups were 0.01 m/s (median = 0.003 m/s) and 0.0002 m/s (median =0.001 m/s), respectively. These levels are too small to make any significant impact on thermal snapshot satisfaction; however, occupants in the uncomfortable group experienced relatively higher air velocity which may somewhat contribute to draft in cool environments. Therefore, occupants' comfort may likely be influenced by air velocity. Indeed, occupants indicated drafts as the third thermal comfort problem (mean = 3.875; std. dev = 1.30) after hot temperature (mean = 3.36; std. dev = 1.32) and cold temperature (mean = 3.64; std. dev = 0.907) in first and second positions respectively.

4.5.2 Air quality

The mean level of PM_{10} was 24.57 µg/m^3 (median= 23.35 µg/m^3) for the poor group slightly higher than the good group with 14.76 µg/m^3 (median = 15.63 µg/m^3). Conversely, the mean concentration of $PM_{2.5}$ was slightly lower in the poor group (mean = 4.50 µg/m^3) compared to the good group (mean = 5.00 µg/m^3). In terms of statistical significance, there were no differences in the measured $PM_{2.5}$ between the IAQ snapshot satisfaction groups; but a statistically significant difference in mean measured concentration levels in PM_{10} between poor and good groups of 9.81 (95% CI, 1.09 to 18.54), $t(20) = 2.46$, $p = .029$, $d = 1.46$ was recorded.

Furthermore, a correlation analysis showed a moderately statistically significant negative association ($r = -.471$, $p = .027$) between IAQ snapshot satisfaction and PM_{10}. It can therefore be stated that occupants have become more sensitive to particles of appreciable size, and thus IAQ snapshot satisfaction decreases with increased PM_{10} concentration.

The results showed higher CO levels in the IAQ poor group (mean = 1.12 ppm; median = 1.31 ppm) than in the IAQ good group (mean = 1.01 ppm; median = .96 ppm). However, no statistically significant difference in the measured CO levels was observed between the two groups. Similarly, the differences in CO_2 proved statistically insignificant. Nevertheless, CO_2 concentration levels in the poor group were generally higher than in the good group. The mean level in the IAQ poor group was 877.98 ppm (median = 972.37 ppm) and 812.73 ppm (median = 775.41 ppm) in the IAQ good group. Regarding TVOC concentrations, the results indicate that the mean TVOC level in the IAQ good group was 737.15 $\mu g/m^3$ (median = 631.64 $\mu g/m^3$) and is slightly lower than the mean concentration of 803.75 $\mu g/m^3$ (median= 790.81 $\mu g/m^3$) in the poor group. The levels followed the conventional thinking that occupants with poor IAQ 'right now' satisfaction experienced higher pollutant levels compared to the occupants with good IAQ satisfaction. However, the statistical insignificance of the differences may be as a result of the smaller respondent size.

4.5.3 Lighting quality

Daylight illuminance levels were distributed over daylight snapshot satisfaction groups. Similarly, the results of electric light illuminance level were distributed over electric light snapshot satisfaction groups. In terms of daylight illuminance levels, occupants satisfied with their indoor daylight environment received mean daylight levels of 169.27 lux (median= 39.03 lux) and was slightly higher than the levels (mean level = 130.31 lux; median = 54.34 lux) in apartments with occupants dissatisfied with their lighting environment. The mean daylight level for the satisfied group was slightly above the threshold level of 150 lx recommended by Li et al. (2016). Similarly, occupants satisfied with electric environment received higher mean illuminance level of 331.23 lux (median = 69.05 lux) than occupants unsatisfied with electric environment, who received 114.96 lux (median = 53.22 lux). Although the differences in mean appeared substantial, the differences in levels were still not statistically significant. The probable explanation may be that the occupants are perhaps used to the lighting levels in their apartments and as such are not bothered about the lighting levels.

4.5.4 Acoustic quality

Background noise level was distributed over occupants' acoustic snapshot or 'right now' satisfaction (i.e. whether satisfied or unsatisfied). Occupants' satisfied with acoustic quality experienced mean A-weighted background noise level of 42.20 dB (median = 42.20 dBA) which was slightly above that of the occupants satisfied with acoustic quality (mean of 38.63 dBA; median = 36.40 dBA). However, the difference in mean background noise levels was not statistically significant. Based on this, it is reasonable to conclude that occupants' subjective judgment may have been largely influenced by sources other than the background noise such as traffic noise, neighbourhood noise.). From the results of the mean of the survey results, the top three disturbing noise sources (mean < 3.10) were: 1) "vehicle noise from street including snowplough", 2) "speech, laughter, TV or music from neighbour", and 3) "impact sound from staircase and floors". It is important to note that occupants have no control over these noise sources. Low frequency noise such as traffic noise is difficult to insulate against. It is not surprising that vehicular noise was deemed most disturbing (mean = 2.74; SD = 1.19).

4.6 Perceived long term IEQ satisfaction and objective measurements

Figure 4.9 shows occupants' satisfaction with the various IEQ factors and IEQ during the two seasons. Occupants generally appeared to be satisfied with their indoor environment in fall compared to winter. Occupants experienced problems with their acoustic environment relative to the other indoor environmental factors (refer to Table A5 in Appendix).

Tables 4.9 and 4.10. show the environmental conditions in the apartments that participated in the occupant survey as grouped into two i.e. acceptable and unacceptable IEQ. Only a minority (i.e. N= 5) of the surveyed occupants were unsatisfied with overall IEQ and as such considered their apartments as unacceptable as presented in the Tables 4.7 and 4.8. Although, the result in this study is consistent with the study by Lai et al. (2009), occupants were generally satisfied with the indoor environment; however, occupants with unacceptable IEQ mostly received lower levels of pollutants, except for PM_{10}. Differences in parameters between acceptable and unacceptable IEQs were relatively small. Low levels of RH have been noted to result in thermal discomfort causing sensory irritation (McGill et al., 2015); nevertheless, occupants with acceptable IEQ obtained lower levels of RH in winter (i.e. 24%) compared to occupants with unacceptable IEQ (i.e. 29.50%). Furthermore, maximum RH (36.52%) was higher than 30% (as showed in Table 4.7) in the majority of occupants with unacceptable IEQ; but RH was lower than 30% in all the occupants with acceptable IEQ. The difference in RH during winter between the two groups was statistically significant ($p = .003 < .05$). This difference was not observed in the fall season which is consistent with Lai et al. (2009). Other factors (such as number of occupants, occupant activities, location of apartments) can also influence this observed difference in RH (Langer et al., 2016).

As expected, occupants with acceptable IEQ (i.e. 10.63 $\mu g/m^3$) obtained significantly lower levels of PM_{10} than in the unacceptable group (i.e. 18.42 $\mu g/m^3$) during the winter. This result is consistent with findings in a similar study conducted in Finland (Du et al., 2015) which reported slightly lower levels of PM_{10} in the rather acceptable group than in the unacceptable group although the differences were not statistically significant. The implication is that occupants can become very sensitive to particulates of reasonable size and thus evaluate their acceptance of IEQ based on PM_{10}.

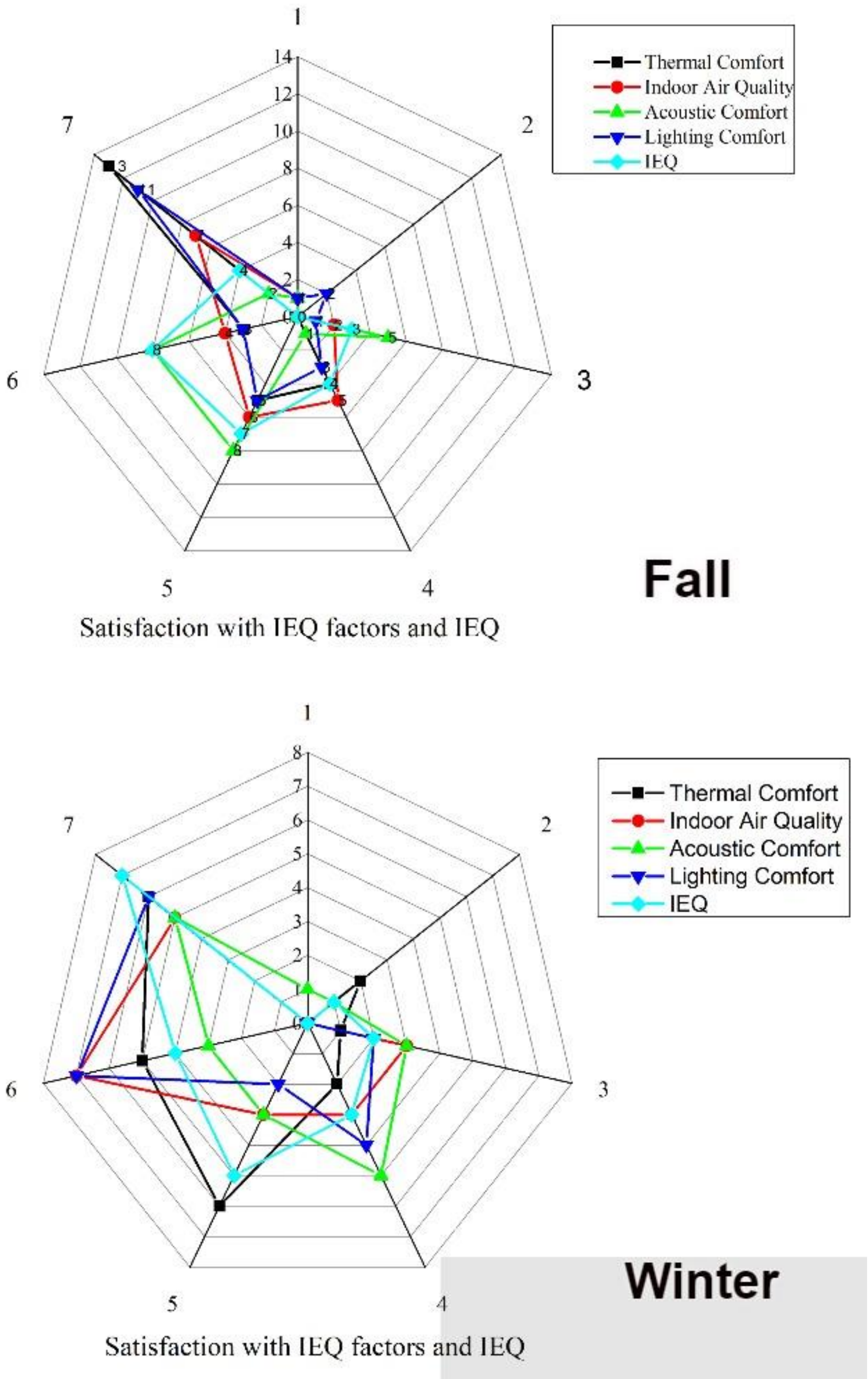

Fig. 4.9. Satisfaction with IEQ factors and IEQ

Table 4.9 Indoor environmental quality (IEQ) parameters in surveyed homes (winter)

	Parameter										
	TVOC	CO2	CO	RH	PM2.5	PM10	Temp	Electric	Natural	AV	BN
‘Acceptable’ IEQ (N=14)											
Mean	1016.89	1176.66	1.52	23.57	5.91	10.63	22.12	441.92	569.79	.005	40.91
SD	344.61	147.17	0.63	2.82	13.36	4.33	1.74	964.54	1601.12	.007	11.01
Minimum	663.12	986.04	0.50	19.60	0.97	2.63	17.35	0.42	0.00	.02	23.40
Maximum	1735.68	1454.44	2.70	27.30	52.25	18.40	24.28	3748	6117	.00	65.10
‘Unacceptable’ IEQ (N=5)											
Mean	827.98	1061.86	1.40	29.50	4.06	18.42	21.74	64.64	233.37	.004	40.60
SD	109.58	162.57	0.36	4.12	0.94	3.32	1.77	35.32	418.81	.005	8.75
Minimum	674.24	828.40	1.04	25.90	2.69	14.86	19.32	3.00	0.00	.01	25.90
Maximum	918.48	1274.00	1.85	36.52	5.13	23.91	23.36	88.61	966.60	.00	49.20
p-value (Mann-Whitney t-test)	.343	.219	.823	.003*	.014*	.005*	.754	.107	.444	.893	.754

Table 4.10 Indoor environmental quality (IEQ) parameters in surveyed homes (Fall)

	Parameter									
	TVOC	CO2	CO	RH	PM2.5	PM10	Temp	Natural	AV	BN
‘Acceptable’ IEQ (N=14)										
Mean	828.72	834.77	1.09	44.40	5.16	13.99	22.49	184.03	0.00	36.82
SD	268.54	160.49	0.35	3.86	3.18	7.61	1	268.01	0.01	7.71
Minimum	554.18	609.15	0.77	36.32	1.05	2.71	20.37	1.54	0.00	27.70
Maximum	1407.24	1083.03	2.04	54.29	12.32	28.28	24.27	1038.00	0.02	56.10
‘Unacceptable’ IEQ (N=5)										
Mean	780.36	864.68	1.05	40.83	5.79	19.30	22.26	198.46	0.00	38.09
SD	280.97	238.98	0.50	4.76	3.35	12.06	1.92	207.01	0.00	6.06
Minimum	595.76	553.46	0.62	33.01	12.29	5.00	20.16	2.05	0.00	29.20
Maximum	1305.52	1234.63	2.16	47.22	2.39	34.99	25.73	520.80	0.01	46.00
p-value (Mann-Whitney t-test)	0.73	0.96	0.40	0.09	0.67	0.41	0.53	0.65	0.78	0.50

5 CHAPTER FIVE

LONG TERM MEASUREMENT

5.1 Introduction

This chapter presents and discusses the long-term measurement results on IAQ and thermal comfort conducted between the fall (September-November 2016) and winter (December-February 2017) period. The chapter presents results and discussions on seasonal variations, hourly variations between weekdays and weekend, and correlations between environmental factors.

5.2 Seasonal variation

Table 5.1 presents the long term environmental descriptive statistics by seasons. The levels were all below the national thresholds. Although most of the indoor pollutant median levels were within the reference national threshold, median and peak level of CO_2 in winter (1355 ppm; 4800 ppm) and peak level of CO_2 in fall (936 ppm; 7769 ppm) measuring periods exceeded reference exposure levels (1000 ppm or 650 ppm above ambient level) thus compromising IAQ. With respect to the differences in pollutant concentration between the two seasons, the differences were found to be statistically significant for all measured parameters, using an independent t-test ($p < .05$). This can probably be attributed to two factors: 1) window opening which particularly characterizes non-heating seasons; 2) room occupancy levels which increases for the most part in winter since people tend to spend more time at home. The main difference between the fall and the winter periods is that in general the levels of concentrations observed in the winter were higher than measured concentrations observed in the fall, except for PM. From the Table 5.1, PM fall levels (i.e. 8.81 $\mu g/m^3$) were statistically significantly slightly higher compared to winter (i.e. 7.63 $\mu g/m^3$). Based on this result, this may be due to the higher PM outdoor concentration values infiltrating the indoor environment in the fall period perhaps because of open windows which largely characterizes non-heating seasons (Burgos et al., 2013; Coombs et al., 2016; Ni et al., 2016). Conversely, the higher CO levels in winter may be attributed to, as identified by Chaloulakou and Mavroidis (2002), 1) increased volume of traffic since the weather favours the use of vehicles, 2) the different engine operating conditions as a result of lower winter temperatures, and 3) the accumulation of pollutants during the winter due to the prevailing meteorological conditions.

