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CALIBRATED ENERGY SIMULATIONS OF POTENTIAL ENERGY

SAVINGS IN ACTUAL RETAIL BUILDINGS

A Dissertation in
Architectural Engineering
by
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ABSTRACT

Retail stores are commercial buildings with high energy consumption due to their typically large volumes and long hours of operation. This dissertation assesses heating, ventilating and air conditioning saving strategies based on energy simulations with input parameters from actual retail buildings. The dissertation hypothesis is that “Retail store buildings will save a significant amount of energy by (1) modifying ventilation rates, and/or (2) resetting set point temperatures. These strategies have shown to be beneficial in previous studies. As presented in the literature review, potential energy savings ranged from 0.5% to 30% without compromising indoor thermal comfort and indoor air quality. The retail store buildings can be ventilated at rates significantly lower than rates called for in the ASHRAE Standard 62.1-2010 while maintaining acceptable indoor air quality. Therefore, two dissertation objectives are addressed: (1) Investigate opportunities to reduce ventilation rates that do not compromise indoor air quality in retail stores located in Central Pennsylvania, (2) Investigate opportunities to increase (in summer) and decrease (in winter) set point temperatures that do not compromise thermal comfort.

This study conducted experimental measurements of ventilation rates required to maintain acceptable air quality and indoor environmental conditions requirements for two retail stores using ASHRAE Standard 62.1_2012. More specifically, among other parameters, occupancy density, indoor and outdoor pollutant concentrations, and indoor temperatures were measured continuously for one week interval. One of these retail stores were tested four times for a yearlong time period. Pollutants monitored were formaldehyde, carbon dioxide, particle size distributions and concentrations, as well as total volatile organic compounds.

As a part of the base protocol, the number of occupants in each store was hourly counted during the test, and the results reveal that the occupant densities were approximately 20% to 30%
of that called by ASHRAE 62.1. Formaldehyde was the most important contaminant of concern in retail stores investigated. Both stores exceeded the most conservative health guideline for formaldehyde (OEHHA TWA REL = 7.3 ppb). This study found that source removal and reducing the emission rate, as demonstrated in retail stores sampled in this study, is a viable strategy to meet the health guideline.

Total volatile compound were present in retail stores at low concentrations well below health guidelines suggested by Molhave (1700μg /m²) and Bridges (1000 μg /m²). Based on these results and through mass–balance modeling, different ventilation rate reduction scenarios were proposed, and for these scenarios the differences in energy consumption were estimated. Findings of all phases of this desertion have contributed to understanding (a) the trade-off between energy savings and ventilation rates that do not compromise indoor air quality, and (b) the trade-off between energy savings and resets of indoor air temperature that do not compromise thermal comfort. Two models for retail stores were built and calibrated and validated against actual utility bills. Energy simulation results indicated that by lowering the ventilation rates from measured and minimum references would reduce natural gas energy use by estimated values of 6% to 19%. Also, this study found that the electrical cooling energy consumption was not significantly sensitive to different ventilation rates. However, increasing indoor air temperature by 3°C in summer had a significant effect on the energy savings.

In winter, both energy savings strategies, ventilation reduction and decrease in set points, had a significant effect on natural gas consumption. Specially, when the indoor air temperature 21°C was decreased to 19.4°C with the same amount of ventilation rate of Molhaves guideline for both cases.
Interestingly, the temperature of 23.8°C (75°F), which is the lowest value of ASHRAE 55 thermal comfort for sedentary people (cashiers) and the highest value for thermal comfort adjustments due to activity level (customers and workers) that are calculated by using empirical equation, was the optimum temperature for sedentary and active people in Retail store buildings.
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I raise my glass high in your direction,
And celebrate your love for education.
Chapter 1

Introduction

This chapter consists of five sections. Section 1.1 provides a narrative about retail store buildings and their energy consumption. Section 1.2 describes the reasons that retail stores often consume the most energy. Section 1.3 presents this study’s two main objectives. Section 1.4 explains the hypotheses of this study. Section 1.5 summarizes the structure of this dissertation.

1.1. Background

Commercial buildings are one of the main energy consumers in the U.S. (EIA, 2011). Among the commercial buildings, retail store buildings generally have floor plans with a simple square footprint, but large energy requirements. They are usually windowless, single story buildings with height of roughly 9 m (29ft) or more, ranging in sizes from 8,361 to 23226 m² (90,000 to 250,000 ft²) (Krettova, 2009). These buildings are often made of corrugated metal, concrete blocks, or brick walls. Many stores are surrounded by large treeless parking lots to provide one-stop shopping for customers. An area of equal to at least a dozen football fields are occupied by a typical Wal-Mart or Target supercenter parking lot. Figure 1-1 shows the approximate areas of different big box store, their areas of parking lots and a football field (in green) for a comparative visual analysis.
1.2. Problem Statement

Retail stores in the U.S. are ranked second in the total energy consumption after the office buildings (PNNL, 2011). According to the U. S. Environment Protection Agency, retail buildings spend $13 billion every year on energy (Fedrizz et al., 2003). In Thailand, the energy consumption of retail store buildings also account for the second largest consumption of energy (Yamtraipat et al., 2004). Overall, retail buildings are intense energy consumers because of their large volumes and long hours of operation. Specifically, retail store heating, cooling and ventilation consumed from 21% to 48% of the total energy used in the U.S. retail buildings, depending on the climate zones that these buildings are located in (EIA, 2006). Figure 1.2 shows energy consumption in retail buildings by end use. In Thailand, the average electrical

Figure 1-1. Average Square Footage for Various Retail Spaces
consumption by air-conditioning systems is around 54% of the total average electrical consumption in commercial sector (Chirarattananon and Taweekun, 2003; Yangchareon and Limmeechokchai, 2003). In Japanese commercial sector, retail store buildings account for approximately 40% of energy consumption (Suzuk et al., 2011), around 3% of UK electricity consumption (Hill et al., 2010). Moreover, retail profits are directly dependent on the energy utilization, and, therefore, can be negatively affected if a retail store is not carefully managing their heating, ventilating and air conditioning (HVAC) system.

![Energy Consumption by End Use](image.png)

Figure 1-2. Energy consumption in retail store buildings by end use (EIA, 2006)

Reducing energy consumption in retail spaces are understood to pose particular challenge in many areas; among those areas are setting appropriate indoor air temperature and meeting ventilation rate requirements. On one side, many retail spaces have low occupancy rates. On the other side, many retail spaces have either low or significant sources of contaminates. Two alternative procedures for selecting the minimum ventilation rates required by buildings were provided by ASHRAE 62.1_2010. The VRP procedure is the more widely used that sums two quantities: the minimum rate of outdoor air supply per unit floor area, and the minimum rate of
outdoor air supply per person. For 44 buildings were tested, the average rates was of 25 L/s Which is far above the ventilation rates specified by the VRP and found that in 64% of these building did not satisfy 80% of the occupant in term of indoor air quality (Zaatari et al.2013). Also, in the open literature, there are no studies connecting actual occupancy and ventilation rate in retail store buildings. Bridges et al. 2012 suggested the idea that acceptable air quality using the performance –based indoor air quality procedure, can be obtained in retail stores with ventilation rates less than those specified in the ventilation rate procedure.

The indoor air quality procedure IAQP is commonly used to dilute indoor generated pollutants that contribute the greatest to the burden of disease, the contaminants of concern. Among the pollutants found in retail stores is Formaldehyde. Previous studies related to reduction of formaldehyde concentrations proposed increasing ventilation rates, but they did not specify quantitative ventilation rates to achieve targeted performance in retail store buildings.

In addition, existing studies did not perform optimization between modifying ventilation rates and set-point indoor temperatures to find control strategy with minimal energy consumption. Also, these studies did not calibrate energy simulation models used to make recommendations.

1.3. Research Objectives

To address this knowledge gap, my dissertation investigates the opportunities of
1). Reducing of ventilation rates that do not compromise indoor air quality in retail stores located in Central Pennsylvania.
2). Increasing in summer and decreasing in winter set point temperatures that do not compromise thermal comfort.
3). Optimization between reduction in ventilation rate and modifying set-point temperatures
1.4. Research Hypothesis

Retail store buildings could potentially save a significant amount of energy by modifying ventilation rates, or set point temperatures. These strategies have shown to be beneficial in previous studies. As presented in the literature review, a potential energy savings ranges from 0.5% to 30% without compromising indoor thermal comfort and indoor air quality. The retail store buildings can be ventilated at rates significantly lower than rates called for in the ASHRAE Standard while maintaining acceptable indoor air quality. Also, the results presented support the idea that the stores can be maintained at lower or higher than design setpoint temperatures while maintaining thermal comfort.

1.5. Outline of Dissertation

This dissertation is organized into five chapters: chapter 1 covers a general overview of the energy consumption of retail stores in terms of ventilation rates procedures and indoor air temperature setting points. Chapter 2 provides a literature review on important issues of dissertation in order to identify the existing knowledge gap and explicitly propose the methodologies to fill the knowledge gap. Chapter 3 presents methodology to achieve the objectives of this dissertation. Chapter 4 proposes two energy models and compared them with utility bills. Chapter 5 covers the first objective of this study while Chapter 6 covers the second objective, including the optimization between first and second objective. Finally, Chapter 7 concluded the dissertation with a summary, and lesson learned, and recommendation for future works and studies. Ultimately, this work provides new knowledge related to impact of ventilation rates required by using two ventilation rate procedures VRP and IAQP, and reset indoor air temperature in summer and winter on energy consumption for retail store buildings.
Chapter 2

Literature Review

Operation cost of ventilation, cooling and heating are typically ranked as the second highest cost in retail sector energy (depending on operating hours) (ASHRAEI, AIA, IESONA, USGBC, USDOE, 2011), making those systems the best targets for energy savings. Energy savings for retail buildings have widely been studied using different strategies. This chapter focuses on distinguishing between the present study and relevant literature. It is divided into two sections: Section 2.1 reviews energy savings by modifying Ventilation Rates; Section 2.2 reviews energy savings by reset indoor set point air temperature.