Table 5.1 Descriptive statistics by seasons

	N	Median (P25-P75)	Min-Max	p	References
					National
CO (ppb)					
Fall	1487	29.96 (17.67-41.92)	0.05-945.53	.001	10000
Winter	759	38.29 (25.37-55.49)	3.05-127.20		
PM (μg/m³)					
Fall	1487	8.81 (4.21-14.37)	0.00-1250.16	.000	50
Winter	759	7.63 (5.55-10.32)	0.00-84.56		
TVOC (ppb)					
Fall	1487	258.96 (187.96-358.29)	125.00-2140.33	.000	30000
Winter	759	374.17 (252.41-550.92)	125.08-1323.15		
CO_2 (ppm)					
Fall	1487	936.11 (678.35-1297.06)	450.42-7769.33	.000	1000
Winter	759	1355.17 (913.69-1995.94)	450.42-4800.69		
Temperature (°C)					
Fall	1487	22.60 (21.66-23.41)	18.26-28.68	.000	21-24
Winter	759	21.90 (21.17-22.71)	16.03-25.20		

TVOC is primarily emitted from indoor sources such as cleaning products, air fresheners, manufactured wood products (Colton et al., 2014; McGill et al., 2015). Median TVOC levels in winter is more than 100 ppb compared to fall levels. This is probably because the increase levels of TVOC in winter was that the residual indoor emissions from local sources were inadequately ventilated during this period. Nonetheless, the overall levels of TVOC in both seasons were fairly lower compared to the national threshold (30000 ppb) and studies measuring TVOC in low-income buildings in a temperate region of US (i.e. 1283 ppb) (e.g. Coombs et al., 2016); but higher than levels (i.e. 20 ppb) reported in Austria (e.g. Rojas et al., 2015a). Indoor temperature in both seasons (fall = 22.60 ^{o}C; winter = 21.90 ^{o}C) were within levels noted to provide indoor comfort. The indoor environment appeared comfortable than the indoor environment of most low-income buildings investigated in Northern Europe (Santamouris et al., 2014). Santamouris et al. (2014) reported indoor temperature of 50 low-income homes. The mean indoor temperature was 15.9 ^{o}C with an ambient temperature of 0.9 ^{o}C. In this study, the corresponding ambient temperature to the minimum temperature (16.8 ^{o}C) recorded was -36^{o}C thus accounting for the lower indoor temperature.

5.3 Correlation between PM and CO indoor concentrations

As showed in Figure 5.1, CO and PM have strong R^2 (0.99) with a stronger correlation in the fall period ($r = 0.99$; $p < .000$) compared to the winter ($R^2 = 0.14$). During the fall period, indoor PM exposure explained about 99% of the variation in CO concentration. As a result previous studies often tend to use CO as a surrogate for PM exposure because of ths strong relationship (Ni et al., 2016). Furthermore, the relationship between the concentration of CO and of the PM fits a linear function in the fall period. As PM rose, the concentration of carbon monoxide tended to increase in direct proportion. The probable explanation for this strong relationship maybe the heavy influnece of the emission source (which is likely be an outdoor source e.g. automobiles). This point is emphasised in the weak R^2 (i.e. 0.14) for the winter period where transportation or infiltration of outdoor concentration are negated by the closing of windows for thermal comfort reasons.

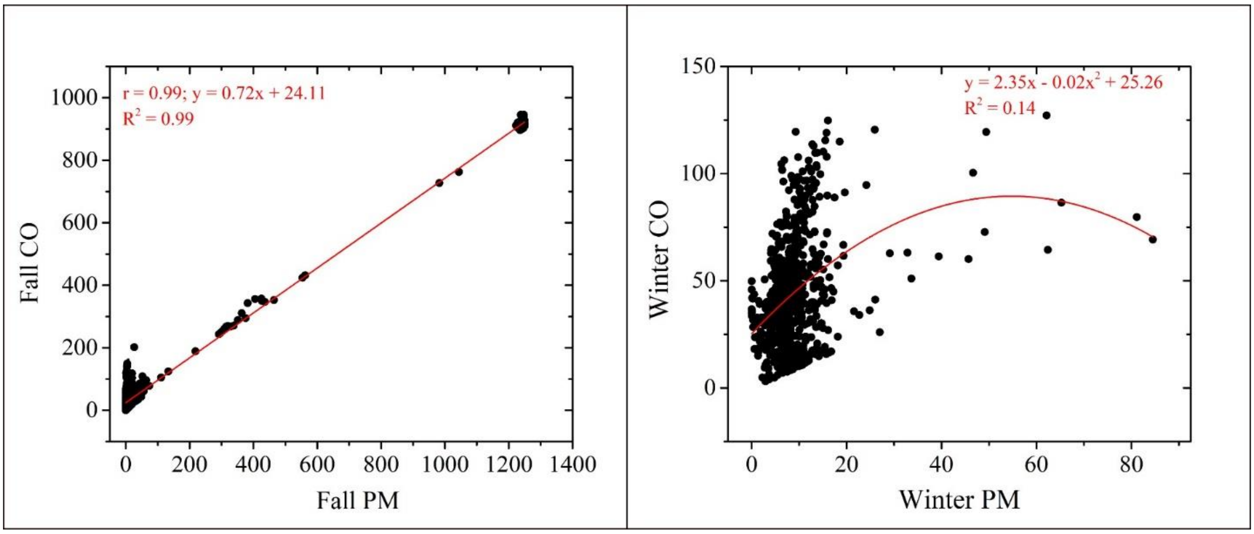

Fig. 5.1 Relationship between CO and PM

5.4 Relationship between the measurment results and the factors affecting indoor air quality

Temperature, humidity and indoor chemistry have moderating influence on indoor TVOC (Jo & Sohn, 2009; Ye et al., 2017). To explore this relationship, the following regression and correlation analyses were conducted.

5.4.1 Relationship to temperature

Figure 5.2 shows the measured TVOC concentration as a function of temperature. The relationship between the concentration of TVOC and of the temperature fits a linear function with the lowest point at 21°C. As the temperature rose, the concentration of TVOC tended to increase, and the value of the determinant R^2 was 0.63 during the weekdays (i.e. Monday to Friday). Similarly, the concentration of TVOC and of temperature fits a linear on Sundays with a slightly lower value of the determinant R^2 (0.58). This result supports previous studies (Jo & Sohn, 2009; Ye et al., 2017) which found increases in temperature to be associated with an increase in the TVOC concentration. Increase in temperature is noted to increase the emission rate of TVOC increasing diffusion and decreasing partitions. However, unlike Jo and Sohn (2009) who found minimal significance of the relationship (R^2 = 0.46), this study have moderate R^2 with a stronger correlation (weekdays: $r = 0.80$, $p < .05$; Sundays: $r = 0.77$, $p < .05$) implying a moderate significance of this relationship. Surprisingly, an inverse relationship is observed during Saturday. However, the R^2 was nonetheless statistically significant (0.65) with a stronger correlation ($r= -0.82$, $p <.05$). This relationship is unexpected and the only probable explanation may be that the possibility of increased indoor sources during the Saturday as a result of increased in occupancy. It won't be farfetched to assert that friends and family gather together.

5.4.2 Relationship to Humidity

Similar to the relationship to temperature, measured TVOC is plotted against RH in Fig. 5.3. The R^2 for weekday, Sunday, and Saturday were 0.44, 0.04 and 0.024, respectively implying minimal statistical significance of this relationship ($p < .05$). The relationship between the TVOC and the RH fits a linear function during the weekday and Saturday; and a quadratic function during Sunday.

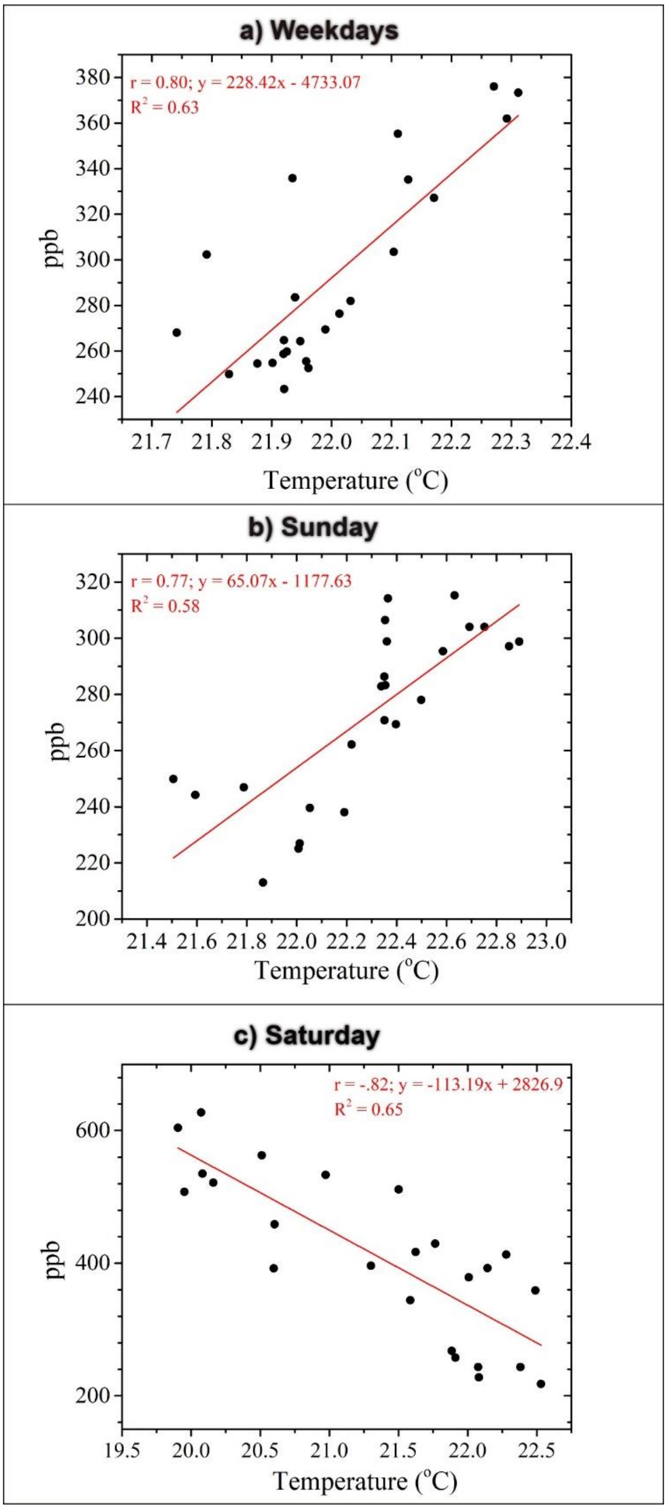

Fig. 5.2. TVOC's concentration distribution by temperature

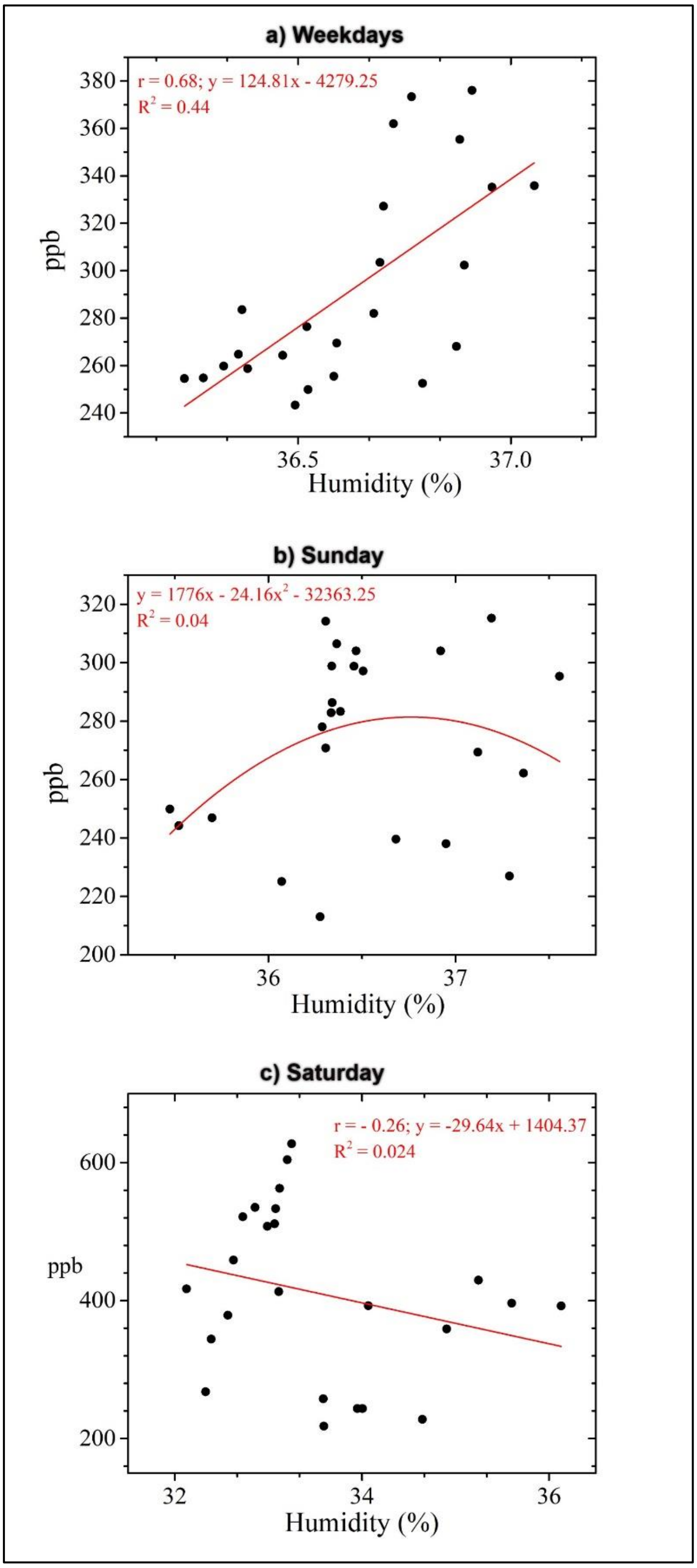

Fig. 5.3 TVOC's concentration distribution by relative humidity

5.5 Weekly variation of air quality

The summary of the t-test between the two categories is presented in Table 5.2 for both fall and winter. In the table, the mean levels of the two groups (i.e. weekend and weekday) are presented for the respective measurement seasons. The standard deviation and the p-value from the tests that indicates the statistical significance are also showed.

Table 5.2 Comparison of indoor environmental parameters

		Fall				**Winter**			
		Mean	SD	t	p	Mean	SD	t	p
CO (ppb)	WD	50.79	8.58	-7.74	.00*	43.11	11.13	-.43	.67
	WE	87.25	21.41			44.39	9.75		
CO_2 (ppm)	WD	1113.11	237.95	1.25	.22	1592.95	429.31	.09	.93
	WE	1041.63	147.06			1582.33	350.07		
PM ($\mu g/m^3$)	WD	36.37	9.79	2.75	.01*	8.68	2.11	-1.14	.26
	WE	21.46	24.13			10.00	5.25		
TVOC (ppb)	WD	307.68	65.53	1.25	.22	439.62	118.20	.09	.93
	WE	288.01	40.50			436.89	96.38		
Temperature	WD	22.50	0.51	-1.09	.28	21.96	0.44	2.88	.01*
(^{0}C)	WE	22.68	0.58			21.54	0.57		
Humidity (%)	WD	40.89	0..38	5.67	.00*	33.84	0.43	.44	.66
	WE	39.99	0.68			33.71	1.34		

WD = Weekday; WE = Weekend
* = significant at 5% level

5.5.1 Carbon monoxide

There was no statistically significant difference between the categories in winter. On the contrary, during the fall period, statistically significant difference (see Table 5.2) was reported between weekdays and weekend (p = .00, t = -7.74). For the fall period, the diurnal cycles of indoor concentrations for weekdays and weekends are presented in Fig 5.4a. The diurnal cycle of indoor concentration for the weekend has a characteristic steady trend with a sudden rise (125 ppb) in the night. This happened in the night after 6:00 p.m. On the other hand, the diurnal cycle of indoor concentrations for the weekday has two characteristic mild peaks, one during the morning (8:00–9:00 a.m.) (i.e. 70 ppb) and one during the evening (4:00–5:00 p.m.) (i.e. 50 ppb). These low levels were expected since there was no combustion in the apartments. However, the mild rise in both the morning and evening during the weekday may correspond to a higher traffic flow (perhaps from the nearby highway) during those times of the day as people commute to and from work respectively. Further, the level of concentration on weekend was always higher than weekdays' concentrations (WD mean = 50.79; WE mean = 87.25). Again, this result was expected since it has been postulated that outdoor sources of CO might be the reasonable influence of the indoor levels. The apartments have windows opened which would maximize the infiltration of outdoor CO in the apartments. However, no information on AER which would have been helpful to understand exchanges between indoor and outdoor environment. Notwithstanding, the presupposition appears to be confirmed by the winter diurnal cycles (Fig. 5.4b), where both weekend and weekday almost followed a similar concentration pattern.