2.1. Energy Savings by Modifying Ventilation Rates

Ventilation rates have an important impact on the buildings in term of indoor air quality and energy consumption. The energy consumption of ventilation rates ranges from 2% to 6% for five U.S. climate zone (EIA). It is clear that determining the proper rates of ventilation air goes beyond business considerations. The consequences of these decisions are a two-sided problem. On one hand, the cost of clean air is expensive in terms of initial cost and operation cost, due to the energy required for heating, cooling and humidifying or dehumidifying (Papadopoulos et al., 2002). On the other hand, reduction in ventilation rates can have a negative effect on the quality of air in buildings, producing economic consequences, such as low productivity and an increase in sick building syndrome. Choosing the proper amount of outdoor ventilation air to supply in a building is a design and building concern. This is an important task for the designer who plays a significant role in specifying equipment that can supply appropriate ventilation rate required by code. The cost of conditioning and moving ventilation air that can be an essential fraction of the
total energy cost of the building is an owner concern (Grimsrud et al. 2009). A set of ventilation standards published by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), Standard 62, is the basis for most ventilation requirements in building codes. This standard has been updated about once each decade (Grimsrud et al., 2009).

ANSI/ASHRAE Standard 62.1-2010 consists of two main procedures for determining ventilation rates. The first procedure, Ventilation Rate Procedure VRP, defines ventilation requirements to provide indoor air quality for different sorts of building according to their function. The second main procedure is called the Indoor Air Quality Procedure (IAQP). In this procedure, the amount of ventilation rate that maintains the levels indoor air contaminants below recommended limits is calculated. The first process is relatively straightforward. According to the function of the space, one step determines the amount of ventilation rate in L/s (cfm) per person; second step determines amount of ventilation rate per floor area L/s.m² (cfm/ft²). These values of ventilation rates are required by Standard 62-2010 for the space under full occupancy and to be adjusted to account for ventilation effectiveness.

2.1.1 Ventilation rate procedure VRP

ASHRAE Standard 62-2001 under conditions of intermittent occupancy allows for a reduction in the design occupancy by using the average occupancy instead of the design occupancy for spaces in case of the design occupancy is based on a peak lasting 3 h or less. However, no one is permitted to reduce design occupancy more than 50% (Persily et al., 2003).

Several previous studies estimated the amount of energy savings for different building types. For example, for seven existing retail stores constructed in 2003 located in seven U.S. climate zones, the energy savings range from 0.04 % to 2.29 % for 50% reduction in outside air
flow rate (Haves et al., 2008). The base-case design value is approximately 2.7 m³/m².h (0.15cfm/ft²). In a second study, for office building in San Francisco it is shown that by lowering the minimum supply air volume from 30% to 20% and 10% at the base-case design temperature set points (21.5°C - 24°C), energy savings around 17% and 27% respectively. Also, for a wide range of indoor cooling air temperatures (28°C, 82.4°F) or indoor heating air temperatures (17.5°C, 63.5°F) the energy saving reach 40-60% and 33-40%, respectively, as shown in Figure 2-1 (Hoyt et al., 2009).

Figure 2-1. Annual Energy Use for the Prototype in San Francisco with VAV Minimum Fractions at 10%, 20%, and 30% (Hoyt et al., 2009).

2.1.2 Ventilation rate procedure IAQP for Total Volatile Organic Compounds and Formaldehyde in Retail Stores

Total volatile compounds are a total loading of many substances such as hydrocarbons, toluene, benzene, alcohols. Those compounds have a big implicated in sick building syndrome (Heinsohn. R, et.al, 2003). TVOC vary significantly between compounds in term of health impacts. For example, benzene causes carcinogen. Formaldehyde has negative health effects such as cancer, Asthma, Neurotoxicity.
Grimsrud et al. investigated a retail store in Stillwater, Minnesota the ventilation rate called for 1.8 m³/m²/h (0.098 cfm/ft²), while maintaining critical pollutant levels below the guideline limit of 1000 µg/m³ instead of 5.4 m³/m².h (0.295 cfm/ft²) that was called by ASHRAE 62-1989 perspective method. In other study of a retail store with 93,000ft² (14,000 cfm retail space) in Stillwater, Minnesota, the ventilation rate required called for 2.7 m³/h.m² (0.15 cfm/ft²) instead of 4.2 m³/h.m² (0.23 cfm/ft²) to keep TVOC below 1000 µg/m³ ASHRAE PR-1995-96 (Bridges et 1997, Grimsrud et al. 1999). Also Bridges et al. (2013) investigated three Target stores located in different region of United State Roseville MN, Mt Dora, FL and Rockville, and indicated that the ventilation rate could be lowered to continuous (24 hour/day) 1.25 m³/h.m² (0.068), while maintaining total volatile compounds and formaldehyde concentrations below guide line levels of 1000 µg/m³ for TVOC and 100 µg/m³ (81 ppb) WHO_30 min [quests], 123 µg/m³ [100ppb] OSHA_8hr [staff] Table 2.1 articulate summary of the relevant literature. The previous studies addressed in this section show that the IAQP ventilation rate is considered as one of potential control strategies for formaldehyde and TVOC contaminates. However, Waynu et al. who investigated nineteen retail stores in California suggested the application of one or more of the following: 1) reduce emission rates, 2) increase dramatically the amount of ventilation rates, or 3) implement effective air cleaning in order to reduce formaldehyde from indoor air below OEHHA guidelines. This study concluded that for some stores, source control is a viable strategy to meet the California health guideline. Also Chao et al. recommended that source control reduction and ventilation rate improvement should be implemented to reduce formaldehyde below WHO limit 0.08 ppm because the air cleaners alone were not enough. Results of experiments conducted of for air cleaning with activated carbon fiber filter ACF in Lawrence Berkeley National Laboratory indicated that maximum removal efficiency was achieved in the range of 25% -30% by heating the ACF media to 150ºC and ACF
did not perform well for unheated regeneration (Meera et al.). Also, the results of this study concluded that mass balance modeling showed that the combination of ACF air cleaner and 50% reductions in ventilation will substantially reduce concentrations of indoor formaldehyde by 12% 40%. Benfhlet mentioned that activated carbon filter is not common for commercial buildings.

Table 2-1. Summary of the Relevant Literature for Ventilation Rates

<table>
<thead>
<tr>
<th>Study</th>
<th>Building Type/Location</th>
<th>Baseline</th>
<th>Acceptable IAQ/ Thermal Comfort</th>
<th>Ventilation Rate</th>
<th>Annual Energy Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haves, 2008</td>
<td>Retail store</td>
<td>Design value</td>
<td>N/A</td>
<td>- 50%</td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td>Chicago /Forth/Worth/Phoenix/Tampa/Seattle/New York /Pasadena</td>
<td>2.7 m³/m².h</td>
<td>0.15 cfm/ft²</td>
<td></td>
<td>- 0.04% to 2.29% Gas</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>49.25% to 66.94%</td>
</tr>
<tr>
<td>Hoyt, 2009</td>
<td>Office</td>
<td>Supply air volume</td>
<td>N/A</td>
<td>20%</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>San Francisco, Miami, Phoenix, Minneapolis</td>
<td></td>
<td></td>
<td>10%</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridges, 1997 Grimsrud,1999</td>
<td>Retail store</td>
<td>A ASHRAE 62.1</td>
<td>TVOC below 1000 µg/m³</td>
<td>2.7 m³/h.m²</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Stillwater, Minnesota</td>
<td>(Max-Floor area )</td>
<td>4.2 m³/h.m²</td>
<td>(0.15 cfm/ft²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.23 cfm/ft²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridges, 2013</td>
<td>Retail Store</td>
<td>TVOC below 1000 µg/m³</td>
<td>HCHO below</td>
<td>-100 µg/m³ (81 ppb) WHO_30 min [quests]</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Roseville, MN. Mt Dora, FL. Rockville,MD.</td>
<td>1.25 m³/h.m²</td>
<td>0.068 cfm/ft²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Indoor Set Point Air Temperatures

Air conditioning systems consume an extremely high amount of energy in order to provide a tight set point temperature for the space. However, field and lab studies show that occupant comfort does not really need a narrow range or a uniform temperature (Hoyt et al., 2009). Several results from large field studies show that occupants accept a much wider temperature range than is typically applied in practice (Arens, 2009). A
narrow indoor temperature requires more energy than a wide range, where the building may be allowed to work lower or higher temperatures for longer period of time (Arens et al., 2009). Yamamoto and Abe (1994) figured out that the temperature set point of computer room can be increased to 28°C without causing discomfort for occupants. In addition, the results of the experiment conducted in six office rooms show that energy savings could be achieved by increasing and decreasing room temperature set points in summer and winter, respectively, without compromising indoor thermal comfort and sensation (Wang et al., 2009).

Many studies estimate energy savings by increasing and decreasing set point room air temperatures in summer and winter. For instance, in one study by Haves et al. (2008) as the occupied cooling and heating set-point air temperature increases or decreases by 2°F to 76°F and 68°F, respectively, for seven store buildings in seven U.S. climate zones, the annual energy consumption are lower by the range of 0.96 % to 1.84 % for electricity and of 20.83 % to 46.84 % for gas. The range of 1-3% of energy costs is the annual savings. In a second study by Arnes et al. (2009) concluded that in commercial buildings, for each degree Kelvin change in indoor set point temperature change results in, approximately, 7% of savings of heating/cooling energy. Also, a third study, developed by the U. S. Department of Energy in Minneapolis, Francisco, Phoenix and Miami, shows that by increasing the interior cooling air temperature in large office buildings each 1°C results in energy savings of 7-15% depending on the location of a building. In addition, the energy savings for San Francisco, Phoenix and Miami vary from 35-45%, when the range in interior temperature is widening to 28°C (82.4°F), with
the exception for Minneapolis because of a small annual number of cooling hours (Hoyt et al., 2009).