5.5.2 Particulate matter

Statistically significant differences between the categories only existed in the fall period ($p = .01$; $t = 2.75$). Hourly mean concentration during weekdays was higher than weekend (approximately 15 $\mu g/m^3$). In the winter, there was no reported statistically significant differences between weekday and weekend. During fall period, the diurnal cycle revealed interesting contrast in the evening after 4 p.m. Whilst weekdays level of concentration steadily declined, there was a concentration increase near 70 $\mu g/m^3$ during weekend. As seen from the Fig 5.5a the concentration level on weekday was consistently higher (averaging 30 $\mu g/m^3$) than the weekend for most part of the hours of the days. PM on weekdays in fall was found to be within the same range and also follow the same concentration pattern as the CO on weekdays in fall suggesting possible the same outdoor sources. As a result, emission from automobiles should be the main reason for the levels of PM on weekdays, whereas the high levels after 6:00 p.m. on weekend may be from both indoor and outdoor sources. It was possible that friends and family gather together causing resuspension of particles because of occupant activities. Note that smoking is not allowed inside the apartments but is allowed in front of apartments. Therefore, outdoor smoking cannot be completely ruled out in this instance.

For the winter period (see Fig. 5.5b), there is a sharp concentration peak (i.e. 24 μg/m^3) observed in the morning (i.e. 9:00-10:00 a.m.) for weekend, which can be explained by resuspension of dust from the floor finishes when disturbed as a result of vacuuming. However, weekdays observed an undulated trend with mild peaks 15 μg/m^3 and 8 μg/m^3 in the morning (10:00 a.m.) and evening (7:00 p.m.) hours, respectively.

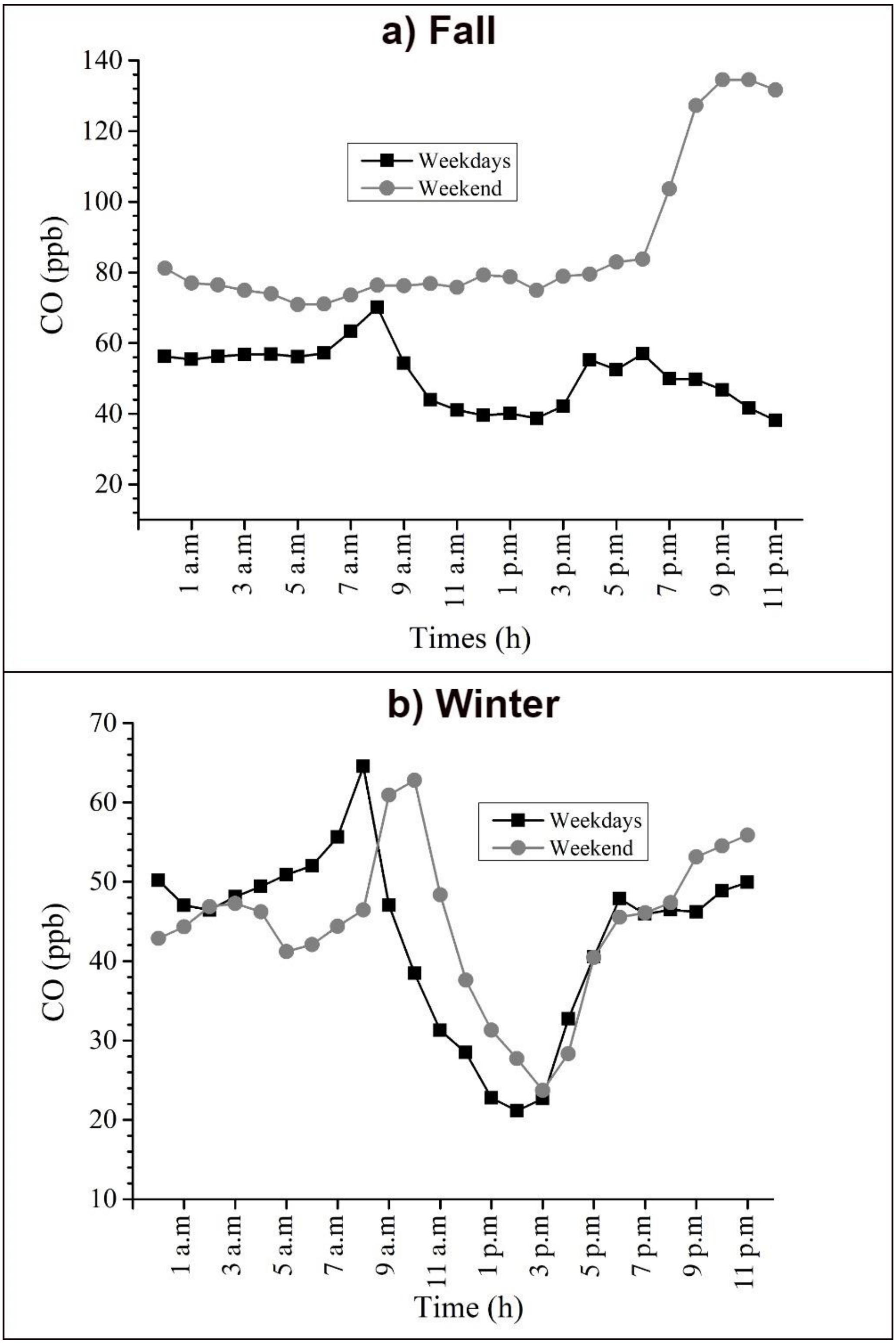

Fig. 5.4 Average diurnal cycle of indoor CO concentrations for weekdays and weekend

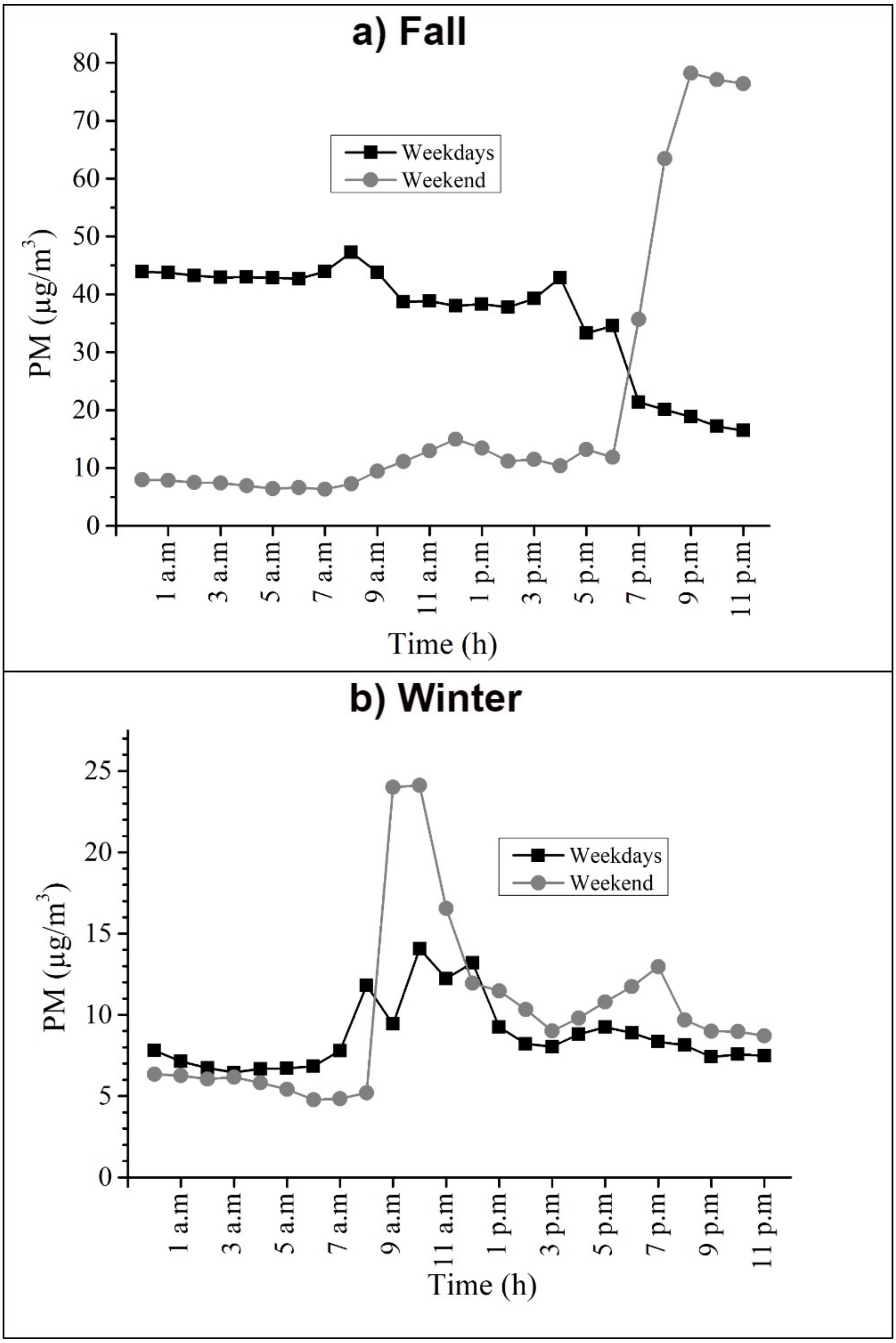

Fig. 5.5 Average diurnal cycle of indoor PM concentrations for weekdays and weekend

5.5.3 Total Volatile Organic Compound (TVOC) and Carbon Dioxide

Mean levels of TVOC and CO_2 were higher on weekdays (TVOC = 307.68 ppb; CO_2 = 1113.11 ppm) compared to weekend (TVOC = 439.62 ppb; 1592.95 ppm) during the fall. Similarly, in winter, mean levels of TVOC and CO_2 were systemically higher on weekend compared to weekdays (refer to Table 5.2). Statistically significant differences were not observed in TVOC or CO_2 during the weekdays compared to the weekend in both the fall and winter periods. The observations of CO_2 and TVOC levels revealed interesting but unexpected trends. The concentration changes, for both observed categories in both seasons, were similar in pattern. The similarity in pattern suggests that the main factors that determined TVOC and CO_2 concentrations were most probably the occupants and the efficiency of the ventilation to reduce concentration levels. It is, however, important to mention that whereas CO_2 sometimes exceeded the maximum allowable indoor levels (1000 ppm), TVOC were lower than the reported levels (1300 ppb) in other studies (Coombs et al., 2016) and within recommended levels (300 $\mu g/m^3$).

The TVOC and CO_2 levels in weekdays in the winter and fall periods appeared to follow the same pattern (Figs. 5.6 & 5.7). In other words, the concentration levels behaved the same way. There are two successive peaks in the morning (1500 ppm.) and night (1450 ppm) during weekdays in fall with a huge decline in CO_2 levels in between. After the first concentration peak in the morning, the decrease of concentrations observed can be attributable to the fluctuating density of occupant (and thus local ventilation efficiency) during the weekdays. A similar behavior is observed during the winter period. In this case, concentration peaks are higher than in the fall, but the trend can be explained by a similar occupancy pattern. However, the increase in concentration levels (CO_2 = 800 ppm; TVOC = 200 ppb) can be linked to inadequate ventilation to reduce the concentration of these two pollutants.