In the same study, when the setpoint indoor air temperature is decreased by 1°C from 21.5°C (70.7°F) to 20.5°C (68.9°F), the energy savings reaches 4-17% for San Francisco, Phoenix and Minneapolis, being here the exception Miami because the heating load is small year-round. At low setpoint temperature 17.5°C (63.5°F), the total energy savings ranges from 17-35%. Figure 2-2 shows the results of this study (Hoyt et al., 2009) and table 2.2 articulate summary of the Set point literature review.

Figure 2-2. Percent Energy Savings for Widened Air Temperature Set Points Relative to Conventional Setpoint Range in San Francisco, Miami, Phoenix, and Minneapolis (Hoyt et al., 2009)
Table 2-2. Summary of the Relevant Literature of Reset Indoor Air Temperature

<table>
<thead>
<tr>
<th>Study</th>
<th>Building Type/Location</th>
<th>Baseline</th>
<th>Thermal Comfort</th>
<th>Reset</th>
<th>Annual Energy Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haves, 2008</td>
<td>Retail store Chicago/Forth/Worth/Phoenix/Tampa/Seattle/New York/Pasadena</td>
<td>Design Conditions 23.3°C(74°F) Cooling 21.5°C(70°F) Heating</td>
<td>N/A</td>
<td>+2°F Cooling -2°F Heating</td>
<td>Electricity 0.96% to 1.84% Gas 30.83 % to 43.00%</td>
</tr>
<tr>
<td>Hoyt, 2009</td>
<td>Office San Francisco, Miami, Phoenix, Minneapolis</td>
<td>24°C(75°F) Cooling 21.5°C (71°F) Heating</td>
<td>Wide range of indoor Air temperature were accepted</td>
<td>+1°C +4°C -1°C -4°C</td>
<td>Electricity 7%-15% 35-45% Gas 7%-14% 17%-35%</td>
</tr>
<tr>
<td>Yamtraipat, 2004</td>
<td>Offices/ Thailand</td>
<td>20°C (68°F)</td>
<td>Comfortable vote 80%</td>
<td>°C +1/+2/+3/+4/+5/+6</td>
<td>Electricity % 6/12/18/24/30/36</td>
</tr>
<tr>
<td>Arnes, 2009</td>
<td>Commercial Building</td>
<td>N/A</td>
<td>N/A</td>
<td>+1/-1</td>
<td>7%</td>
</tr>
<tr>
<td>Wang, 2009</td>
<td>Offices/ China</td>
<td>N/A</td>
<td>97% Cooling 98% Heating</td>
<td>27°C Cooling 23°C Heating</td>
<td>Electricity % 18.7 % 23.8%</td>
</tr>
</tbody>
</table>

Except Minneapolis* Except Miami†
Chapter 3

Methodology

3.1. Introduction

This project addresses energy savings by modifying ventilation rates that do not compromise indoor air quality and by increasing or decreasing indoor air set point temperature in summer or winter that does not compromise thermal comfort in two retail stores from 14 field case studies in ASHRAE RP 1596 (Siegel et al., 2013). The following research activities are used in order to achieve the objectives of the thesis:

3.1.1 Building Case studies

Two box retail stores located in central Pennsylvania that has 5 U.S. climate zones (moderate to cold climate). The envelope of these buildings is medium weight. Window and door glazing area represents only 10% of the total wall area. Plug loads include equipment such as lighting exhibitions, computers, Refrigerators, freezers and other equipment. Both stores were conditioned and mechanically ventilated with direct expansion roof top units (RTU) systems electrical cooling for summer and natural gas for heating. Cooling gas is used for heating. Store 1 is a one- general merchandise store with a site ID (MiP). The floor space area is 11,300 m² (122,000 ft²) with 83% retail area, and its volume 66,800 m³ (2,360,000 ft³). Retail store 2 is a one – story grocery store with a site ID (MbP). The floor space area is 16,600 m² (178,000 ft²) with 94.8% retail area and its volume 99,500 m³ (3,510,000 ft³). A total number of 23 and 44 RTUs for retail store 1 and 2 respectively with a constant air volume (CAV). The working hours for the stores are 11 and 24 hours respectively. Figure 3.1 shows a flow chart consists of two parts
that present the two case studies store 1 and 2 and their relation with the ASHRAE project 1596. The above part (above dash line) explains the measured data from the project and the bottom part explain this study.

Figure 3-1 Relationship between Measured Data from ASHRAE Project 1596 and Current Study for Two Case Studies, Store 1 and Store 2
3.1.2. Energy Modeling

Energy simulation program (EnergyPlus) is an effective tool that allows building engineering designers and building manager to predict and evaluate energy consumption for their buildings. Energy simulation software has opportunity to produce yearly, hourly energy consumption data by end use for heating, cooling, fan, lighting, plug loads, etc. (Carlos Duarte et al., 2013). In addition, the EnergyPlus software has been selected because it has been extensively validated and it provides flexibility with many input parameters (De Wilde and Tian, 2009). Typical retail occupancy rates, equipment operation schedules, lighting schedules were all simulated on hourly basis. Simulations were performed using weather data from the National Oceanic and Atmospheric Administration (NOAA) weather station for central Pennsylvania (2011).

3.1.3 Manufactures Technical Data

Technical specification data for Rooftop units such as design capacities and unit rating are provided by manufacturers AAON and during the walk-through protocol for gathering data as shown in figure 3.2. Appendix A presents more detail technical specifications. Mechanical drawings were also collected during visits to the sites.
Field measurements will be based on the ASHRAE RP1596 project. This project develops the most robust database of indoor air quality, ventilation, occupant survey, and building measurements for the U.S. retail store buildings. Fourteen retail buildings were measured between April 2011 and July 2012, half of these building located in the hot and humid climate of central Texas and half in the cold and dry climate of central Pennsylvania.
3.2.1. Sampling Approach

The following are different sampling approach for measuring quantitative data regarding ventilation and qualitative data regarding indoor air quality:

3.2.1.1 Store Occupancy

As a part of the field measurements, a costumer number of the stores were determined on the basis (1) the hourly transaction numbers over the test days were provided by store administrators that are recorded by each store computer system (check-out counters) and (2) thermal imaging directional people counters installed in front of exit doors to quantify the relationship between actual numbers of people going out of the door and the hourly transaction numbers.

3.2.1.2 Carbon Dioxide Concentrations Measurement

Telaire CO₂ sensors or Q-trak sensors with accuracy ± 50% are used to measure CO₂ in the indoor retail stores, rooftop supply air streams, and outdoors. Telaire CO₂ sensors were used to measure indoor CO₂ concentrations in five locations as shown in 3.3 in retail area of store for five days. Each sensor was placed at height ranges from 1.1 m (3.6ft) to 2.0 m (6.6ft) above the floor taking in consideration that in these locations the costumers have not direct exposure to the sensors as shown in figure 3.4.

The average concentration value from the five CO₂ measurements in the retail space was used for ventilation rate estimates and air quality analyses in the building.
CO₂ concentrations were also monitored in most RTUs using Telaire CO₂ sensors and Q-trak. Each Telaire CO₂ sensors connected with a HOBO data logger and it was placed in the RTU supply air stream for 30 minutes to measure the CO₂ concentration. During the monitoring
time, the doors of the RTU were tightly closed for more than three minutes so as to sample RTU air for at least three minutes. Either Telaire CO$_2$ sensor or Q-trak sensor was used to measure the outdoor CO$_2$ concentrations. A shelter was used to on the roof of the retail store buildings to protect the CO$_2$ sensors from weather.

### 3.2.1.3. SF6 sampling

Room air samples were collected in the retail space at multiple sampling locations, after releasing the SF6 into the building and waiting 60 minutes for mixing. At several sampling locations, room air samples were collected in the retail space. Around 18 sampling locations were used. Simultaneously, three field technicians collected the air samples with 500 mL plastic syringes. To finish the collection process, the air samples were injected into 1 L Tedlar sample bags as shown in figure 3.5. Samples were collected in intervals ranging from 4 to 6 minutes, depending on the size of the test store. Generally the total sampling time was 4 hours. Around 180 Tedlar sample bags were collected for each store. In addition to the sample bags, QA/QC bags, including trip blanks and trip standard bags were prepared and mixed in with the sample bags prior to analysis. Within 48 hours of collection all samples were analyzed using a Lagus Autotrac SF6 analyzer generally. The Tedlar air sampling bags were cleaned and reused after each test. The cleaning procedure included purging each bag with zero grade compressed air or pure nitrogen gas at least 3 times. After purging, 12 to 16 sample bags were randomly selected and analyzed for SF6 using the Autocracy SF6 analyzer.
3.2.1.4. VOCs

Summa Canister samples were used to collect indoors VOCs for two stores. Outdoor samples were collected using Summa Canisters for retail stores 1 and 2. Procedures and methods described in U.S. EPA Method TO-15 (U.S. EPA, 1999b) were used to collect all Summa Canister samples. 4.0 hours was the nominal sample time for Summa Canister samples. Usually in the middle of the day, the indoor air samples were collected during the mobile sampling event in the shopping cart or basket used for mobile sampling. Concurrently the Outdoor Summa Canister samples were collected on the roof of the retail site with the mobile sampling event. Directly after the completion of the sampling event, the Summa Canisters were packed into boxes provided by the analytical laboratory, sealed with a chain of custody strip and shipped by ground transportation to the analytical laboratory for analysis.
3.2.1.5. TVOC

In order to monitor the TVOC concentration a photoionization detector (PID) was used for each test. The PID was a model ppbRAE Plus PGM-7240 manufactured by RAE Systems. In the shopping cart or basket the PID was located during mobile sampling the PID was collocated with the Summa canister, and sorbent tube sampling system for every test. After finishing the mobile sampling event, the PID was returned to the permanent sampling location. Sampling for TVOC was completed simultaneously with sulfur hexafluoride SF₆ decay tests. Figure 3.6 shows the photoionization detector (PID) that was used for monitoring the TVOC.