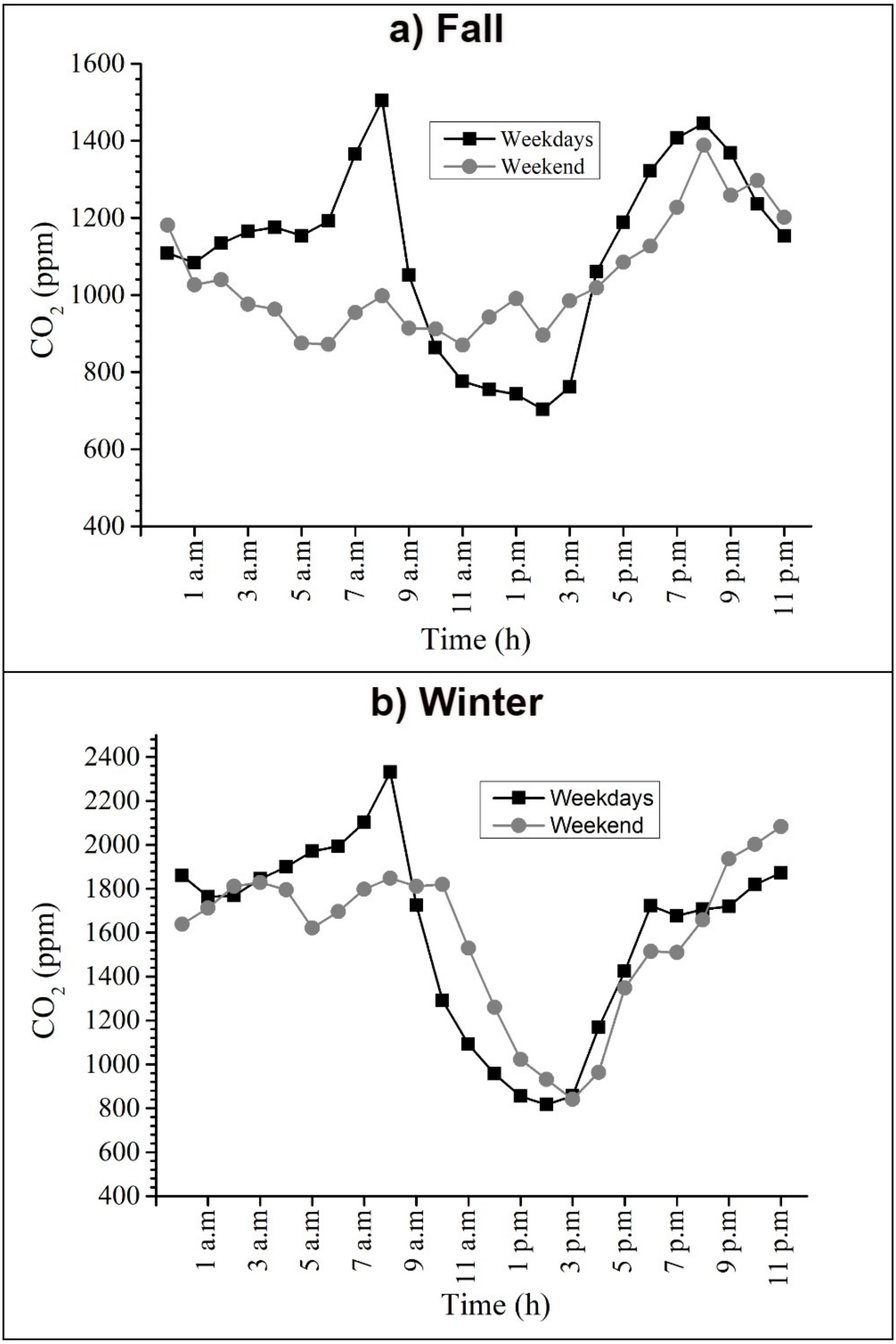

Fig. 5.6 Average diurnal cycle of CO_2 for weekdays and weekend

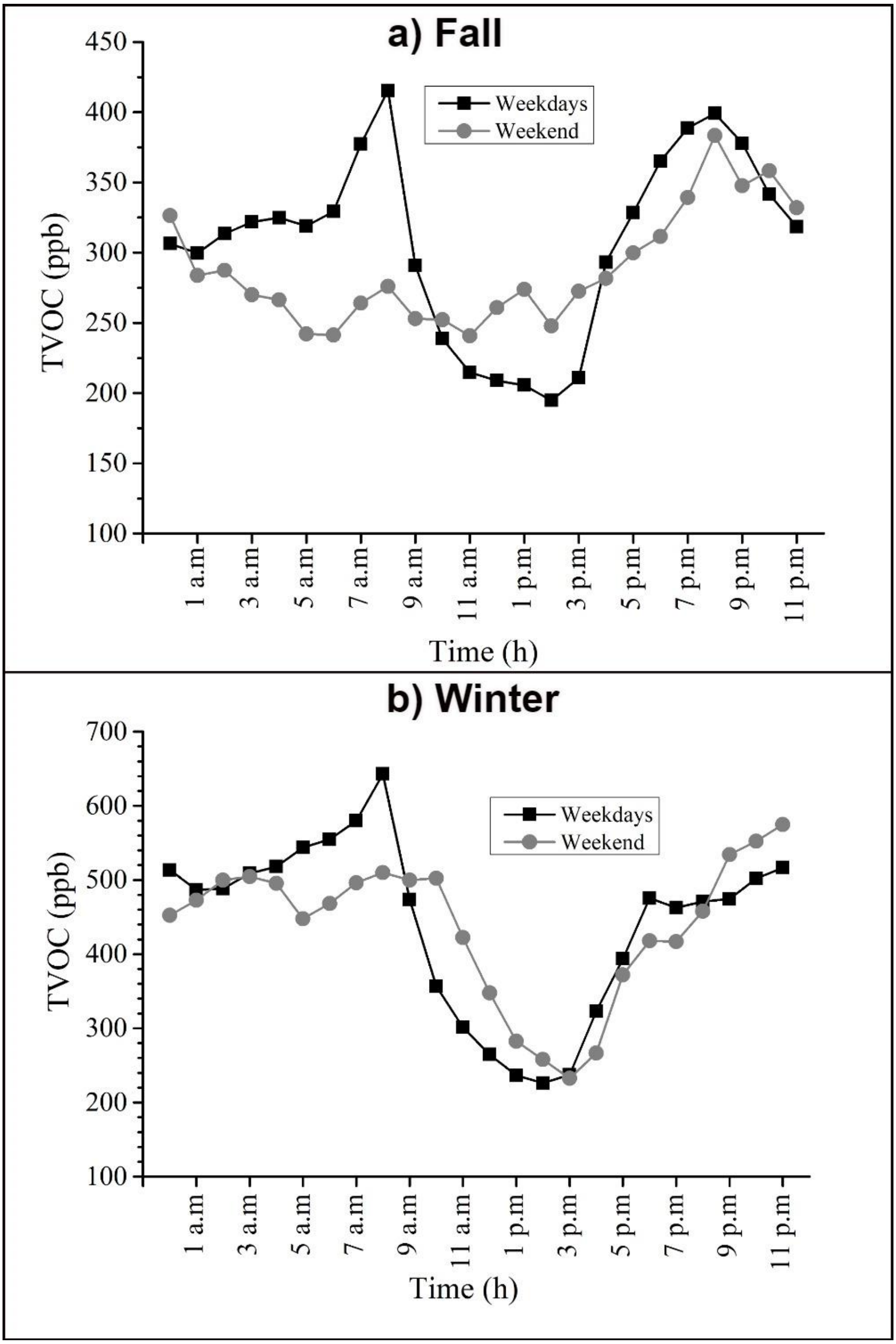

Fig. 5.7 Average diurnal cycle of indoor TVOC for weekdays and weekend

5.5.4 Temperature and RH

The mean temperature difference between weekend (22.68 ^{o}C) and weekdays (22.50 ^{o}C) was not more than 0.50 ^{o}C in the fall. Conversely, mean temperature on weekdays (21.96 ^{o}C) was marginally higher than mean temperature on weekend (21.54 ^{o}C). Although the difference was still less than 0.50 ^{o}C in winter, it was statistically significant ($p = 0.01$; $t = 2.88$). The hourly mean variation of the indoor temperature in the winter period for the two categories is presented in Fig. 5.8b. The weekend diurnal cycle appears to behave in a sinusoidal manner while weekdays appeared to be an upward continuous trend. The average minimum (20.6 ^{o}C) for the weekend occurred at 4:00 a.m. For the most part of the day, temperature levels during weekdays were marginally higher than the weekends. This may be attributed to outdoor temperatures which perhaps dropped compared to the weekdays. However, during this period, outdoor temperatures were not measured. This also shows the importance to concurrently measure outdoor climatic conditions to help understand IEQ performance data.

Unlike indoor temperature, statistically significant difference between weekdays and weekend was observed in relative humidity during the fall period. The weekdays RH levels appear to mirror inversely the weekend RH levels (refer to Fig. 5.9a). The difference between weekdays and weekend appeared to vary widely during the early hours of the day (3:00-8:00 a.m.) and the gap closes as the day progresses (Fig. 5.9a). Occupants' activity during the latter part of the day may be the probable explanation to this considerable change in this trend in RH. For instance, heating of water and cooking of meal will certainly give rise to levels in RH as seen by the measurement results of this variable in the evening.

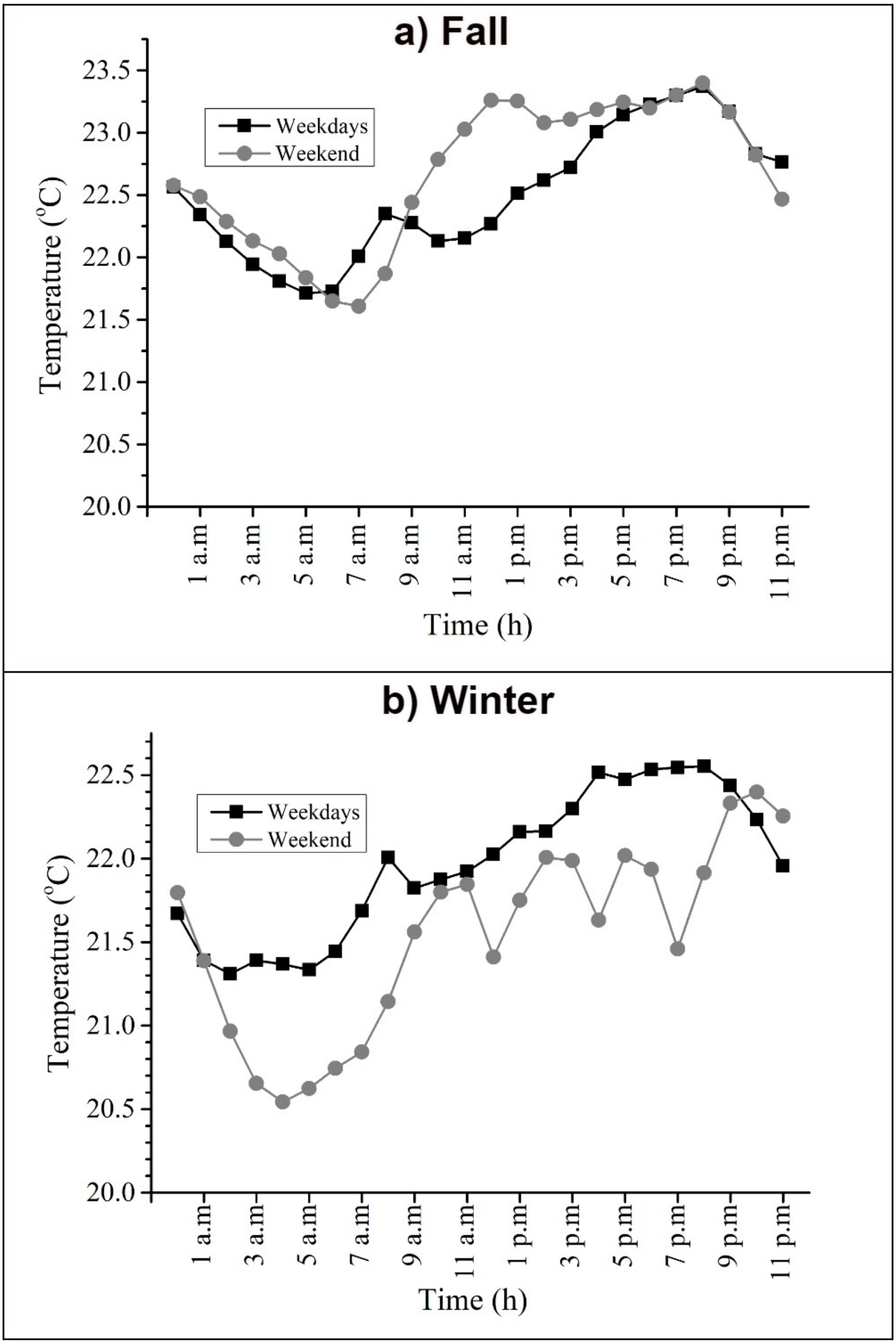

Fig. 5.8 Average diurnal cycle of indoor temperature for weekdays and weekend

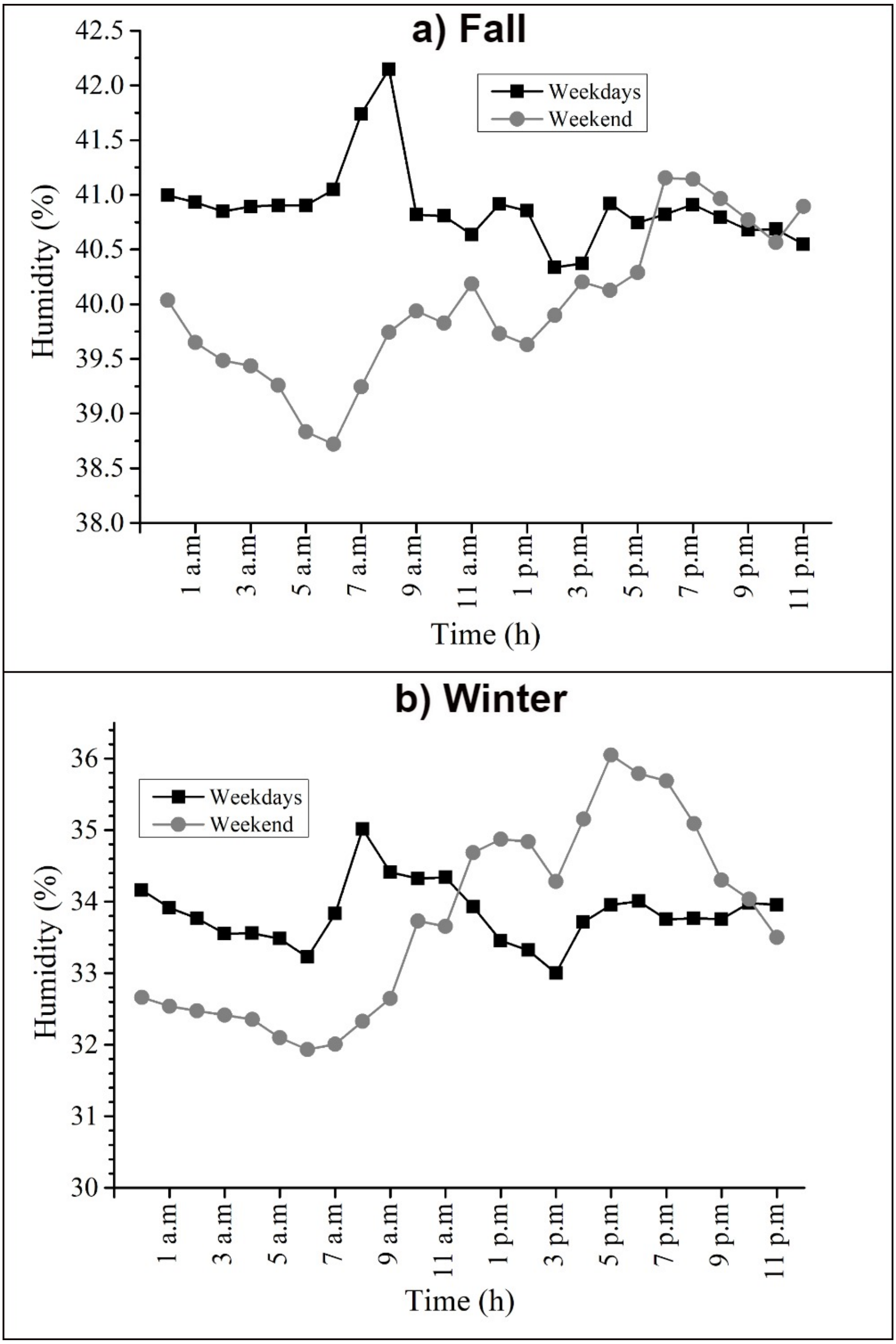

Fig. 5.9 Average diurnal cycle of indoor relative humidity for weekdays and weekend

6 CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This study is one of the most comprehensive snapshot field measurement studies that utilises mixed methodology to assess IEQ performance of green affordable housing to date. The study has investigated the actual environmental performance of green affordable housing in fall and winter seasons, particularly as it relates to IEQ. This has led to a number of research findings and this chapter summarises the entire research; and then presents the main conclusions, and the limitations of the research. These are followed by some consideration of potential practical implications of the research findings particularly in relation to design, maintenance and public health, and also some recommendations for further research.

6.2 Attaining the study objectives

In chapter one of this study, the background to this study was presented. The main issue revealed among other things included affordable housing is likely to have deteriorated indoor environment and green features have been noted to improve these indoor conditions. To understand the performance of these recently built green affordable housing, the following research objectives were posited:

- To develop a methodology for evaluating IEQ in green residential buildings
- To investigate the indoor environmental performance of green affordable housing (self-reported satisfaction and objective measurement)
- To assess the relationship between self-reported subjective satisfaction and objective measurement; and
- To explore the influence of seasonal variation (i.e. fall and winter) on IEQ performance.

- To explore the variation of hourly time series of measured selected IAQ factors in fall and winter seasons; weekend and weekdays.

To achieve these objectives, the study aimed at evaluating actual building performance (IEQ) of the green affordable housing. The succeeding subsection highlights the review of the objectives and how they were attained.

6.2.1 Review of study objectives

Objective 1: To develop a methodology for evaluating IEQ in green residential buildings

This objective is addressed in Chapters 2 and 3. A review of the literature on IEQ methodology (i.e. methods and tools) on residential buildings revealed that studies have often been unilaterally limited to either only occupant survey (subjective measurement) or field measurements (objective measurement) providing less information on the IEQ performance of green low-income housing. Although subjective opinions can be very informative, they fail to capture sometimes IEQ issues that may have other implications (e.g. energy) and have incomplete diagnostic capability to explore the indoor environment. However, other factors such as psychological and physiological states of occupants are typically accounted for in surveys. The review also showed that physical measurements for the most part were minimally measured based on only thermal comfort and IAQ. Moreover, IEQ physical investigation required usually a combination of devices and multiple sensors to measure the IEQ of a space in order to capture data into a single system. In view of this, a customized tripod cart was created to allow easy mobility of multiple sensors, which is usually a challenge in physical measurement; and also to enable a one-point measurement of the state of IEQ. The limitations and problems reported about IEQ physical measurement made sole reliance on objective measurement to understand the quality of indoor environment often problematic. Thus, methodology developed was based on the reviewed literature adapting and customising existing protocols and surveys from recognised standards and published articles, and fusing it with experts' knowledge. The methods developed comprised physical measurement protocol, occupant survey, observation sheet and interviews. Because the quality of IEQ performance and data depend on the details of the data collection; the completion of this methodology is considered the attainment of the first objective. The methodology was deployed in this study following a successful pilot of the methods. The pilot study involved two main apartments and four occupants.