![Figure 3-6. TVOC concentration a photoionization detector _PID](image)

3.2.1.6. Formaldehyde and acetaldehyde

Indoor and outdoor samples were collected using the methods and procedures described in the U.S. EPA Compendium Method TO-11A. Formaldehyde / acetaldehyde sampling system consisted of a DNPH tube, vinyl tubing and a calibrated air pump. 200 mL/min was the nominal flow rate for DNPH samples. The nominal sampling time was 4.0 hours producing a sample volume of 48 L. Indoor samples
were collected during the mobile sampling event in the shopping cart or basket used for mobile sampling. Following sample collection, the flow rate through the DNPH sample system was validated using a calibrated volumetric flow meter. Validated DNPH tubes were capped, sealed in a plastic bag, and stored in cooler packed with “blue ice” to maintain a storage temperature below 4 °C. Prior to shipment to the analytical laboratory, DNPH tubes were stored in a freezer in the laboratories. DNPH tubes were shipped overnight to the analytical laboratory in coolers packed with blue ice for analysis.

3.2.1.7. Total Outdoor Air Exchange Rate

The measured SF6 decay data and single mass balance equation 5.1 were used to calculate the outdoor air exchange rate for each retail stores air volume.

\[ V \frac{dC}{dt} = Q_{IN}C_{out} - Q_{OA}C \]

Where:

\( C \) = the SF6 concentration in the building air [ppb],

\( V \) = the volume of building air [m³],

\( t \) = the time [h],

\( Q_{in} \) = the airflow rate from building to outdoors [m³/h],

\( Q_{OA} \) = the airflow rate from outdoors to building [m³/h], and

\( C_{amb} \) = the tracer concentration in outdoor air [ppb].

The contribution of SF6 mass from the outdoors was assumed to be zero \( (C_{out} = 0) \). Also, the building air volume may be assumed constant.

For a uniform concentration, Equation 1.5 simplified to:

\[ V \frac{dC}{dt} = -Q_{OA}C \]

Combining like terms and integrating Equation 1.5 becomes:
\[
\ln \frac{C(t)}{C(0)} = -\frac{Q_{OA}}{V} t = -AER \times t
\]

Where:

- \( C(t) \) = the SF6 concentration at time \( t \) [ppb],
- \( C(0) \) = the initial SF6 concentration [ppb], and
- \( AER \) = the outdoor air exchange rate for the building [h-1].

### 3.2.2. Mechanical Ventilation Rates

In order to calculate the fraction of mechanical ventilation rates, concentration of carbon dioxide are required so that the Carbon dioxide concentrations are measured for 22 days every 5 minutes in 3 different locations, each rooftop unit for supply air \( C_{SA} \), outdoor \( C_{OA} \), and indoor air \( C_{IN} \) in five different locations. The outdoor air fraction \( f \) and the mechanical ventilation rate in each RTU can be calculated by using equation (1) and (2) respectively:

\[
MVR \text{ fraction (f) } = \frac{C_{SA} - C_{IN}}{C_{OA} - C_{IN}} \quad (1)
\]

\[
MVR = f \times \text{ supply air flow rate (measured)} \quad (2)
\]

### 3.2.3. Rooftop Unit Supply Air Flow Rates

Three values are measured using Trueflow Metering plate, which has two sizes 14” and 20”), Digital pressure DG-700 and flow gage: (1) Normal static operation pressure (NSOP) value in RTU at normal running conditions, (2) true flow operation pressure (TFOP) value which is the pressure difference across the Trueflow plates, and (3)true flow static operation pressure (TFSOP) value which is the static pressure in the RTU when the real filters are removed and the
Trueflow plates are installed. Equation (3) was used to calculate the supply air flow rate in RTUs:

\[ V_{SA} = C_p \times \sqrt{TFOP} \times \sqrt{NSOP} / \sqrt{TF SOP} \]  

(3)

\( V_{SA} \) is flow rate (CFM), \( C_p \) is the plate coefficient 115 for 14 inch plate and 154 for 20 inch plate.

3.3. Air Temperature Measurements

The temperature sensors with data logging function were places in each store at five different locations, one in the center and another four near each corner of the floor area. At each location, three temperature sensors were fixed at three different elevations: 0.1 m, 1.1 m, and 1.7 m above the floor, to measure and record the temperature fluctuation during 4 to 5 days as shown in figure 3.7 and 3.8. The accuracy of the temperature sensors is ±0.5°C. The sampling frequency was set to 5 min. The air temperature measurements were done in April 2012 for store 1, and in September 2011 for store 2. The horizontal temperature difference among the five different locations provide information on how well the air was mixed in the store, while the vertical temperature difference among the three heights provide information about the air stratification. Base on the data from the tree buildings, the air was well mixed with the exception of the areas in the immediate proximity of refrigerators. The average temperature from the 15 sensors during the whole sampling time was used as an input parameter for the energy simulations.
Figure 3-7. Approximate Air Temperature Sampling in Five Locations with Elevations of 0.1 m (0.33ft), 1.0 m (3.3ft), and 1.7 m (5.58ft) in Each Location.

Figure 3-8. Air Temperature Sensors in 3 Elevations of 0.1 m (0.33ft), 1.0 m (3.3ft), and 1.7 (5.58ft)
Chapter 4

Building Energy Analysis based on Utility Bills

4.1. Input Parameters

Simulation input data will be provided by actual input parameters from measurements and walk-through investigation data from the studied retail buildings such as the building size, shape, orientation, construction materials, heating, ventilation, and air-conditioning (HVAC) system size and type, interior and exterior lighting. Different indoor set point temperatures for summer and winter months were used and schedules of internal loads such as lighting and people were considered. Time periods that correspond to store open and store closed times were considered. For store 1, store open hours is from 7:00 am till 11:00 pm and for case study store 2 the store open 24 hours. Some of other input data are provided from a Commercial Building Energy Consumption Survey – CBECS (EIA, 2006) and ASHRAE standards.

4.2. Energy Model Validation

The purpose of building energy simulation analysis is to assess and quantify the energy savings. To reach this goal, energy simulation models for retail stores were built using the EnergyPlus software. ASHRAE Guideline 14 was used to validate the influence of parameter modification on the accuracy of the energy simulation. This Guideline uses statistical equations for building energy models and provides discussions and equations on computing uncertainties for calibrated computer models (ASHRAE-14, 2002). Two accuracy criteria were used: the Root Mean Square Error (RMSE) and Mean Bias Error (MBE). The Root Mean Square Error measures of how close the predicted energy use to the actual one based on the monthly consumption while the Mean Bias Error indicates of long-run performance of the model. The summary of the criteria is shown in Table 4.1.
Coefficient of variation of the root mean square error (CVRMSE):

\[ CVRMSE = 100 \times \frac{\sum(y_i - \hat{y}_i)^2}{(n-1)}^{1/2} / \bar{y} \]

Normalized mean bias error (NMBE):

\[ NMBE = 100 \times \frac{\sum(y_i - \hat{y}_i)}{(n-1)\bar{y}} \]

Where  \( y_i \): Actual energy use during time period \( i \) (here it is each month)

\( \hat{y}_i \): Predicated energy use during time period \( i \)

\( \bar{y} \): Arithmetic mean of the sample of \( n \) observations

\( n \): Number of observations (here \( n=12 \) months)

4.1 A summary of the Criteria of Acceptable Tolerance for Monthly Energy Use Data

<table>
<thead>
<tr>
<th>Criteria</th>
<th>M&amp;V Guideline</th>
<th>ASHRAE Guideline 14</th>
<th>IPMVP</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMBE %</td>
<td>± 15</td>
<td>± 5</td>
<td>± 20</td>
</tr>
<tr>
<td>CVRMSE %</td>
<td>± 10</td>
<td>± 15</td>
<td>± 5</td>
</tr>
</tbody>
</table>

4.3. Results and discussions

A comparison between the predictions of EnergyPlus models of two case studies stores 1, 2 and utility billing data was performed in order to validate the models. For case studies 1 and 2, simulations were performed for twelve consecutive months from the billing period 1/1/2011 to 12/31/2011. Figures 4.1 to 4.4 show a summary of actual monthly natural gas and electrical consumption verses predicted model consumption.
Figure 0-1: Annual Simulation Results vs Utility Bill Data – Natural Gas, Store 1

Figure 4-2. Annual Simulation Results vs Utility Bill Data – Electricity, Store 1
Figure 4-3. Annual Simulation Results vs Utility Bill Data – Natural Gas, Store 2

Figure 4-4. Annual Simulation Results vs Utility Bill Data – Electricity, Store 2
Equations 4.1 and 4.2 equations were used to calculate the accuracy of the predicted. All results met the ASHRAE error criteria as shown in table 4.2. Overall, the results indicate good agreement between predicted models and actual utility bills total energy use. More specifically of electrical consumption, the store 1 falls litemail of the middle of guideline ± 5 while store 2 was very close to be out of guideline. Regarding gas consumption although both stores in guideline, store 2 with a value – 4.9 was very close to lowest acceptable guideline ± 5.

4-2. Simulation Model Criteria Vs ASHRAE Guideline 14

<table>
<thead>
<tr>
<th>Criteria</th>
<th>ASHRAE Guideline 14</th>
<th>Simulation Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gas Consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Store 1</td>
</tr>
<tr>
<td>NMBE %</td>
<td>± 5</td>
<td>-2.06</td>
</tr>
<tr>
<td>CVRMSE %</td>
<td>± 15</td>
<td>8.77</td>
</tr>
</tbody>
</table>
Chapter 5

Building Energy Performance Simulation based on Ventilation Rates

5.1. Ventilation Rate Procedure (VRP)

The ventilation rate procedure that is provided in ASHRAE Standard 62.1-2010 includes two required components, which are based on the occupancy rate and floor area. The VRP is the more widely used procedure. The standard recommends the minimum ventilation rate based on the floor area for a retail sale space of 0.6 L/s∙m2 (12 cfm/ 100 ft2) and for a supermarket of 0.3 L/s∙m2 (6 cfm/ 100 ft2). When the occupancy-based minimum ventilation requirements were added to the floor area ventilation rates, the required total ventilation rate should be 1.2 L/s∙m2 (24 cfm/ 100 ft2) for a retail area and 0.6 L/s∙m2 (12 cfm/ 100 ft2) for a supermarket. The VRP is assumed to maintain an acceptable indoor air quality as perceived by at least 80% of occupants (Zaatari et al., 2013).