Objective 2: To investigate the indoor environmental performance of green affordable housing

To achieve this objective, field measurement of physical indoor environment was carried out. This involved measurement of four main environmental factors (i.e. thermal comfort, IAQ, acoustic quality and lighting comfort) using the measurement protocol developed in objective 1. Snapshot measurement took place for a 15-min period in the fall season (September-October, 2016) and winter (January, 2017). As mentioned in objective 1, the majority of the studies only measured the thermal environment and IAQ and took that to mean the overall physical environmental performance. In this study, acoustic and lighting quality were investigated in addition to thermal comfort and IAQ. Spaces monitored included bedrooms one, bedrooms two and living rooms of the studied apartments. This was deemed to be an adequate representation of individual apartments based on scientific literature. The data on the physical environment confirmed the subjective satisfactory of indoor environmental conditions. The reported parameter levels were within recommended levels for most of the measured parameters and that could lead to occupant comfort both in the fall and winter seasons. Reported RH levels in winter were below 30%, which could cause discomfort. But in cold climates, these levels are necessary to prevent condensation on surfaces. Background noise levels were above the recommended threshold for residential buildings making the acoustic environment of the studied apartments somewhat poor. There were also slight differences between the levels in the fall and winter seasons. The fulfilment of the second objective led to the third objective.

Objective 3: To assess the relationship between self-reported subjective satisfaction and objective measurement

Following the successful pilot of the questionnaire, self-administered paper-based questionnaires were given to occupants during the main study whilst physical measurements were on-going. Through the questionnaire, occupants reported their satisfaction with their indoor environment. All together the survey yielded 22 responses. Statistical analysis conducted on the data included descriptive statistics, correlation and tests of differences. Although subjective measurement is informative, it does not adequately capture IEQ performance since occupants respond differently to indoor conditions. Thus, the attainment of this objective was through comparison of subjective responses and objective measurement. The subjective satisfaction responses were two: snapshot or 'right now' or transient and long-term (or IEQ acceptance). These responses were further categorised into two dichotomous groups (i.e. comfortable/good/satisfied/acceptable versus uncomfortable/poor/unsatisfied/unacceptable). The physical data was distributed over these subjective responses. The distribution was helpful in understanding the pollutant levels across the two categories. An independent and Mann-Whitney t-tests were conducted to test differences between distribution on snapshot or 'right now' groups in fall only, and distribution on IEQ in both seasons respectively. Concerning differences in the snapshot or 'right now' or transient groups in the fall season, there was no statistically significant differences in all the parameters except PM_{10}. Further, there was not any consistent pattern between these two groups, as to whether one group consistently had improved indoor environmental condition. In some instances, occupants with self-reported poor IAQ satisfaction experienced relatively lower levels of pollutants compared to those in good group. For the overall IEQ acceptance, no statistically significant differences were observed in the fall season between the two groups, but statistically significant differences were reported in three parameters (RH, $PM_{2.5}$ and PM_{10}) in the winter season.

Objective 4: To explore the influence of seasonal variations (fall and winter) on IEQ

Drawing on the findings of the objective 2, a Wilcoxon-signed rank was performed to determine the statistical significant differences in the measured parameters between the fall and winter seasons. Through the assessment, differences in some environmental parameters in certain blocks proved statistically significant between fall and winter. Six parameters: RH, TVOC, CO_2, CO, $PM_{2.5}$ and background noise varied with the two seasons. Not surprisingly, amongst the parameters which had higher winter values were TVOC, CO_2, and CO. Surprisingly, PM had higher levels in the fall than in the winter despite studies in literature which suggest that levels of indoor PM are higher in winter, just like any other pollutants, because of the closing of windows, low ventilation. Another surprising result which is contrary to findings in literature is the statistical insignificant differences in $PM_{2.5}$ between the fall and winter seasons.

Objective 5: To explore the variation of hourly time series of measured selected IAQ factors in fall and winter season; weekend and weekdays

This objective is addressed in chapter 5. Long term field measurement using less expensive equipment (i.e. foobot) were placed in the living rooms and basements of two apartments (one in block B and one in block E) to investigate the hourly time series of IAQ and thermal comfort in the fall (September-November 2016) and winter seasons (December-February 2017). Moreover, differences in parameters between weekdays and weekend were determined. The concentration levels in winter were, for the most part, higher than in the fall period. The weekdays' indoor diurnal concentration cycles of TVOC, CO_2, in both seasons and CO in winter followed similar patterns, with indoor concentrations showing two characteristic peaks (in the morning and evening) which can be attributable to occupancy pattern and outdoor levels. For weekdays, number of occupants increased in the morning and evening leading to increasing levels in CO_2 and TVOC. For CO, morning and evening indicated times when either people were commuting to or from work thus increasing number of automobiles on the road leading to higher infiltration levels indoors. Further, statistically significant differences were observed in concentration levels (i.e. CO, PM, and RH) between weekdays and weekend during the fall period for reasons related to window-opening behaviour, occupant activities. During the winter period, statistically significant differences existed in temperature levels.

6.3 Main conclusion

The main conclusions drawn from the research are that:

- The indoor environments of the studied apartments, to a large extent, were well within recommended levels of pollutants with the possibility of improving occupants' satisfaction.
- Seasonal changes had an effect on indoor environmental performance, as some of the parameters showed statistically significant differences. Generally, the levels of pollutants in winter were higher compared to the fall season, except for PM.
- Satisfied occupants often experienced low levels of pollutants compared to occupants who indicated they were unsatisfied with their indoor environment. In terms of statistically significant differences in parameters between satisfied and unsatisfied occupants, only differences in RH and PM were statistically significant.
- Concentration levels peaked in the mornings and evenings during weekdays for most of the pollutant. TVOC and CO_2 followed a similar pattern implying perhaps insufficient ventilation especially during the winter period.

In summary, IEQ is indispensable in green low-income housing.

6.4 Practical implication of the study

The insight given by this study has implications for design, construction and management of green affordable housing and these are considered below:

- The findings suggest that in low-income housing it is important to consider other unrelated environmental factors, such as building characteristics (e.g. orientation, size of space) and occupant characteristics (e.g. occupant density, in the design, construction, operation and maintenance of buildings.
- Improving and maintaining a natural partnership, in which there is a default collaboration among the community, designers, builders, health professionals (public health and environmental health specialists) will help deliver sustainable buildings where all aspects of sustainability (energy, health, environment, cost, durability) are present.
- Since seasonal variation was found to influence IEQ, and thermal comfort and indoor air quality appeared inferior in winter, this suggests potential design and control problems which could be addressed during design stage and occupant education at occupancy stage respectively. However, a more detail investigation is required to ascertain the reasons for these results. Nonetheless, occupant education should be intensified to educate occupants on behaviours that affect IAQ.
- Also, the reported low satisfaction with acoustic quality and background noise levels were above recommended residential levels. This suggests comprehensive sound attenuation strategies are necessary to improving acoustic environment of low-income housing. Noise attenuation strategies such as exterior façade and interior partition with higher ASTC, and refrigerators with lower noise levels should be employed in

residential housing irrespective of the green certification system being followed as this appeared to be a major problem.

- The results of the study provide further evidence on the need for education of occupants on their interaction with indoor environment, such as keeping of sources of TVOC, or pet keeping. As part of the occupant education, occupants should be taught beyond controls and usability of thermostat to include the effects of chemicals with high TVOC content such as cleaning agents, fragrance.

- These results provide evidence to support the decision of governments to employ green principles for low-income housing and to renovate existing social housing since the pollutant levels in the majority of the apartments were below recommended threshold noted to pose problems. The results would also aid strategic decision making by designers and real estate managers with regards to green shadowing for low-income housing since the levels of non-LEED-certified apartments had similar performance to the LEED-certified apartments.

6.5 Limitations of the study

Despite these valuable findings, it is important to acknowledge the weakness of the data, specifically pertaining to the scope, the number of household respondents. The number of apartments investigated was relatively small, so was the number of household respondents for the survey. A major limitation is that although the research design adopted for this study is adequate to achieving the overarching aim, the research is only focused on a small portion of green social housing. The physical measurement waas also snapshot for only 15 minutes with the likelihood of either underassessing or overassessing the IEQ. It is therefore possible to observe differences in the results of subjective and objective measurements with large number of apartments and also long term measurement. Thus, careful interpretations of the findings in this study are required given the limited number of apartments investigated against the overall Canadian green social housing. Getting access into houses was sometimes difficult because of availability of occupants which made it difficult to measure some environmental parameters such as illuminance level to be measured around the same time in both seasons. Further, limited number of IEQ instrument hindered the concurrent measurement of illuminance levels both indoor and outdoor, possibly causing a bias in the DF levels reported in this study. Also, the size of the apartment and the bulkiness of the cart made it difficult to get measurements from the exact same spot within all rooms while occupants and other house wares are present.

6.6 Recommendations for future study

Based on the observed limitations and the research findings, the following are recommended for future studies:

- This study only provides a snapshot the IEQ performance of green low-income housing and as such there is the scope for future studies on the parameters investigated in this study. Future research should focus on a large size of occupants and number of apartments to draw a more conclusive practical measures to improve IEQ in affordable housing.
- To complement the evaluation of IEQ in these apartments, it is important that future studies evaluate their effect both on health and well-being of occupants and energy performance. Low-income housing is noted to be frugal in their energy usage, but since utilities were paid for by the provincial government the effect might be different.
- Future studies should be based on long term measurement and include children in the scope since they represent the largest population and are most susceptible to poor IEQ.

- Occupants' behaviour (such as window-opening) and activities (e.g. cooking, dishwashing) preceding the measurements were not recorded which could have provided more explanation in the subtle nuances reported in this study. Occupant behaviour is a key issue in IEQ assessment. Occupant behaviour is complex and multidisciplinary. Therefore, it is important for researchers to study in detail the influence of occupant behaviour on IEQ.

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APPENDICES

APPENDIX I: PUBLICATIONS

<u>Refereed Journal Papers</u>

Akom, J. B., Sadick, A.-M., Issa, M. H., Rashwan, S., & Duhoux, M. (2018). The indoor environmental quality performance of green low-income single-family housing. *Journal of Green Building, 13*(2), 98-120. doi: 10.3992/1943-4618.13.2.98

Akom, J. B., Sadick, A.-M., Issa, M. H., Rashwan, S., & Duhoux, M. Seasonal variation in indoor environmental quality of green low-income housing. Advances in Building Energy Research **(under review)**

Refereed Conference Papers and Extended Abstracts

Akom, J. B., Sadick, A., Issa, M., Duhoux, M. and Rashwan, S. (2017). Validation of a methodology to evaluate indoor environmental quality in green residential buildings, *Canadian Society for Civil Engineers Annual Conference*, Leadership in Sustainable Infrastructure, Vancouver, 2017, May 31-June 3

Akom, J. B., Sadick, A., Issa, M., Duhoux, M. and Rashwan, S. (2016). A mixed-methods research methodology for evaluating indoor environmental quality in green and conventional residential buildings, *COBRA conference*, September 20-22, 2016, Toronto, Canada

Akom, J. B., Sadick, A., Issa, M., Duhoux, M. and Rashwan, S. (2016). A review of research investigating indoor environmental quality in green and conventional buildings, *Canadian Society for Civil Engineers Annual Conference*, Resilient Infrastructure, London, 2016, June 1-4.

Akom, J. B., Sadick, Abdul-Manan, Issa, M. H., Duhoux, M. and Rashwan, S. (2018). "Comparison of Weekdays' And Weekend's Indoor Environment in Green Low-income Homes", 2019 Sustainable Built Environment Conference: Europe Retrofit (SBE19 NL), Eindhoven, Netherlands, November 5 - 6, 2018.

APPENDIX II: HUMAN ETHICS APPROVAL

UNIVERSITY OF MANITOBA | Research Ethics and Compliance
Office of the Vice-President (Research and International)

Human Ethics
208-194 Dafoe Road
Winnipeg, MB
Canada R3T 2N2
Phone +204-474-7122
Fax +204-269-7173

APPROVAL CERTIFICATE

March 11, 2016

TO: **Joshua Boeteng Akom** **(Supervisor: Mohamed Issa)**
Principal Investigator [redacted]

FROM: **Zana Lutfiyya, Chair**
Education/Nursing Research Ethics Board (ENREB)

Re: **Protocol #E2015:107 (HS19207)**
"Evaluation of Indoor Environmental Quality of Green and Conventional Residential Houses."

Please be advised that your above-referenced protocol has received human ethics approval by the **Education/Nursing Research Ethics Board**, which is organized and operates according to the Tri-Council Policy Statement (2). **This approval is valid for one year only and will expire on March 11, 2017**.

Any significant changes of the protocol and/or informed consent form should be reported to the Human Ethics Secretariat in advance of implementation of such changes.

Please note:

- **If you have funds pending human ethics approval, please mail/e-mail/fax (261-0325) a copy of this Approval (identifying the related UM Project Number) to the Research Grants Officer in ORS in order to initiate fund setup. (How to find your UM Project Number: http://umanitoba.ca/research/ors/mrt-faq.html#pr0)**

- **if you have received multi-year funding for this research, responsibility lies with you to apply for and obtain Renewal Approval at the expiry of the initial one-year approval; otherwise the account will be locked.**

The Research Quality Management Office may request to review research documentation from this project to demonstrate compliance with this approved protocol and the University of Manitoba *Ethics of Research Involving Humans*.

The Research Ethics Board requests a final report for your study (available at: http://umanitoba.ca/research/orec/ethics/human_ethics_REB_forms_guidelines.html) **in order to be in compliance with Tri-Council Guidelines.**

umanitoba.ca/research

APPENDIX III: FIELD OBSERVATION SHEET CHECKLIST

PARAMETER	ITEMS	OPTIONS	TICK
Air Quality	Location of the building	Industrial area Mixed industrial / residential area Commercial area Mixed commercial / residential area City centre, densely packed housing Town, with no or small gardens Suburban, with larger gardens Village in a rural area Rural area with no or few other homes nearby	
	Nearby potential sources of outdoor air pollution that might influence the indoor environment.	None Car parking close to the building Attached garage Direct access from basement or roof car park Busy road Power plant for the building Other power plant Industry Cooling towers Built on a landfill site Waste management site (e.g. tip or dump) Agricultural sources	
	Type of outdoor air filter (Give type and class) Position of ventilation system intake	None Roof facade Ground Other	

Thermal Comfort	Type of external solar shading devices	vertical blinds shutters roller shutters louvers screens window films horizontal blinds awnings / canopies overhangs vertical fins Blind between glazing
	How are the external solar shading devices controlled	No control Individual up Automatic
	Visible air leaks	Walls Ceiling
	Are there operable windows in the home?	Yes Yes, some (estimate % apartment area with operable windows) Yes, but occupants are not allowed to open them No
	Mode of ventilation in building	Operable windows Other natural ventilation (e.g. passive stack) Mechanical ventilation Hybrid / mixed mode
	Type of mechanical ventilation	Exhaust system only - toilets, bathroom, kitchen, other polluted rooms only - also other rooms Supply system only Balanced system Balanced system with dual ducts Other
	Location of air supply devices inside home	None Floor Windowsill

		Ceiling High on wall Low on wall Other (Multi-code)
	Location of air exhaust devices inside home	None High Low
	Temperature Outside Precipitation Inside Temperature Heat Radiator	 Thermostat setting: Reading: On Off
Lighting	Do neighbouring buildings cause significant obstruction of daylight to the building?	
	Sky is	Clear Mixed (Sun + Clouds) Overcast
Acoustics	Potential noise sources outside the building that might influence the indoor environment.	None Car parking close to the building Busy road Railway or station Air traffic Sea, river or canal traffic Building, construction etc Sports events Other entertainment or leisure Factories or works Other commercial premises Forestry, farming etc Community buildings (i.e. Church, Halls, etc.)
General	Clothing	

APPENDIX IV: MEASUREMENT PROTOCOL

Table A1. THERMAL COMFORT

Requirement	Unit	Instrument	Accuracy	Maximum Concentrations
Temperature	Degree Celsius (°C)	Campbell Scientific 109-L	±6 °C	18 – 24°C[1, 2]
Relative Humidity	Percentage (%)	GrayWolf IQ 610	±3% for RH > 80%	≤ 60% [1]; 65 – 70 [3]; 20 – 60 [2]
Air Velocity	Metres per second (m/s)	GrayWolf AS-201 hotwire anemometer probe	±2%	

Additional Information:
Measurements shall occur in the living room/dining, bedrooms and kitchen. Measurements would be carried out every one minute for less than 15minutes at a mounting height of **1.45m above floor level** (i.e. human breathing zone as standing and seating, at both Kitchen and Living room respectively) because of the relatively small sizes of the rooms. In the Bedroom, mounting height shall be at **1.10m above floor level** (i.e. human breathing zone as lay). Sampling positions shall be at five points i.e. in the middle and at the corners of the room[4].

[1] McGill, G. et al. Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing. International Journal of Sustainable Built Environment (2015), http://www.dx.doi.org/10.1016/j.ijsbe.2015.03.002

[2] Ministry of social affairs and health. Finnish housing health guide (Sosiaali- jaterveysministeri€o, “Asumisterveyohje”, Oppaita 2003:1). ISBN 952-00-1301-6,
ISSN 1236e116X. Helsinki. 2003 [In Finnish)].

[3] Hui, X., Li, B., and Zheng, J. (2006). *Evaluation of IEQ in Urban Residential Buildings in Chongqin China*. Paper presented at the The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

[4] Li, Q., You, R., Chen, C., and Yang, X. (2013). A field investigation and comparative study of indoor environmental quality in heritage Chinese rural buildings with thick rammed earth wall. *Energy and Buildings*, *62*, 286-293.

Table A2. AIR QUALITY

Requirement	Unit	Instrument	Accuracy	Maximum Concentrations
Carbon Dioxide (CO_2)	Parts per million (ppm)	GrayWolf IQ-610	±3% of meter reading	650 - 1000[5]; 1200-1500[6]; 530 - 1500[7]
Carbon Monoxide (CO)				2ppm; 9ppm; 8.6 (8hr) ppm or 25 (1hr); 6.9 (8hr); 2.43 (24hr)
Total Volatile Organic Compounds (TVOC)	Microgram per cubic meter (µg/m³)			300 – 25,000 µg/m³
Particulate Matter ($PM_{2.5}$)		GrayWolf PC-3016A	50%	25 (24hr) µg/m³ ; 40 (24hr) µg/m³ ; 10-25 µg/m³
Particulate Matter (PM_{10})			100%	50 (24hr) µg/m³; 20-50 µg/m³
Radon	bq/m³	Sun Clear Corporation, model 1028	N/A	200 – 300 Bq/m³

Additional Information:
Measurements shall occur in the living room/dining, bedrooms and kitchen. Measurements would be carried out every one minute for less than 15minutes at a mounting height of **1.45m above floor level** (i.e. human breathing zone as standing and seating, at both Kitchen and Living room respectively) because of the relatively small sizes of the rooms. In the Bedroom, mounting height shall be at **1.10m above floor level** (i.e. human breathing zone as lay). Sampling positions shall be in the middle of the rooms.
Radon shall have a 24-hour exposure time.

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[5] Lai, A. C. K., Mui, K. W., Wong, L. T., and Law, L. Y. (2009). An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. *Energy and Buildings, 41*(9), 930-936.

[6] European Union Standard cited from Du, L., Prasauskas, T., Leivo, V., Turunen, M., Pekkonen, M., Kiviste, M., and Haverinen-Shaughnessy, U. (2015). Assessment of indoor environmental quality in existing multi-family buildings in North-East Europe. *Environ Int, 79*, 74-84. doi: 10.1016/j.envint.2015.03.001

[7] IGBC, Pearl, NABERS green certification

Table A3. ACOUSTICS

Requirement	Unit	Instrument	Accuracy	Measurement
Background Noise Level	Decibel (dB)	831 class 1 sound level meter	≤ ±5 dB	• With the sound sources shut down, background noise level would be measured in the receiving room at the same sampling area and instrument range setting averaging 30s at each position.
Apparent Transmission Loss (ATL)	Decibel (dB)	BAS001 speaker, BAS002 amplifier, and 831 class 1 sound level meter	N/A	• Two signal sources (distance between them ≥ 2m) shall be used as showed in the Figure. The distance of the sound source from the separating partition shall not be less than 5m, or placed at the corner most distant from the separating partition. • The measurement shall be in third octave bands with a mid-band frequencies of 100 to 5000 Hz • Doors present at both source and receiving rooms shall be closed • Average Sound Pressure Levels (SPL) would be taken using manually scanned sound level meters 30s averaging time in the source room first, with the sources operating in the source rooms. The distance of the sound level meter shall not be less than 1m from the sources. Similar process shall be repeated in the receiving room. • The speed of the sound meter level shall remain as constant as practical

Additional Information: The sources room shall be determined by the operator in one of the rooms separated by portioning, specifically a room in adjoining apartment. Where couple exists, the room with a coupled side shall be used as the source room. Sampling positions or areas shall be as showed in **Fig. 2.** The difference between the Sound levels in the receiving room and the background at any frequency shall be at least **10 dB** to prevent the increase in sources sound level and consequently repetition of all level measurements.

ATL will be found using this formula: $\boldsymbol{ATL = \overline{L}_1 - \overline{L}_2 + 10\log\left(\frac{S}{A_2}\right)}$, where: $\overline{L}_1$ = the average sound pressure level (in dB) in the source room; $\overline{L}_2$ = the average sound pressure level (in dB) in the receiving room; S = the area of the test partition (in m^2); A_2 = the sound absorption in the receiving room (m^2). $A_2 = 2\left(V^{2/3}\right)$, where: V = room volume (in m^3).

Table A4. LIGHTING

Requirement	Unit	Instrument	Accuracy	Measurement
Daylight Factor	Percentage (%)	N/A	N/A	• DF is calculated under an overcast sky. • The residential unit is varied facing four cardinal points (i.e. North, East, West or South).
Average illuminance level	Lux	Delta Ohm LP PHOT 01	±4%	• Measurement is collected at three distinct zones (perimeter, middle or internal). • Mounting height is at 0.90m above floor level

Additional Information:

The rooms (i.e. Living Room/Dinning, Bedrooms) are divided into three distinct zones using a sampling grid of 0.2 x 0.2m[8]. The sampling point is at the intersection of the grid.

The average illuminance level shall be the arithmetic average of the illuminance levels at the sampling points within the sampling space.

[8] Cheong, C., Kim, T., and Leigh, S.-B. (2014). Thermal and Daylighting Performance of Energy-Efficient Windows in Highly Glazed Residential Buildings: Case Study in Korea. *Sustainability*, *6*(10), 7311-7333. doi: 10.3390/su6107311

APPENDIX V: INTERVIEWS OF DESIGNERS

1 INVITATION

UNIVERSITY OF MANITOBA

Faculty of Engineering
Department of Civil Engineering

E1-368
15 Gillson Street
Winnipeg, Manitoba
Canada R3T 5V6
Tel (204) 474-8212
Fax (204) 474-7513

Dear designer,

SUBJECT: INVITATION TO PARTICIPATE IN IEQ INTERVIEW

Project Title: Evaluation of Indoor Environmental Quality of Green and Conventional Residential Buildings.

The aim of the study is to develop and validate a methodology for measuring indoor environmental quality (IEQ) in LEED-certified and non LEED-certified residential homes.
You are invited to participate in an interview by the University of Manitoba and ft3 concerning the above-named project. Your participation is requested because of your lead role in the design and construction of the houses being studied. Participation should take you less than an hour. Your participation is voluntary and you can withdraw from this study at any time. Subsequent arrangements such as date, time, etc. will be made following your acceptance to participate in the study.
This research has been approved by the Education/Nursing REB. If you have any concerns or complaints about this project you may contact Dr. Mohamed Issa or the Human Ethics Coordinator (HEC). Details of their contact information may be found below:

Dr. Mohamed Issa
University of Manitoba
E3-589, EITC, 15 Gillson Street
Winnipeg, MB, R3T 2N2
Phone: (204) 474-8786
Fax: (204) 474-7513
Email: Mohamed.Issa@ad.umanitoba.ca

Or
Pinar Eskicioglu, B.Kin, M.Sc.
Human Ethics Coordinator
Office of the Vice-President (Research and International)
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Winnipeg, MB R3T 2N2
Ph: 204-474-7122
Fax: 204-269-7173
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To participate in this interview, please indicate in reply to the email of the principal investigator below.
Best wishes
Joshua Boateng Akom,
Principal Investigator
E3-386, EITC, 15 Gillson Street
Winnipeg, MB, R3T 5V6,
[redacted]

2 CONSENT FORM

UNIVERSITY OF MANITOBA

Faculty of Engineering
Department of Civil Engineering

E1-368
15 Gillson Street
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Canada R3T 5V6
Tel (204) 474-8212
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Project Title: Evaluation of Indoor Environmental Quality of Green and Conventional Residential Buildings.

Principal investigator and contact information: Joshua Boateng Akom, 15 Gillson Street, Winnipeg, MB, R3T 2N2, email: akomj@myumanitoba.ca

Advisor and contact information: Mohamed Issa, 15 Gillson Street, Winnipeg, MB, R3T 2N2, email: Mohamed.Issa@umanitoba.ca

Sponsor (if applicable): Natural Sciences and Engineering Research Council of Canada

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Why have you been invited to participate?
You are being invited to participate in a study aiming at evaluating indoor environmental quality of green and conventional buildings. Please read this consent form carefully before deciding whether or not to participate in this study. Your participation in this project is voluntary and you may withdraw from the project at any time prior to submitting your responses at the end of the interview. Your decision to participate or not to participate will be kept in confidence by the researchers.

Project team
The project team includes Dr. Mohamed Issa and Mr. Joshua Boateng Akom
Mr. Joshua Boateng Akom is an MSc student at the Department of Civil Engineering, University of Manitoba. He is the principal investigator working with the advisor (Dr. Mohamed Issa) on this project.
Dr. Mohamed Issa has more than nine years experience in the field of Post-Occupancy Evaluation (POE) at the University of New Brunswick, the National Research Council and the University of Manitoba. His research work has focused on the POE of energy and IEQ in office and school buildings and the life cycle costing of these buildings, focusing on green buildings specifically. He has published extensively on the topic.

Why is the study being done?
As you may be aware there are claims that green residential buildings perform better indoor than their counterpart, conventional residential buildings. However, there are no scientific evidence to support this. Also, green building certification (e.g. Leadership in Energy and Environmental Design) provides guidance on the design and construction of buildings, but does not require extensive evaluation of post construction and operation. Indoor environment assessment is important to ensure sustainability of green homes in practice. The outcome of this study, therefore, will not only add to the lacking comparative studies on indoor environmental quality of residential buildings. It will also serve as a vital resource for the design and operation of residential buildings to improve occupant satisfaction.

What are you asked to do?
You are asked to be involved in an interview regarding the study of indoor environment quality in green and conventional residential buildings. You will be providing information on the design consideration and construction of these buildings. The interview should take about less than an hour of your time. It will be conducted by the principal investigator, Joshua Boateng Akom. Only the interviewer and interviewee will be in attendance.

Potential harm, Risk and Benefits
There is no known harm or direct benefits to participating in the study. However, your participation will help us better evaluate the indoor environmental quality in LEED- and non LEED-certified residential buildings. Your response and other responses will lead to measurement of predicted against actual performance, which would inform future operations and maintenance of the buildings.
You are not required to respond to any question in the interview that you find to be distressing. You will be able to conclude the interview without having to respond to questions you find to be distressing. With the exception of this consent page, none of the questions that will come up in the

interview has restrictions that require you to respond to them before proceeding to other questions**.**

Privacy and confidentiality

All data (recordings and transcripts) will be stored on a password secured computer, and any hardcopy information (transcript sheets) stored in secured lockers at the UoM office of the principal investigator. Only the principal investigator will have access to the raw data, both on the password secured computer and secured lockers. However, the processed data in aggregate form will be made accessible to the advisor also. All information gathered from you will be strictly confidential. The information will be completely anonymized to ensure that your responses do not reveal your identity. Also, mailing addresses will be stored in another secured locker separate from the locker of the anonymized data. Reports and research publications resulting from this study will be based on group averages but not individual responses. The designers (ft3) or industry partners will only be given aggregated data.

At the end of April, 2016, all individual survey responses and mailing addresses will be shredded and recorded values permanently deleted. These data will not be stored in any format by the researchers.

Dissemination

At the end of this study, a report will be prepared using anonymized and aggregated data and submitted to the industry partners. The purpose of this will be to provide the firm with the necessary information required to provide a suitable indoor environment. Further, the key findings and the methods employed will be presented at research conferences and also submitted to academic journals for publication. This will add to the growing body of literature on IEQ, and specifically the lacking comparative studies on residential buildings.

You have the right to change your mind

You are free to withdraw from the study at any time, and to refrain from responding to any questions, without prejudice or consequence. Simply indicate in writing to the research team if you decide to do so. You will not be required to provide an explanation whatsoever for doing so.

Can you request a summary of the study results?

You can request a summary of the study results either in electronic or printed version. This summary will be available by the end of April 2016. To request a summary of the results, please contact the principal investigator, at [redacted] The requested summary shall be submitted in person to you.

Should you have any questions or concerns regarding this research project, you are welcomed to contact the advisor or the Human Ethics Coordinator of the University of Manitoba below:

Dr. Mohamed Issa
University of Manitoba
E3-589, EITC, 15 Gillson Street
Winnipeg, MB, R3T 2N2
Phone: (204) 474-8786
Fax: (204) 474-7513

Email: Mohamed.Issa@ad.umanitoba.ca

Or

Pinar Eskicioglu, B.Kin, M.Sc.
Human Ethics Coordinator
Office of the Vice-President (Research and International)
208 – 194 Dafoe Road
University of Manitoba
Winnipeg, MB R3T 2N2
Ph: 204-474-7122
Fax: 204-269-7173
Pinar.Eskicioglu@umanitoba.ca
www.umanitoba.ca/research

Ethics review

This research has been approved by the University of Manitoba Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator (HEC). A copy of this consent form has been given to you to keep for your records and reference.

How to participate

If you agree to participate in this interview and agree to the information contained herein, the interview will begin right after.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at the research records to see that the research is being done in a safe and proper way.

Participant's signature……………………………….. Date………………………………

Researcher's signature…………………………......... Date………………………………

3 INTERVIEW SURVEY QUESTIONS

SECTION 1: DEMOGRAPHICS

1. What is your role in this organisation?

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2. What is your level of academic qualification?

   …………………………………………………………………………..
3. How long have you been working in this organisation?

   …………………………………………………………………………..
4. What is your years of professional experience?

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5. Do you have any experience with Green (LEED) buildings?

   Yes …………   No………….
6. If Yes, how many designs or buildings have you worked on?

   …………………………………………………………………………..

SECTION 2: BUILDING CHARACTERISTICS AND INDOOR ENVIRONMENT

7. Could you briefly describe the significant design intent (goals) of these types of buildings? Was there a precedent building or two that inspired the design of this building? If so, for what reason(s) were these precedents?

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8. Were there any significant changes in terms of the design process between the two types of houses – Green and Conventional? Could you briefly comment on them? You may want to comment on the Integrated Design Process or Integrated Delivery Process.

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9. Are there any publications about the building? E.g. LEED documentation and plans or any internally conducted research or technical report.

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10. What successes and challenges have occurred with respect to the design features? Can you comment on successes and challenges with technologies during construction, commissioning, or operation? How about unanticipated costs related to these?

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11. If you are aware of them, tell me about the indoor environmental quality goals, and successes of both the Green and Conventional houses. Please describe the goals, successes, challenges and strategies for each of the following:

i. Thermal Comfort

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ii. Air Quality

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iii. Acoustics

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iv. Lighting

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12. What was the intended use and intended number of occupants of the building? Are you aware of any changes to these proposed uses?

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13. Now that the building is built, could you describe some things that have surprised you, or that you have learned from? (both positive and negative)

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14. If in a radon-affected area, what foundation construction and ventilation strategies (control of pressure difference) were incorporated into the design (or other measures) to control ingress of radon?

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15. Are there any other pertinent details about the successes or challenges of the performance of this building that we haven't discussed yet?

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4 INTERVIEW RESPONSE

Interviewer: Do you have any experience with green/LEED buildings?

Answer: *"Yes, I have worked on over 40 green/LEED building projects"*

Interviewer: Can you briefly describe the specific design intent, goals and features you had in mind for the LEED homes and non-LEED ones? i.e. what were you looking to accomplish specifically in these homes?