5.1.1. Occupancy Rates

The result of the hourly transaction numbers over test days for 14 retail stores that were visited for the ASHRAE Project 1596-RP are shown figure 5.1. It presents a distribution of hourly transaction numbers at the check-out counters during the test week. A wide range of transaction numbers at 25th to 75th percentile and the squares presenting the average values ranging from 4 to 242 people per hour is shown on the boxplot below. The occupancy rates ranged from 1 to 17 people/ 100 m2 according to the floor area component. It is clearly shown that the occupancy rate, depending upon building functions/uses. The transaction numbers in general merchandise stores are typically higher than the rates observed in furniture or electronic stores.
Transaction rates of zero do not necessarily mean the store was unoccupied. They cannot represent the actual occupancy rates because customers may leave the store without a purchase. Furthermore, multiple people could leave a store with each transition. The average person traffic passage across the automatic entrance doors was approximately 1.3 times greater than the transaction rate accounted by the store. Consequently, the hourly transaction rates were multiplied with an adjustment factor of 1.3. This factor is compared to a finding in a study that examined door usage in public buildings, including retail stores and healthcare facilities (Jareemit et al., 2014).

More specifically, the correlation between the hourly transaction numbers which were recorded by the store’s computer system (provided by the store administration) and hourly people counter are shown in table 5.1 for store 1 that has a site code of MiP for ASHRAE Project -1596 2012 ) and figure 5.2 illustrates this relationship.
Table 5-1. Relationship between Hourly Transaction Numbers and People Counter

<table>
<thead>
<tr>
<th>Time</th>
<th>People Counter Reading</th>
<th>Hourly Transaction Numbers</th>
<th>Ratio People Counter To Hourly Transaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00 – 9:00</td>
<td>43</td>
<td>29</td>
<td>1.48</td>
</tr>
<tr>
<td>9:00 – 10:00</td>
<td>95</td>
<td>74</td>
<td>1.29</td>
</tr>
<tr>
<td>10:00 – 11:00</td>
<td>175</td>
<td>126</td>
<td>1.39</td>
</tr>
<tr>
<td>11:00 – 12:00</td>
<td>266</td>
<td>194</td>
<td>1.37</td>
</tr>
<tr>
<td>12:00 – 13:00</td>
<td>298</td>
<td>227</td>
<td>1.32</td>
</tr>
<tr>
<td>13:00 – 14:00</td>
<td>301</td>
<td>221</td>
<td>1.36</td>
</tr>
<tr>
<td>14:00 – 15:00</td>
<td>294</td>
<td>206</td>
<td>1.43</td>
</tr>
<tr>
<td>15:00 – 16:00</td>
<td>292</td>
<td>208</td>
<td>1.41</td>
</tr>
<tr>
<td>16:00 – 17:00</td>
<td>319</td>
<td>230</td>
<td>1.38</td>
</tr>
<tr>
<td>17:00 – 18:00</td>
<td>297</td>
<td>213</td>
<td>1.39</td>
</tr>
<tr>
<td>18:00 – 19:00</td>
<td>263</td>
<td>182</td>
<td>1.44</td>
</tr>
<tr>
<td>19:00 – 20:00</td>
<td>246</td>
<td>166</td>
<td>1.49</td>
</tr>
<tr>
<td>20:00 – 21:00</td>
<td>236</td>
<td>144</td>
<td>1.64</td>
</tr>
<tr>
<td>21:00 – 22:00</td>
<td>131</td>
<td>81</td>
<td>1.62</td>
</tr>
</tbody>
</table>

Figure 5-2. Hourly Transaction Vs People counter Number of Customers for Store 1
The trend of hourly customer numbers is repeatable on a daily basis for the stores. The transaction numbers for the same hour on different days had some variability. Typically, Saturday and Sunday have higher transaction numbers than the number recorded on Monday through Friday. Figure 5.3 represents hourly customer numbers of four consecutive 17 days and it was a good example of their repeatability. In general, the customer numbers did not vary by season when comparing values of different test weeks in the same store as shown in figure 5.4.
Figure 5-3. Hourly and Daily Occupancy Profile from 4/2 to 4/12_2012 for store 1
5.1.2. Carbon Dioxide Concentrations

Table 5.2 shows results of average concentrations CO2 of the store building. The results indicate that the indoor concentrations of CO2 are lower by 25 to 57% than ASHRAE Standards 62.1-2010 guideline, which is 700 PPM plus outdoor CO2 concentrations. Figure 5.5 shows how the indoor CO2 concentration follows the hourly transaction numbers, which can be an approximate indicator of the occupancy rates and how the fluctuation of indoor CO2 concentration has obvious diurnal patterns. Appendix A shows the overall average indoor concentration in 14 retail stores, as indicated by the open square, ranged from 381 ppm to 716 ppm.
Table 5-2. Average Measured Carbon Dioxide Concentrations CO2 for Store1

<table>
<thead>
<tr>
<th>Locations</th>
<th>Average Concentration CO₂ (PPM)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>463</td>
<td>187</td>
</tr>
<tr>
<td>2</td>
<td>813</td>
<td>764</td>
</tr>
<tr>
<td>3</td>
<td>463</td>
<td>59</td>
</tr>
<tr>
<td>4</td>
<td>479</td>
<td>149</td>
</tr>
<tr>
<td>5</td>
<td>477</td>
<td>60</td>
</tr>
</tbody>
</table>

Average of five locations 539 244

Outdoor Concentration

<table>
<thead>
<tr>
<th>Locations</th>
<th>Average Concentration CO₂ (PPM)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>375</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>375</td>
<td>25</td>
</tr>
</tbody>
</table>

Figure 5-5. Average indoor CO₂ concentrations is consistent with the hourly transaction rates over 24 hours for Site GeP (ASHRAE PR-1596)
5.1.3. Mechanical Ventilation Rate Scenario

Finding appropriate ventilation rate strategies that can secure acceptable indoor air quality while maintaining wide range of setpoint temperatures that do not compromise thermal comfort is a challenging task for heating ventilating and air conditioning systems (HVAC) designers and operators. Based on the prescriptive ASHRAE standard 62.1- 2010, two Scenarios A, B, and C of required ventilation rates were used as the following:

**Scenario A: Occupant component**

**Scenario A1:** actual ventilation rates required for measured occupancy number

**Scenario A2:** maximum ventilation rate required for default Occupancy number (15 person/ 100 m², 15 Person/ 1000 ft²).

**Scenario B: floor component and occupant components**

**Scenario B1:** the lowest value, minimum ventilation rate required by floor Component 0.6 L/s.m² (0.12 cfm/ft²).

**Scenario B2:** the highest value, maximum ventilation rates required by floor component and default occupancy number

**Scenario A: Occupant component:**

Figure 5.6 and Figure 5.7 show number of occupants that was counted for one week in April 2012 for store 1 and for 5 days in July 2012 for store 1 and 2 respectively. The hourly counter numbers for retail stores 1 and 2 was in the range of 30 -600 and 107- 759 people /hour respectively and the peak customer number of 602 and 759 was found at 15:00 pm for both retail stores. Also these results presented that the peak occupancy numbers for retail stores 1 and 2 were around 40% and 30% lower than ASHRAE maximum number.
Based on occupancy results the ventilation rates required for scenarios, A and B were calculated and presented in figures 5.8 and 5.9 repetitively and the amount for ventilation rates had the same patterns.

![Graph](image1)

**Figure 5-6. Average Measured Daily Occupancy 2_8 April 2012 vs ASHRAE _max for Store 1**

![Graph](image2)

**Figure 5-7. Average Measured Daily Occupancy 23_27 July 2012 Vs ASHRAE Standard for Store 2**
Figure 5-8. Occupancy Ventilation Rates Required 2-8 April 2012, Vs ASHRAE Standard for Store 1

Figure 5-9. Occupancy Ventilation Rates Required 23-27 July 2012, Vs ASHRAE Standard for Store 2
Scenario B: Floor and Occupant components, the lowest value of minimum ventilation rate required by floor Component 0.6 L/s.m² (0.12 cfm/ft²) and the highest value, maximum ventilation rates required by floor component and default occupancy number (15 person/ 100 m², 15 Person/ 1000 ft² and 3.8 l/sec. m², 7.5cfm/ft²).

Figure 5-10. Average Daily Measured Ventilation Rates Vs ASHRAE Standard 12_19 April, 2012 for Store 1

Figure 5-11. Average Daily Occupancy Vs ASHRAE_max Ventilation Rates for Store 2
Scenario B shows that both stores working with approximately maximum 22% (average 13 %) of ventilation rate above the minimum ventilation rate that is required by floor component of ASHRAE Standard during a few hours of the days from 17:00 to 20:00 pm and by only 4 to 10% during the rest of working hours. Overall, the retail stores are generally operated with a very close amount of minimum outdoor ventilation rates required by ASHRAE Standard 62.1. Figures 5.10 and 5.11 represent these results.

5.2 Indoor Air Quality Procedure (IAQP)

This part investigate the idea that weather the acceptable indoor air quality by using indoor air quality procedure (IAQP), can be obtained in retail stores with ventilation rates less than those required by ventilation rate procedure (VRP). The effectiveness of different ventilation rates in controlling volatile organic compounds VOCs that found in the retail stores is a key consideration for the IAQP.

5.2.1. Volatile organic compounds Results

A number of 228 indoor and outdoor sampling at retail stores were identified and quantified. In order to facilitate the analysis, VOCs grouped into 14 VOC categories that have similar chemical structure and/or potential exposure specifications as presented in table 5.3.