Answer: *"durability, energy efficiency, water efficiency, quality control"*

Interviewer: Were you able to accomplish these design goals and features in the LEED homes and non-LEED ones? Did you run into any specific challenges with respect to them at any point in time? Were there any specific challenges (e.g. technology) during the construction, commissioning and operation phases that you're aware of?

Answer: *"there were challenges in meeting the airtightness requirements during construction of the Thompson housing"*

Interviewer: Can you briefly describe the specific design intent, goals and features with respect to indoor environmental quality (IEQ) for the LEED homes in particular? Were you able to accomplish these goals and features? Did you run into any specific challenges with respect to them at any point in time? Were there any specific challenges during the construction, commissioning and operation phases that you're aware of?

Answer: *"**Thermal comfort** - no specific requirements in LEED for Homes, however several requirements contribute to improved comfort. Energy performance was the main driver of LEED certification and as such influenced thermal comfort. The goals were not that innovative, but we wanted to make sure they were just good. 3rd party inspection / testing of systems helped to ensure design and install is performing as intended.*
***Air quality** - 3rd party inspection / testing of ventilation system performance during construction helped to ensure issues were found and corrected so good IAQ could be achieved.*
***Acoustics** - No special noise attenuation strategies were used except that contained in the building codes. So interior partitions between units have high STC to minimize sound transmission between adjacent units.*
***Lighting** - advanced lighting package was targeted and achieved"*

Interviewer: What was the expected number of occupants in each LEED and non-LEED home? Do you know the actual number of occupants in each home?

Answer: *"3 and 4-bedroom units with high occupant density, actual occupants unknown"*

APPENDIX VI: INTERVIEWS OF FACILITY MANAGER

1 INVITATION

UNIVERSITY OF MANITOBA

Faculty of Engineering
Department of Civil Engineering

E1-368
15 Gillson Street
Winnipeg, Manitoba
Canada R3T 5V6
Tel (204) 474-8212
Fax (204) 474-7513

Dear facilities manager,

SUBJECT: INVITATION TO PARTICIPATE IN IEQ INTERVIEW

Project Title: Evaluation of Indoor Environmental Quality of Green and Conventional Residential Buildings.

The aim of the study is to develop and validate a methodology for measuring indoor environmental quality (IEQ) in LEED-certified and non LEED-certified residential homes.
You are invited to participate in an interview by the University of Manitoba and ft3 concerning the above-named project. Your participation is important because of your role as a facilities manager of the houses which are being studied in this project. Participation should take you less than an hour. Your participation is voluntary and you can withdraw from this study at any time. Subsequent arrangements such as date, time, etc. will be made following your acceptance to participate in the study.
This research has been approved by the Education/Nursing REB. If you have any concerns or complaints about this project you may contact Dr. Mohamed Issa or the Human Ethics Coordinator. Details of their contact information may be found below:

Dr. Mohamed Issa
University of Manitoba
E3-589, EITC, 15 Gillson Street
Winnipeg, MB, R3T 2N2
Phone: (204) 474-8786
Fax: (204) 474-7513
Email: Mohamed.Issa@ad.umanitoba.ca

Or

Pinar Eskicioglu, B.Kin, M.Sc.
Human Ethics Coordinator
Office of the Vice-President (Research and International)
208 – 194 Dafoe Road
University of Manitoba
Winnipeg, MB R3T 2N2
Ph: 204-474-7122
Fax: 204-269-7173
Pinar.Eskicioglu@umanitoba.ca
www.umanitoba.ca/research

To participate in this interview, please indicate in reply to this email of the principal investigator below.
Best wishes,
Joshua Boateng Akom,
Principal Investigator
E3-386, EITC, 15 Gillson Street
Winnipeg, MB, R3T 5V6,
[redacted]

2 CONSENT FORM

UNIVERSITY OF MANITOBA

Faculty of Engineering
Department of Civil Engineering

E1-368
15 Gillson Street
Winnipeg, Manitoba
Canada R3T 5V6
Tel (204) 474-8212
Fax (204) 474-7513

Project Title: Evaluation of Indoor Environmental Quality of Green and Conventional Residential Buildings.

Principal investigator and contact information: Joshua Boateng Akom, 15 Gillson Street, Winnipeg, MB, R3T 2N2, email: akomj@myumanitoba.ca

Advisor and contact information: Dr. Mohamed Issa, University of Manitoba, 15 Gillson Street, Winnipeg, MB, R3T 2N2, email: Mohamed.Issa@umanitoba.ca

Sponsor (if applicable): Natural Sciences and Engineering Research Council of Canada

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.**Why have you been invited to participate?**

You are being invited to participate in a study aiming at evaluating indoor environmental quality of green and conventional buildings. Please read this consent form carefully before deciding whether or not to participate in this study. Your participation in this project is voluntary and you may withdraw from the project at any time prior to submitting your responses at the end of the interview. Your decision to participate or not to participate will be kept confidential.

Project team

The project team includes Dr. Mohamed Issa and Mr. Joshua Boateng Akom

Mr. Joshua Boateng Akom is an MSc student at the Department of Civil Engineering, University of Manitoba. He is the principal investigator working with the advisor (Dr. Mohamed Issa) on this project.

Dr. Mohamed Issa has more than nine years experience in the field of Post-Occupancy Evaluation (POE) at the University of New Brunswick, the National Research Council and the University of Manitoba. His research work has focused on the POE of energy and IEQ in office and school buildings and the life cycle costing of these buildings, focusing on green buildings specifically. He has published extensively on the topic.

Why is the study being done?

As you may be aware there are claims that green residential buildings perform better indoor than their counterpart, conventional residential buildings. However, there are no scientific evidence to support this. Also, green building certification (e.g. Leadership in Energy and Environmental Design) provides guidance on the design and construction of buildings, but does not require extensive evaluation of post construction and operation. Indoor environment assessment is important to ensure sustainability of green homes in practice. The outcome of this study, therefore, will not only add to the lacking comparative studies on indoor environmental quality of residential buildings. It will also serve as a vital resource for the design and operation of residential buildings to improve occupant satisfaction.

What are you asked to do?

You are asked to be involved in an interview regarding the study of indoor environment quality in green and conventional residential buildings. You will be providing responses on the operation of these buildings under your management. The interview should take about less than an hour of your time. It will be conducted by the principal investigator, Joshua Boateng Akom; and it will involve only the interviewer and interviewee.

Potential harm, Risk and Benefits

There is minimal risk or direct benefits to participating in the study. However, your participation will help us better evaluate the indoor environmental quality in LEED- and non LEED-certified residential buildings. Your response and other responses will lead to measurement of predicted against actual performance, which would inform future operations and maintenance of the buildings.

You are not required to respond to any question in the interview that you find to be distressing. You will be able to conclude the interview without having to respond to questions you find to be distressing. With the exception of this consent page, none of the questions that will come up in the interview has restrictions that require you to respond to them before proceeding to other questions.

Privacy and confidentiality

All data (recordings and transcripts) will be stored on a password secured computer, and any hardcopy information (transcript sheets) stored in secured lockers at the UoM office of the principal investigator. Only the principal investigator will have access to the raw data, both on the password secured computer and secured lockers. However, the processed data in aggregate form will be made accessible to the advisor also. All information gathered from you will be strictly confidential. The information will be completely anonymized to ensure that your responses do not reveal your identity. Also, mailing addresses will be stored in another secured locker separate from the locker of the anonymized data. Reports and research publications resulting from this study will be based on group averages but not individual responses. The designers (ft3) or industry partners will only be given aggregated data.

At the end of April, 2016, all individual survey responses and mailing addresses will be shredded and recorded values permanently deleted. These data will not be stored in any format by the researchers.

Dissemination

At the end of this study, a report will be prepared using anonymized and aggregated data, and submitted to the designers (i.e. ft3). The purpose of this will be to provide the firm with the necessary information required to provide a suitable indoor environment. Further, the key findings and the methods employed will be presented at research conferences and also submitted to academic journals for publication. This will add to the growing body of literature on IEQ, and specifically the limited studies on residential buildings.

You have the right to change your mind

You are free to withdraw from the study at any time, and to refrain from responding to any questions, without prejudice or consequence. Simply indicate in writing to the research team if you decide to do so. You will not be required to provide an explanation whatsoever for doing so.

Can you request a summary of the study results?

You can request a summary of the study results either in electronic or printed version. This summary will be available by the end of April 2016. To request a summary of the results, please contact the principal investigator, at [redacted] The requested summary shall be submitted in person to you.

Should you have any questions or concerns regarding this research project, you are welcomed to contact the advisor or the Human Ethics Coordinator of the University of Manitoba below:

Dr. Mohamed Issa
University of Manitoba
E3-589, EITC, 15 Gillson Street
Winnipeg, MB, R3T 2N2
Phone: (204) 474-8786
Fax: (204) 474-7513
Email: Mohamed.Issa@ad.umanitoba.ca

Or

Pinar Eskicioglu, B.Kin, M.Sc.
Human Ethics Coordinator
Office of the Vice-President (Research and International)
208 – 194 Dafoe Road
University of Manitoba
Winnipeg, MB R3T 2N2
Ph: 204-474-7122
Fax: 204-269-7173
Pinar.Eskicioglu@umanitoba.ca
www.umanitoba.ca/research

Ethics review

This research has been approved by the University of Manitoba Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator (HEC). A copy of this consent form has been given to you to keep for your records and reference.

How to participate

If you agree to participate in this interview and agree to the information contained herein, the interview will begin right after.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.
The University of Manitoba may look at the research records to see that the research is being done in a safe and proper way.

Participant's signature………………………………….. Date………………………………

Researcher's signature……………………………......... Date………………………………

3 INTERVIEW SURVEY QUESTIONS

1. What is your role in this organization?

   ………………………………………………………………………..

2. How long have you been in the field of facilities management for?

   ……………………………………..…………………………

3. Do you have any experience with green/LEED buildings?

   Yes ………… No………….

4. If yes, how many green/LEED building projects did you work on?

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5. Did you encounter anything new or different when you started managing these LEED-certified homes and non-LEED ones? Did you receive any relevant operation and maintenance training?

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6. Do you have any specific goals with respect to IEQ? Do you have any specific strategies in place to accomplish them? Were you able to accomplish these goals and strategies? Did you run into any specific challenges with respect to them at any point in time?

   v. Thermal Comfort

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vi. Air Quality

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vii. Acoustics

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viii. Lighting

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7. Ft3 Architects expected X number of occupants in each home. What is the actual number of occupants in each home? If applicable, what accounts for this discrepancy?

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8. Do the occupants have any specific complaints with respect to IEQ in the LEED-certified and non-LEED homes?

ix. Thermal Comfort

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x. Air Quality

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xi. Acoustics

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xii. Lighting

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9. Do you have any operation and maintenance records for these homes that you can provide us with? Do you have any IEQ records in particular that you can provide us with?

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10. Do you provide any operation and maintenance training to home occupants: in terms of controls and how to take proper care of the homes? Do you provide them with any feedback about the IEQ performance of their homes?

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11. How regular do you inspect or check homes with subsequent repairs?

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12. Do you have any diagnostic tool that helps you evaluate the seriousness of IEQ problems, and that help tenants to rectify ‘minor’ problems?

13. Do you have an asbestos management plan for these homes?

Yes [ ] No [ ]

If yes, can you elaborate on that plan?

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14. How often are supply air ducts cleaned? How often are supply and exhaust air devices cleaned?

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15. Are there any lead components in these homes and where are they located?

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16. Are you aware of any issues related to mold or radon in these homes?

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THANK YOU

4 INTERVIEW RESPONSE

Interviewer: Did you encounter anything new or different when you started managing these LEED-certified homes and non-LEED ones? Did you receive any relevant operation and maintenance training?

> Answer: "*No I have found no difference in managing the LEED certified homes and the non-LEED ones"*

Interviewer: Ft3 Architects expected X number of occupants in each home. What is the actual number of occupants in each home? If applicable, what accounts for this discrepancy?

> Answer: "*We follow the National Occupancy Standards. There could be up to two occupants per bedroom"*

Interview: Do the occupants have any specific complaints with respect to IEQ in the LEED-certified and non-LEED homes?

> Answer: *"Thermal Comfort – Air conditioning not working properly in the beginning. Several air locks in the G.O. Thermal. The unit are slow to heat and cool the tenant expect the it to happen immediately.*
>
> *Acoustics – Family Housing Normal Noise"*

Interview: Do you have any operation and maintenance records for these homes that you can provide us with? Do you have any IEQ records in particular that you can provide us with?

> Answer: "*Yes, there was training for some staff when the units were turned over from the contractor to us. But I was not part of the original training"*

Interview: Do you provide any operation and maintenance training to home occupants: in terms of controls and how to take proper care of the homes? Do you provide them with any feedback about the IEQ performance of their homes?

> Answer: *"The thermostats that were originally installed in the unit where not easy to operate. We were called several times to unit to repair heat and A/C once the thermostats were replaced the calls stopped"*

Interview: How regular do you inspect or check homes with subsequent repairs?

> Answer: *"At minimum we are in the unit once a year as we are required to complete an Annual Unit Inspection. The tenant is also responsible to call into our call centre and report any repairs that are need in the unit"*

Interview: Do you have any diagnostic tool that helps you evaluate the seriousness of IEQ problems, and that help tenants to rectify 'minor' problems?

Answer: *"We are responsible to repair everything in the unit the tenant is not responsible at all"*

Interviewer: How often are supply air ducts cleaned? How often are supply and exhaust air devices cleaned?

Answer: *"When a unit is vacated and before a new tenant moves in or as needed"*

APPENDIX VII: OCCUPANT SURVEY

1 INVITATION

UNIVERSITY OF MANITOBA

Faculty of Engineering
Department of Civil Engineering

E1-368
15 Gillson Street
Winnipeg, Manitoba
Canada R3T 5V6
Tel (204) 474-8212
Fax (204) 474-7513

Dear occupant,

INVITATION TO PARTICIPATE IN INDOOR ENVIRONMENTAL QUALITY RESEARCH

Project Title: Evaluation of Indoor Environmental Quality of Green and Conventional Residential Buildings.

The aim of the study is to develop and validate a methodology for measuring indoor environmental quality (IEQ) in LEED-certified and non LEED-certified residential homes.

This email is to invite you to participate in a study investigating the indoor environment of your house. This study will involve the physical measurement of temperature, pollutants, noise, etc., observation of your home's indoor environment; and finally a survey on your satisfaction with your indoor environment. Your participation in this study is absolutely voluntary, and a consent form will be attached to the survey questions; of which you are to read and to indicate your participation. Also, there will be a physical monitoring of your indoor environment. The estimated completion time for the questionnaire based on multiple test run ranges 15 to 20 minutes. Further, the physical monitoring is expected to last between 3 and 4 hours. The parameters would be measured under normal room environment or conditions and as such would not expect you to alter your activities.

This research has been approved by the University of Manitoba Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact the advisor of the principal investigator for the study, or the Human Ethics Coordinator (HEC) at:

Dr. Mohamed Issa
University of Manitoba
E3-589, EITC, 15 Gillson Street
Winnipeg, MB, R3T 2N2
Phone: (204) 474-8786

Fax: (204) 474-7513
Email: Mohamed.Issa@ad.umanitoba.ca
Or
Pinar Eskicioglu, B.Kin, M.Sc.
Human Ethics Coordinator
Office of the Vice-President (Research and International)
208 – 194 Dafoe Road
University of Manitoba
Winnipeg, MB R3T 2N2
Ph: 204-474-7122
Fax: 204-269-7173
Pinar.Eskicioglu@umanitoba.ca
www.umanitoba.ca/research

To participate in this interview, please indicate in reply to this email of the principal investigator below.

Thank you,

Joshua Boateng Akom,
Principal Investigator
E3-386, EITC, 15 Gillson Street
Winnipeg, MB, R3T 5V6,
[redacted]

2 CONSENT FORM

UNIVERSITY OF MANITOBA

Faculty of Engineering
Department of Civil Engineering

E1-368
15 Gillson Street
Winnipeg, Manitoba
Canada R3T 5V6
Tel (204) 474-8212
Fax (204) 474-7513

Project Title: Evaluation of Indoor Environmental Quality of Green and Conventional Residential Buildings.