Table 5-3. VOC Categories

<table>
<thead>
<tr>
<th></th>
<th>Formaldehyde</th>
<th>8</th>
<th>Isopropanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Acetaldehyde</td>
<td>9</td>
<td>C5-C10 carbonyls</td>
</tr>
<tr>
<td>3</td>
<td>Ethanol</td>
<td>10</td>
<td>BTEXS (benzene, toluene, ethyl benzene, xylene, styrene)</td>
</tr>
</tbody>
</table>
VOCs were present in both case studies of retail stores at low concentrations at a level below health guide lines with the exception of formaldehyde and acetaldehyde. Recommended exposure limits (RELs) for workplace potential hazardous air contaminants were published by The National Institute for Occupational Safety and Health (NIOSH). Since the concentrations observed for individual VOCs in Categories 3 - 14 are well below their respective reference exposure limits (NIOSH RELs) so that no individual VOC in Categories 3 - 14 is a serious health concern for employees working in the stores sampled in this study.

Indoor formaldehyde concentrations present in both retail stores 1 and 2 the amount of 15.46 ppb and 8.28 ppb respectively while acetaldehyde only present in case study 2 with indoor concentration in the range of 8 ppb to 75 ppb. The highest concentration occurred in the store 2 where bread baking occurred and because acetaldehyde is naturally present in ripe fruits and is a byproduct of baking. Appendix C shows the measured results of indoor concentrations of 14 VOC concentrations for 14 sites including two stores 1 and 2 which they have according to ASHRAE project_1596-RP the site codes of Mip and Mbp respectively.
5.2.2. TVOC Results

Photoionization detector PID was used to monitor real-time TVOC concentrations. It was maintained at the fixed sampling location. It was gathered with the summa canister during the mobile sampling event which is 4-hours. This period is a good enough to make a comparison of the average PID TVOC with integrated TVOC concentration calculated by summing the spectated VOC concentrations collected with Summa Canister.

The calculated Summa Canister TVOC concentrations were higher than The PID underestimated the TVOC concentration. One possible explanation for these results is because of the detection principle of the PID. Equipped with a 10.6 eV lamp, the instrument cannot detect organic compounds whose ionization potential is greater than 10.6 eV, such as halogenated compounds (e.g., Freon’s, methylene chloride). The calibration gas choice of isobutylene may also have influenced the results.

Summation of the entire VOC category quantified from the samples collected in the Summa canisters were used to estimate the total TVOC concentration for both retail stores case studies. The TVOC concentrations for retail stores were 144.9 ppm (369.9 µg/m³) and 658 ppm (1323 µg/m³) respectively. Although, ASHRAE Standard 62.1 recommends not using TVOC as a target of TVOC concentration, Mohave (2003) recommended that Total Volatile organic compound can be used as an indicator for the presence of VOC indoors. He proposes to use them as a screening tool, and as an indicator of overall sensory irritation. In This study, TVOC concentrations from 1.7 to 25 mg/m³ were used as references for the lower and upper values of the range of thresholds reported by Molhave (2002). These concentrations were reported to cause symptoms ranging from irritation of the eyes, nose, or throat; to headaches and feeling of sleepiness. None of the sites sampled in this study approached the upper threshold. Also, Bridges et al. (2013) describe their use of the TVOC concentrations 1000µg/m³ (1 mg/m³) as a one-sided test that they use this information as an indicator of a possible problem concern. A value greater than 1000 µg/m³ clearly is an indication of the presence of a VOC problem while a value of less than 1000 µg/m³ is an indication of the lack of a VOC.
5.2.3. Outdoor Air Exchange Rates

The measured outdoor air exchange rate ranged from 0.38 h\(^{-1}\) to 0.69 h\(^{-1}\) and from 0.4 h\(^{-1}\) to 0.56 h\(^{-1}\) with average values of 0.54 and 0.5 for store 1 and 2 and uncertainty of 0.085 and 0.5 respectively. Table 5.4 presents a summary of outdoor air exchange rates by SF\(_6\) decay test for two case studies and the number of repeated measurements in the same store.

<table>
<thead>
<tr>
<th>Store # / measurement #</th>
<th>Outdoor Air Exchange Rate h(^{-1})</th>
<th>uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>0.69</td>
<td>0.13</td>
</tr>
<tr>
<td>1/2</td>
<td>0.66</td>
<td>0.10</td>
</tr>
<tr>
<td>1/3</td>
<td>0.38</td>
<td>0.05</td>
</tr>
<tr>
<td>1/4</td>
<td>0.43</td>
<td>0.06</td>
</tr>
<tr>
<td>2/1</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>2/2</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>2/3</td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td>2/4</td>
<td>0.51</td>
<td>0.51</td>
</tr>
</tbody>
</table>

5.3. Contaminate Modeling

The indoor air quality procedure (IAQP) in ASHRAE Standard 62.1 prescribes the use of a steady-state mass-balance analysis to determine the minimum outdoor airflow rate required to achieve the concentration limits chosen for each contaminant. The whole building emission rate (WBER) is the net amount of pollutant emitted per unit floor area per unit time. A time-averaged mass balance (Riley et al., 2002) is used to derive the whole building emission rate, with the following assumptions: (1) the space is well-mixed, (2) the penetration factor from outdoors to indoors of the contaminant is unity, and (3) losses by homogeneous and heterogeneous reactions are negligible when compared to removal by ventilation.
Formaldehyde and TVOC WBERs were calculated in accordance with Equation (1) using concentrations and air exchange rates measured during the sampling event:

\[
WBER = AER \times (C_{in}-C_{out}) \times \frac{V}{A}
\]

Where:

\(WBER\) = whole building emission rate \([\text{mg/m}^2\cdot\text{h} \text{ or } \mu\text{g/m}^2\cdot\text{h}]\),

\(AER\) = the air exchange rate \([\text{h}^{-1}]\),

\(C_{in}, C_{out}\) = the indoor and outdoor mass concentrations of the pollutant considered \(\text{[\mu g/m}^3 \text{ or mg/m}^3\)],

\(V\) = the volume of the retail space \([\text{m}^3]\), and

\(A\) = the surface of the retail floor \([\text{m}^2]\).

The WBERs for TVOC and for a particular building revealed that they were independent of the ventilation rate, under the assumption that (1) outdoor concentrations were negligible when compared to indoor concentrations, and (2) losses by homogenous and heterogeneous reactions are constant as ventilation changes. Because of these assumptions the WBER is constant, and may be used to determine the minimum air exchange rate that would lead to an indoor concentration equal to the reference concentration chosen, as shown in Equation 5.2. Rearranging Equation 5.1, we obtain the air exchange rate:

\[
WBER = AER \times C_{in} \times \frac{V}{A} = AER\text{MIN} \times C_{ref} \times \frac{V}{A}
\]

Where:

\(WBER\) = the whole building emission rate estimated from the parameters measured at the site \([\text{mg/m}^2\cdot\text{h} \text{ or } \mu\text{g/m}^2\cdot\text{h}]\),
AER = the air exchange rate measured at the site [h⁻¹],

\(C_{\text{in}}\) = the indoor concentration measured at the site [μg/m³ or mg/m³],

\(V\) = the volume of the space [m³],

\(A\) = the area of the space [m²],

\(C_{\text{ref}}\) = the reference concentration selected in Table 5. [μg/m³ or mg/m³], and

\(AER_{\text{min}}\) = the minimum air exchange rate required to reach \(C_{\text{ref}}\) [h⁻¹].

5.3.1. Results of Measured Indoor Concentrations Contaminates

Summary of measured indoor concentrations of Total Volatile Compound (TVOC) and Formaldehyde (HCHO) concentrations are presented in table 5.5 for both case studies.

Table 5-5: Total Volatile Compound (TVOC) and Formaldehyde (HCHO) concentrations

| Date          | Exchange Air Rates h⁻¹ | TVOC         | Formaldehyde
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(C_{\text{in}}) PPb (μg/m³)</td>
<td>(C_{\text{out}}) PPb (μg/m³)</td>
</tr>
<tr>
<td><strong>Store 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/10/2012</td>
<td>0.69</td>
<td>98.2 (245.6)</td>
<td>/</td>
</tr>
<tr>
<td>4/12/2012</td>
<td>0.66</td>
<td>58.1 (141.85)</td>
<td>6 (2.78)</td>
</tr>
<tr>
<td>4/7/2012</td>
<td>0.38</td>
<td>282.7 (719)</td>
<td>/</td>
</tr>
<tr>
<td>4/19/2012</td>
<td>0.43</td>
<td>144.9 (369.9)</td>
<td>49.3(14.67)</td>
</tr>
<tr>
<td><strong>Store 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/20/2011</td>
<td>0.56</td>
<td>948.2 (1900)</td>
<td>/</td>
</tr>
<tr>
<td>1/31/2012</td>
<td>0.4</td>
<td>658 (1323)</td>
<td>/</td>
</tr>
<tr>
<td>5/15/2012</td>
<td>0.52</td>
<td>539 (1103)</td>
<td>/</td>
</tr>
<tr>
<td>7/24/2012</td>
<td>0.51</td>
<td>764 (578)</td>
<td>/</td>
</tr>
</tbody>
</table>
### 5.3.2 Reference exposures levels

Table 5.6 shows the limited values of two pollutants that will be used to calculate the minimum ventilation rates required by the retail stores.

**Table 5-6: Exposure Limits for Total Volatile Compound (TVOC) and Formaldehyde (HCHO)**

<table>
<thead>
<tr>
<th></th>
<th>HCHO ppb (µg/m³)</th>
<th>TVOC µg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEHHA REL acute b</td>
<td>44.8 (55)</td>
<td>/</td>
</tr>
<tr>
<td>OEHHA REL 8-hour</td>
<td>7.3 (8.96)</td>
<td>/</td>
</tr>
<tr>
<td>OEHHA REL chronic c</td>
<td>7.3 (8.96)</td>
<td>/</td>
</tr>
<tr>
<td>OSHA d PEL e TWAf</td>
<td>750 (920)</td>
<td>81.4 (100)</td>
</tr>
<tr>
<td>WHO f 30-min</td>
<td></td>
<td>/</td>
</tr>
<tr>
<td>Mohave, 2002</td>
<td></td>
<td>1,700 – 25,000</td>
</tr>
<tr>
<td>Bridges, 2013</td>
<td></td>
<td>1000</td>
</tr>
</tbody>
</table>

a. Office of Environmental Health Hazard Assessment  
b. 1-hour average  
c. 1-year average  
d. Occupational Safety and Health Administration.  
e. Permissible exposure limit.  
g. World Health Organization recommended guideline.  
f. Time-weighted average (8-hour average).

### 5.3.3. Ventilation Rate Scenarios and specific Approaches

The following steps were used to implement the ventilation rates required to maintain the two stories below guideline limits of TVOC and HCOC:

1) Two case study were subjected to determine the ventilation rate required to maintain The Total volatile compound TVOC below limit required by Molhave (1700 µg/m³) and Bridges (1000 µg/m³) and
the Formaldehyde (HCHO) below limit required by The California Office of Environmental Health Hazard Assessment, OEHHA (7.3 ppb ) as shown in table 5.6.

2) The values of AER 0.43 h⁻¹ and 0.4 h⁻¹ were used with concentrations of Formaldehyde and Total volatile compound TVOC that were sampled simultaneously with a sulfur hexafluoride (SF₆) decay for case studies 1 and 2 respectively.

3) Equation 5.1 was used to estimate the whole-Building emission rates- WBER

4) Based on the results of minimum AER_{min} that was estimated by using equation 5.2 as shown in table 5.7, the ventilation rates were calculated. This table also, presents the values of minimum and maximum ventilation rates required by ASHRAE Standard and the measure values.

5) In this study the measured values of 0.43 h⁻¹ and 0.4 h⁻¹ were used for case study 1 and 2 respectively. These values were chosen because their ventilation rates have the closest values to that are measured by CO2 concentration values. In Addition the two stores have the close values. The outdoor air exchange rates were 14% lower in store 1 and 13% higher in store 2 than the ASHRAE minimum Standard as shown in figure 5.12.

6) The ventilation scenarios were based on no account for infiltration rate and it was considered as a temporary event and the ASHRAE 90.1 asking for pressurization.

7) Floor area for retail sale space areas for stores (1) and (2) are 9,401 m² (101,192 ft²) and 15,714 m² (169,144 ft²) and the volume of 39,484 m³ (1,394,364 ft³) and 94, 284 m³ (3,329,08 ft³).

<table>
<thead>
<tr>
<th></th>
<th>Store 1</th>
<th>Store 2</th>
<th>Store 1</th>
<th>Store 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVOC_Molhave,2002</td>
<td>0.0814</td>
<td>0.3114</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>TVOC_Bridges</td>
<td>0.194</td>
<td>0.5294</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>HCHO_8 hour</td>
<td>0.91</td>
<td>0.4541</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>/</td>
<td>/</td>
<td>0.43</td>
<td>0.4</td>
</tr>
<tr>
<td>ASHRAE_Min</td>
<td>/</td>
<td>/</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>ASHRAE_Max</td>
<td>/</td>
<td>/</td>
<td>1</td>
<td>0.7</td>
</tr>
</tbody>
</table>
5.1.3.1. Ventilation rate scenarios with Formaldehyde

**Scenario A**: Ventilation rates that maintain HCHHO indoor concentrations below Office of Environmental Health Hazard Assessment (OEHA) 3.822 m³/ h.m² (0.218 cfm/ft²) for retail store 1 and 2.724 m³/ h.m² (0.149 cfm/ft²) for Store 2.

**Scenario B**: Measured ventilation rates 1.806 m³/ h.m² (0.0988 cfm/ft²) for store 1, and 2.4 m³/ h.m² (0.1312 cfm/ft²) for store 2.

**Scenario C**: Minimum ventilation rate required by floor component based on ASHRAE Standard 2.16 m³/ h.m² (0.12 cfm/ft²).

**Scenario D**: Maximum ventilation rate required by Occupancy and floor components based on ASHRAE Standard 4.2 m³/ h.m² (0.24 cfm/ft²).

5.1.3.2. Ventilation rate scenarios for Total Volatile Compound

**Scenario A**: Ventilation rates that maintain TVOC indoor concentrations below Molhave, 2002’s reference value which 0.395 m³/ h.m² (0.0216 cfm/ft²) for retail store 1 and
Scenario B: Measured ventilation rates 1.806 m³/ h.m² (0.0988 cfm/ft²) for store 1, and 2.4 m³/ h.m² (0.1312 cfm/ft²) for store 2.

Scenario C: Ventilation rates that maintain TVOC indoor concentrations below Bridges’ reference value which 0.395 m³/ h.m² (0.0216 cfm/ft²) for retail store 1 and 2.725 m³/ h.m² (0.149 cfm/ft²) for Store 2

Scenario D: Minimum ventilation rate required by floor component based on ASHRAE Standard 2.16 m³/ h.m² (0.12 cfm/ft²)

Scenario E: Maximum ventilation rate required by Occupancy and floor components based on ASHRAE Standard 4.2 m³/ h.m² (0.24 cfm/ft²)

Figure 5.13 shows summary of ventilation rates required by stores 1 and 2 respectively.

Figure 5-13. Ventilation Rates Required Based on Different Guideline References
5.3.1.3 Result Discussion

In order to maintain the formaldehyde levels in two retail stores case studies below California’s OEHHA guideline of 8.96 µg/m³ (7.3 PPb), the managers/operators of the retail stores would need to do one or more of the following to control this pollutant: (A) increasing ventilation rates, (B) Source control, (C) implementation of effective air cleaning.

A) The measured ventilation rates values significantly should be increased by 53% and 12%, and the ASHRAE minimum required by floor component by 43% and 21% for retail stores 1 and 2 respectively.

B) A source control is a viable strategy could meet all limited values such as NOISH REL 16 ppb (20µ/m³), OSHA 750 PPb (920µ/m³) and OEHHA REL acute 44.8 PPb (55 µ/m³). Those strategies could be implemented by isolated sources such as Plywood, insulation material, and furniture that is considered as one of the main source of formaldehyde. Also, a reducing in amounts of Formaldehyde emission rates WBER have a potential effect on formaldehyde concentration in store. For instance, the retail stores could be ventilated with the values of less than that are measured in two retail stores by decreasing the formaldehyde emission rates WBER by approximately 50% and 29% in those retail stores.

C) Previous section of this study indicated that Air cleaners were inadequate to remove formaldehyde to meet Health guidelines. Based in a phone communication with Dr. Fisk “Lawrence Berkeley National Laboratory” recommended to contact PURAFIL Company investigating whether a sorbent media could be used for two stores. The company Lab Scientist Mr. Matthew Potts suggested using Purafil Selected Media that has two common methods to deploy. First is a traditional method that trays filled with the sorbent media (filter includes some purafil), while others integrate the sorbent media in to a fiber particle filter which is quite common now (Fisk et al., 2008). The general equation 5.6 (purafil@purafil.com) is used to calculate pounds per hour of media needed for
chemical filtration of roof top units filters for two case studies under their specific conditions of formaldehyde gas concentrations and supply air flow. By dividing the lb gas/ hr by 2.5% which is the media removal capacity

\[
Pounds \ of \ Gas/\text{Hour} = MW \times CFM \times PPM \times N
\]

Where

MW = molecular weight (g/mole)
CFM = supply air volume (ft/\text{min})
PPM = parts per million
`N` = conversion factors = (0.000000153 lb•mole•min/g•ft3•hr)

The results of the media consumption for store 1 and 2 were 48 kg/month and 69 kg/month with a monthly cost of $490 and $704 ($10.2/kg) respectively. According to monthly price of Purafil Selected Media, the air cleaner process is very expansive.

### 5.3.4. Simulation Results

This section describes the results of simulated energy consumption of natural gas and electrical consumption broken out by end use for both stores and the impact of different ventilation rates scenarios on monthly and yearly heating and cooling energy consumption using IAQP of ASHRAE STANDRAD 62.1. Also this section contains cross study comparisons.

### 5.1.4.1. Baseline Modeling Results

Energy use intensity (EUI) breaks –down by end use was used to measure how much energy is consumed per square meter and foot in retail stores. Total building energy use was estimated form the
baseline models for retail stores 1 and 2. Figure 5.14 and 5.15 give the breakdown of annual energy by component end use for the two store buildings respectively. Interior lighting represents the most energy intensive at of 69 kWh/m² (22 kBtu/ft²) and 138 kWh/m² (44 kBtu/ft²) for stores 1 and 2 respectively. Significant variation in EUI are seen when two retail store buildings are compared across store activity type. However, the size of retail stores has limited impact on annual energy use intensity EUI.

![Annual Energy Use Intensity_Retail Store 1](image1)

**Figure 5-14. Estimated Energy Use Intensity of Retail Store 1**

![Annual Energy Use Intensity_Retail Store 2](image2)

**Figure 5-15. Estimated Energy Use Intensity for Retail Store 2**
Also, simulation results for the retail stores were compared to the following building energy survey data:
(1). The site EUI obtained from Commercial Buildings Energy Consumption Survey (CBECS) data (Griffith et al. 2008); (2) Standard 90.1_2004,; and (3) International Energy Conservation Cod IECC 2006 and IECC 2009 (Zhange et al. 2013). Table 5.8 indicates that the total energy use for store 1 is below all reference values (weighted mean values EUI ) except for Standard 90.1_ 2010 and IECC 1012. The total EUI for store 2 was within the range of total weighted mean EUI from CBECS Survey. Also, electricity EUI result of store 1 is within the range of all Electricity EUI reference weighted Mean values.