Principal investigator and contact information: Joshua Boateng Akom, 15 Gillson Street, Winnipeg, MB, R3T 2N2, email: akomj@myumanitoba.ca

Advisor and contact information: Mohamed Issa, 15 Gillson Street, Winnipeg, MB, R3T 2N2, email: Mohamed.Issa@umanitoba.ca

Sponsor (if applicable): Natural Sciences and Engineering Research Council of Canada

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Why have you been invited to participate?
You are being invited to participate in a study aiming at evaluating indoor environmental quality of green and conventional buildings. Please read this consent form carefully before deciding whether or not to participate in this study. Your participation in this project is voluntary and you may withdraw from the project at any time prior to submitting your responses at the end of the survey. Your decision to participate or not to participate will be kept in confidence by the researchers.

Project team
The project team includes Dr. Mohamed Issa and Mr. Joshua Boateng Akom
Mr. Joshua Boateng Akom is an MSc student at the Department of Civil Engineering, University of Manitoba. He is the principal investigator working with the advisor (Dr. Mohamed Issa) on this project.
Dr. Mohamed Issa has more than nine years experience in the field of Post-Occupancy Evaluation (POE) at the University of New Brunswick, the National Research Council and the University of

Manitoba. His research work has focused on the POE of energy and IEQ in office and school buildings and the life cycle costing of these buildings, focusing on green buildings specifically. He has published extensively on the topic.

Why is the study being done?

The indoor environment may be 80% more polluted than outdoor environment. There are also health implications to poor indoor environmental quality because people spent about 70% of their time at home. As you may be aware there are claims that green residential buildings perform better indoor than their counterpart, conventional residential buildings. However, there are no scientific evidence to support this. Also, green building certification (e.g. Leadership in Energy and Environmental Design) provides guidance on the design and construction of buildings, but does not require extensive evaluation of post construction and operation. Indoor environment assessment is important to ensure sustainability of green homes in practice. The outcome of this study, therefore, will not only add to the lacking comparative studies on indoor environmental quality of residential buildings. It will also serve as a vital resource for the design and operation of residential buildings to improve occupant satisfaction.

What are you asked to do?

You are asked to complete a survey regarding your satisfaction with the indoor environment of your home. Also, to permit the measurement of indoor environmental quality parameters such as temperature, humidity, carbon dioxide, etc. and make observation in your house. The survey should take about 15 to 20 minutes of your time. The measurement should take about 3-5 hours. The measurement is expected to capture the natural setting of your home, so your presence will not alter or influence the measurements in any way. But it will give a perfect picture of your home's indoor environment.

Potential harm, Risk and Benefits

There is no known harm or direct benefits to participating in the study. However, your participation will help us better evaluate the indoor environmental quality of your home and will lead to improvement of your space.

You are not required to answer any question in the survey that you find to be distressing. You will be able to submit your responses without having to answer questions you find to be distressing. With the exception of this consent page, none of the questions in the survey has restrictions that require you to answer them before proceeding to other questions or submitting your responses.

Privacy and confidentiality

All data (measurement recordings and survey responses) will be stored on a password secured computer, and any hardcopy information (survey, observation sheet) stored in secured lockers at the UoM office of the principal investigator. Only the principal investigator will have access to the raw data, both on the password secured computer and secured lockers. However, the processed data in aggregate form will be made accessible to the advisor also. All information gathered from you will be strictly confidential. The information will be completely anonymized to ensure that your responses do not reveal your identity. Also, mailing addresses will be stored in another secured locker separate from the locker of the anonymized data. Reports and research publications resulting from this study will be based on group averages but not individual responses. The designers (ft3) or industry partners will only be given aggregated data.

At the end of April, 2016, all individual survey responses and mailing addresses will be shredded and recorded values permanently deleted. These data will not be stored in any format by the researchers.

Dissemination

At the end of this study, a report will be prepared using anonymized and aggregated data and submitted to the design team. The purpose of this will be to provide the firm with the necessary information required to provide a suitable indoor environment. Further, the key findings and the methods employed will be presented at research conferences and also submitted to academic journals for publication. This will add to the growing body of literature on IEQ, and specifically the lacking comparative studies on residential buildings.

You have the right to change your mind

You are free to withdraw from the study at any time, and to refrain from answering any questions, without prejudice or consequence. Simply do not return the questionnaire if you decide to do so. You will not be required to provide an explanation for doing so.

Can you request a summary of the study results?

You can request a summary of the study results either in electronic or printed version. This summary will be available by the end of April 2016. To request a summary of the results, please contact the principal investigator, at [redacted] The requested summary shall be submitted directly to you either in person or via mailing. Should you have any questions or concerns regarding this research project, you are welcomed to contact the advisor or the Human Ethics Coordinator of the University of Manitoba below:

Dr. Mohamed Issa
University of Manitoba
E3-589, EITC, 15 Gillson Street
Winnipeg, MB, R3T 2N2
Phone: (204) 474-8786
Fax: (204) 474-7513
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Or
Pinar Eskicioglu, B.Kin, M.Sc.
Human Ethics Coordinator
Office of the Vice-President (Research and International)
208 – 194 Dafoe Road
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Ethics review

This research has been approved by the University of Manitoba Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator (HEC). A copy of this consent form has been given to you to keep for your records and reference.

How to participate

If you agree to participate in this survey and agree to the information contained herein, paper based questionnaire will be sent to you with a returning postal envelope.

Permission to enter premises

Following your acceptance to participate in this study, the University of Manitoba will be monitoring the physical indoor environment of your house and as such will require your permission to enter your house. The U of M research team will be using a mobile measurement tripods with installed sensors to collect the data over approximately 15 minutes at every predetermined location in the building. The whole monitoring is expected to last between 4 and 5 hours. The equipment will be accompanied by the principal investigator and an assistant who would be happy to answer your questions should you have any.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at the research records to see that the research is being done in a safe and proper way.

Participant’s signature…………………………………….. Date………………………………

Researcher’s signature……………………………......... Date………………………………

3 SURVEY QUESTIONNAIRES

PART 1: BACKGROUND INFORMATION

1. What is your gender?
   a) Male [ ]
   b) Female [ ]
2. How old are you?
   a) 30 or under [ ]
   b) 31-50 [ ]
   c) Over 50 [ ]
3. Please indicate your weight
   a) Below 100 LB [ ]
   b) 100 – 120 LB [ ]
   c) 121 – 140 LB [ ]
   d) 141 – 160 LB [ ]
   e) Above 160 LB [ ]
4. How long have you been living in this house?
   a) Less than 1 year [ ]
   b) 1-2 years [ ]
   c) 3-5 years [ ]
   d) More than 5 years [ ]
5. What is your employment status?
   a) Employed [ ]
   b) Unemployed [ ]

c) Student [ ]

d) Retired [ ]

e) Parental leave [ ]

6. What is your highest level of education?

a) No post-secondary education [ ]

b) Trade certificate [ ]

c) Bachelor degree [ ]

d) Masters or PhD program [ ]

e) Other, please specify ……… [ ]

PART 2: OCCUPANCY

7. What factors informed your choice of renting this house?

a) Comfortable indoor environment [ ]

b) Low energy consumption [ ]

c) Affordability of price or rent [ ]

d) Location in the city [ ]

e) Other environmental factors in the house [ ]

8. How many people currently live in your house including yourself?

………………………………..

9. In a typical day, how many hours do you spend on average indoors in your home?

a) 5 or less [ ]

b) 5-10 [ ]

c) 10-15 [ ]

d) 15-20 [ ]

e) More than 20 [ ]

10. In a typical day, what percentage of your time indoors do you spend on average in each of the following locations? (Please ensure the six entries add up to 100%).

a) Bathroom [ ] %

b) Bedroom [ ] %

c) Kitchen [ ] %

d) Living room [ ] %

e) Common areas of building [ ] %

f) Elsewhere, please specify………………. [ ] %

11. In a typical day, what percentage of your time indoors do you spend on average on each of the following activities in your home (Please ensure the five entries add up to 100%).

a) Sleeping [ ] %

b) Sedentary activities (e.g. reading, watching television etc.) [ ] %

c) Low-intensity activity (cooking, etc.) [ ] %

d) High-intensity activity (exercising) [ ] %

e) Others, please specify……………………………………. [ ] %

12. Do you smoke indoors?

Yes [ ] No [ ]

13. Do you keep pets (dogs, cats, etc.) indoors?

Yes [ ] No [ ]

PART 3: INDOOR ENVIRONMENT QUALITY

Answer the following questions based on the locations (e.g. living room, bedroom) in your home where you spend most of your time.

THERMAL COMFORT

14. Rank the following adaptive control behaviors used to regulate indoor temperature in your home?
    a) Closing or opening windows [ ]
    b) Adjusting indoor shading (e.g. blinds, curtains) [ ]
    c) Regulating thermostat [ ]
    d) Turning on or off air conditioner [ ]
    e) Adjustable air vent (in wall, floor or ceiling) [ ]
    f) Use of portable supplementary electric heater [ ]
    g) Use of portable/ permanent fan [ ]
    h) Fitting of Clothes [ ]
    i) Turning on or off Heat recovery ventilator (HRV) [ ]
    j) Use of air humidifier [ ]
    k) Taking a cold or hot shower/bath [ ]

15. How would you describe your average indoor home temperature during the Fall season?

Daytime

Always warm	Often warm	Sometimes warm	Rarely warm	Never warm

Night

Always warm	Often warm	Sometimes warm	Rarely warm	Never warm

16. How do you feel **RIGHT NOW**?

Too warm	Warm	Comfortable	Cold	Too cold

17. How often do you experience each of the following problems indoors?

Problem	Frequency				
	Always	Often	Sometimes	Rarely	Never
Hot temperature					
Cold temperature					
Humidity too high (damp)					
Humidity too low (dry)					
Drafts from windows or vents					

18. Are the thermostats or fan controls in your room easy to…?

Find			
Yes, very	Yes, quite	No	Don’t know
Use			
Yes, very	Yes, quite	No	Don’t know

19. Overall, how satisfied or dissatisfied are you with your home’s thermal comfort in general?

Very Dissatisfied					Very Satisfied	
1	2	3	4	5	6	7

INDOOR AIR QUALITY

20. Rank the following adaptive control behaviors used to regulate indoor air environment in your home?
    a) Closing or opening windows [ ]
    b) Turning on or off air conditioner [ ]
    c) Adjustable air vent (in wall, floor or ceiling) [ ]
    d) Use of portable/ permanent fan [ ]
    e) Turning on or off Heat recovery ventilators (HRV) [ ]
    f) Use of air humidifier [ ]

21. Do you have a radon problem in your house?
    Yes [ ] No [ ] Not sure [ ]

22. Do you have mold in your house?
    Yes [ ] No [ ] Not sure [ ]

23. How is the air quality in your room **RIGHT NOW**?

No peculiar smell	Slightly smelly	Smelly	Very smelly	Limited tolerance

24. What bothers you about the air quality **RIGHT NOW**? Indicate all that apply

Stuffy/stale	Dusty	Garbage smell	Smoky	Sewer odor

25. How often do you experience each of the following problems indoors?

Problem	Frequency				
	Always	Often	Sometimes	Rarely	Never
Stuffy/stale air					
Unclean/ dusty air					
Garbage smell					
Smoke (e.g. cooking)					

Cigarette smoke
Sewer odor

26. Overall, how satisfied or dissatisfied are you with your home's indoor air quality in general?

Very Dissatisfied					Very Satisfied	
1	2	3	4	5	6	7

LIGHTING QUALITY

27. During the daytime, is there enough daylight in your room without turning on artificial light?

Yes [ ] No [ ] Not sure [ ]

28. How many hours of sunlight do you get on average in your home?

Less than 1	1-2	2-3	3-4	More than 4

29. How many hours of sunlight do you prefer to have in your home?

Less than 1	1-2	2-3	3-4	More than 4

30. How often do you experience each of the following problems indoors?

	Frequency				
Problems	Always	Often	Sometimes	Rarely	Never
Room too dark					
Room too light					
Glare					
Light flicker					
Thermal discomfort					

31. How would you describe the overall daylighting in your room **RIGHT NOW**?

Bright	Slightly bright	Neutral	Slightly dim	Dim

32. How is your home's electric lighting quality **RIGHT NOW**?

Very Dissatisfied					Very satisfied	
1	2	3	4	5	6	7

33. Overall, how satisfied or dissatisfied are you with your home's overall lighting quality in general?

Very Dissatisfied					Very Satisfied	
1	2	3	4	5	6	7

ACOUSTICS QUALITY

34. How satisfied or dissatisfied are you with speech privacy in your home (i.e. ability to have conversations in one room without others overhearing it and vice versa)?

Very Dissatisfied					Very Satisfied	
1	2	3	4	5	6	7

35. How would you describe the noise level in your room **RIGHT NOW**?

No noise	Slightly noisy	Noisy	Very noisy	Limited tolerance

36. How disturbing is each of the following sources of noise to you?

Source of noise	Frequency				
	Always	Often	Sometimes	Rarely	Never
Outdoor noise					
Street (e.g. traffic, garbage truck)					
People					
Animals (e.g. birds)					
Neighbours					
Indoor noise					
Heating, ventilation, air conditioning equipment (HVAC) (e.g. fans, A/C, exhausts, etc.)					
Plumbing (taps and showers)					
Home appliances and electronics					
Speech					
Non-speech (e.g. footsteps)					

37. Overall, how satisfied or dissatisfied are you with your home's sound insulation in general?

Very Dissatisfied					Very Satisfied	
1	2	3	4	5	6	7

OVERALL INDOOR ENVIRONMENT QUALITY

38. Overall how satisfied or dissatisfied are you with your home's indoor environment?

Very Dissatisfied					Very Satisfied	
1	2	3	4	5	6	7

4 SURVEY RESULTS

Table A5: IEQ problems

Problems	Fall		Winter	
	Air quality			
	Mean	Std. Dev	Mean	Std. Dev
Stuffy/Stale air	3.64	1.22	4.06	1.00
Unclean/Dusty Air	3.68	1.46	4.21	0.80
Garbage smell	4.24	0.93	4.08	0.79
Smoke	3.96	0.89	4.00	0.82
Cigarette smoke	4.52	0.77	4.08	0.79
Sewer Odor	4.52	0.87	4.45	0.52
	Lighting Comfort			
Room too dark	4.00	1.41	4.23	0.73
Room too light	4.18	0.99	3.79	1.05
Glare	4.33	0.88	3.5	1.40
Light flicker	4.41	0.84	4.31	0.95
Thermal discomfort	4.11	0.93	3.93	1.14
	Acoustics Quality			
Noise from Street	3.12	1.21	2.74	1.19
Noise from people	3.24	1.16	3.27	1.16
Noise from Animals	4.04	1.17	3.93	1.27
Neighbour noise	3.40	1.04	3.08	1.24
HVAC	4.13	0.92	3.62	1.61
Plumbing	3.46	1.35	3.27	1.35
Home appliances	3.30	1.26	3.55	1.37
Speech	3.48	1.24	3.10	1.29
Non-speech	3.24	1.14	3.10	1.29
	Thermal Comfort			
Hot temperature	3.36	1.32	3.75	1.13
Cold temperature	3.64	0.91	3.60	.74
Humidity too high	4.24	0.93	4.46	.66
Humidity too low	3.92	1.08	4.00	1.29
Drafts	3.87	1.3	3.75	.97

Table A6: Average Indoor temperature during daytime

	Fall	Winter
Always warm	30.8%	4.5%
Often warm	23.1%	13.6%
Sometimes warm	38.5%	22.7%
Rarely warm	7.7%	54.5%
Never warm		4.5%

Table A7: Average Indoor temperature during night time

	Fall	Winter
Always warm	30.8%	4.5%
Often warm	30.8%	18.2%
Sometimes warm	23.1	36.4%
Rarely warm	15.4%	27.3%
Never warm		13.6%