Table 5-8: Annual Site Energy Use Intensity• kBtu /ft²

<table>
<thead>
<tr>
<th></th>
<th>2003 CBECS Survey</th>
<th>Standard 90.1</th>
<th>IECC</th>
<th>Retail Stores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Energy</td>
<td>73.9</td>
<td>77.4</td>
<td>52.2</td>
<td>61</td>
</tr>
<tr>
<td>Electricity</td>
<td>48.8</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>21</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

* All reference values are weighted Mean EUI

5.1.4.2. Ventilation Rate Scenarios Results

The objective of this section is to quantify the impact of varying outdoor air ventilation rates on the heating and cooling energy use of two retail stores. Comparisons were made for the energy required to heat or cool the buildings over a range of five ventilation rates scenarios for total volatile compound TVOC. Energy consumption was evaluated for retail stores under five ventilation scenarios dictated by IAQ requirements.
5.1.4.2.1. Ventilation Rate Scenarios for Natural Gas Heating Consumption Results

Figures 5.16 and 5.17 summarize the results of the annual natural gas heating consumption for two retail store buildings. The results of store 1 indicated that by reducing the ventilation rates from the minimum required by the ASHRAE standard and measured values to Molhave reference, the energy savings were approximately 19% and 15% respectively, and were approximately 16% and 13% when the ventilation rates deceased from the minimum ASHRAE and measured values to Bridges reference. While in the retail store 2 the natural gas energy savings were approximately 6% and 9% when the ventilation rates reduced from measurement and ASHRAE minimum values to Molhave reference value. However, for store 2 the measured ventilation rate had to be increased by 12% in order to satisfy the Bridges reference in this retail store.

Also, table 5.9 presents the annual amount of energy savings of natural heating gas consumption. Overall, the natural gas heating consumption was significantly sensitive to different ventilation rates.
Figure 5-16. Annual Natural Gas Heating Consumption for Different Ventilation Rate Scenarios for Retail Store 1

Figure 5-17. Annual Natural Gas Heating Consumption for Different Ventilation Rate Scenarios Retail Store 2
Table 5-9. Annual Natural Gas Heating Savings for Store 1 and 2

<table>
<thead>
<tr>
<th>Gas Heating Savings</th>
<th>Retail Store 1</th>
<th>Retail Store 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reduction in ventilation Rates m³/h. m² (cfm/ ft²)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured to Molhave</td>
<td>1.806 to 0.395 (0.098 to 0.0216)</td>
<td>15</td>
</tr>
<tr>
<td>ASHRAE Minimum to Molhave</td>
<td>2.16 to 0.395 (0.12 to 0.0216)</td>
<td>19</td>
</tr>
<tr>
<td>Measured to Bridges*</td>
<td>1.806 to 0.668 (0.098 to 0.0365)</td>
<td>13</td>
</tr>
<tr>
<td>ASHRAE Minimum to Bridges *</td>
<td>2.16 to 0.668 (0.12 to 0.0365)</td>
<td>16</td>
</tr>
</tbody>
</table>

Figures 5.18 and 5.19 show the energy savings for natural gas consumption for both retail store buildings and table 5.9 Summarize these results for January 2011. Overall, heating energy savings in the range of 10% to 15% satisfy Molhaves and Bridges references for store 1 and in the range of 3% to 6% to satisfy Molhave reference for Store 2. The ventilation rate scenarios for minimum required and measured should be increased to satisfy Bridges reference.

Figure 5-18. January Natural Gas Consumption of Different Ventilation Rate Scenarios Retail store_ 1
Figure 5-19. January 7- February 4 Natural Gas Consumption with Different Ventilation Rate Scenarios Retail store 2

Table 5-10. Natural heating Gas Consumption with Ventilation Rate Reductions January -2011 Store 1 and 2

<table>
<thead>
<tr>
<th>Natural Gas Heating Savings</th>
<th>Retail Store1 January</th>
<th>Retail Store2 January 7- February 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in ventilation Rates</td>
<td>12%</td>
<td>6%</td>
</tr>
<tr>
<td>Measured to Molhave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASHRAE Minimum to Molhave</td>
<td>15%</td>
<td>4%</td>
</tr>
<tr>
<td>Measured to Bridges*</td>
<td>10%</td>
<td>- 8%</td>
</tr>
<tr>
<td>ASHRAE Minimum to Bridges*</td>
<td>12%</td>
<td>- 10%</td>
</tr>
</tbody>
</table>

* For store 2 the ventilation rates are increased from measured and ASHRAE min values to Bridges limit
5.1.4.2.2. Ventilation Rate scenarios for Electrical Cooling Consumption Results

The impact results for five ventilation rates scenarios on electrical cooling consumption are shown in figures 5.20 and 5.21 respectively. These results indicated that by decreasing the ventilation rates from measured and ASHRAE minimum to Molhave reference, the annual electrical energy consumption for cooling increased by 3% and 4% respectively, and by decreasing them to Bridges reference, the energy consumption increased by 3% and 4% for retail store 1. For retail store 2 by an amount of 0.6% and 0.4%, the energy cooling consumption were increased when the ventilation rates decreased from measured and ASHRAE minimum to Molhave limit. For store 2, the cooling energy consumption decrease by 0.8% and 1% when the ventilation rate values increased from measured and ASHRAE minimum to Bridges limit.

Table 5.11 Summarizes the Annual electrical cooling consumption. In overall, the electrical cooling energy consumption was not significantly sensitive to different ventilation rates.

![Graph showing electrical cooling consumption for different ventilation rate scenarios](image)

Figure 5-20. Annual Electrical Cooling Consumption_2011 with Different Ventilation Rate Scenarios_Store 1
Figure 5.21. Annual Electrical Cooling Consumption_2011 with Different Ventilation Rate Scenarios_Store 2

Table 5.11 Annual Electrical Cooling Consumption _2011 with Ventilation Rate Reductions

<table>
<thead>
<tr>
<th>Reduction in ventilation Rates m³/h. m² (cfm/ ft²)</th>
<th>Retail Store1</th>
<th>Retail Store2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured to Molhave 1.806 to 0.395 (0.098 to 0.0216)</td>
<td>- 3.20 %</td>
<td>- 0.62</td>
</tr>
<tr>
<td>ASHRAE Minimum to Molhave 2.16 to 0.395 (0.12 to 0.0216)</td>
<td>- 4.46 %</td>
<td>- 0.39</td>
</tr>
<tr>
<td>Measured to Bridges* 1.806 to 0.668 (0.098 to 0.0365)</td>
<td>- 2.67 %</td>
<td>0.87</td>
</tr>
<tr>
<td>ASHRAE Minimum to Bridges * 2.16 to 0.668 (0.12 to 0.0365)</td>
<td>- 3.93 %</td>
<td>1.09</td>
</tr>
</tbody>
</table>

* For store 2 the ventilation rates are increased from measured and ASHRAE min values to Bridges limit

Monthly energy simulation results for electrical cooling consumption with five ventilation rate scenarios for retail store 1 in the period of July 2011 and retail store 2 in the period of July 15 to August 14 / 2011 are presented in figures 5.22 and 5.23 respectively and in table 5.12 The results reveal that either increasing or decreasing the ventilation rate has a very small effect on the electrical cooling consumption.
Figure 5-22. Electrical Cooling Consumption _ July 2011 with Different Ventilation Rate Scenarios_Store 1

Figure 5-23. Electrical Cooling Consumption From July 15 to August 14_2011 with Different Ventilation Rate Scenarios_Store 2
Table 5-12. Electrical Cooling Consumption for a Month_ 2011 with Ventilation Rate reduction Store 1 and 2

<table>
<thead>
<tr>
<th>Electrical cooling Savings</th>
<th>Retail Store1_ July</th>
<th>Retail Store2_ July 15- August 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured to Molhave</td>
<td>1.6%</td>
<td>0.72%</td>
</tr>
<tr>
<td>ASHRAE Minimum to Molhave</td>
<td>1.6%</td>
<td>0.44%</td>
</tr>
<tr>
<td>Measured to Bridges*</td>
<td>1%</td>
<td>- 0.94</td>
</tr>
<tr>
<td>ASHRAE Minimum to Bridges *</td>
<td>0.99%</td>
<td>- 1.2</td>
</tr>
</tbody>
</table>

* For store 2 the ventilation rates are increased from measured and ASHRAE min values to Bridges limit

Cross Study Comparisons

The impact of outside ventilation rates on natural gas heating and electrical cooling consumption was found to be comparable to three previous studies. Two of those studies were conducted by Lawrence Berkeley National Laboratory LBNL (Haves et al 2008) and ( Apte et al 2011) and the other study by National Renewable Laboratory NREL ( Benne et al. 2009). Haves study results indicated that a 50% reduction of minimum outside rates resulted in average decreases of 60.4% in gas heating and 1.31% electricity energy usage for the seven retail store models as shown in table 5.13.

Table 5-13. Energy Savings with 50% Reduction in Outside Air Flow Rates (Haves et al 2008)

<table>
<thead>
<tr>
<th>Location</th>
<th>Annual Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electricity</td>
</tr>
<tr>
<td>Chicago</td>
<td>0.52%</td>
</tr>
<tr>
<td>Forth Worth</td>
<td>3.42%</td>
</tr>
<tr>
<td>Phoenix</td>
<td>1.62%</td>
</tr>
<tr>
<td>Seattle</td>
<td>-0.04%</td>
</tr>
<tr>
<td>Pasadena</td>
<td>0.35%</td>
</tr>
<tr>
<td>New York</td>
<td>0.50%</td>
</tr>
<tr>
<td>Tampa</td>
<td>2.29%</td>
</tr>
<tr>
<td>Average</td>
<td>1.31%</td>
</tr>
</tbody>
</table>
The results of the second study LBNRL (Apte) for big retail stores in California as shown in table 5.14 indicated that when the ventilation rates reduced from 0.14 cfm/ft² to 0.04 cfm/ft² and from 0.24 cfm/ft² to 0.04 cfm/ft² in two different zone 3B and 3C in California (9.3 California zone) resulted in increased cooling energy. Literature review section has more detail about those studies.

The results of third studies as shown in table 5.15 demonstrated that for the existing stock, 90.1-2004 compliant, and advanced technology group buildings, the natural gas EUI was increased by 21.4%, 20.3%, and 8.9% while the electricity EUI was increased by 0%, 2.8% and 3.1% when the ventilation rates decreased from Turket ventilation limit for existing stock buildings, as required by 62.1-2004 limit for both 90.1 and advanced technology buildings to no minimum mechanical ventilation limit.

Table 5-14. Percent Change in EUI for Big Box retail Stores by climate zone ((Apte et al. 2011)

<table>
<thead>
<tr>
<th>Reduction in ventilation rate cfm/ft²</th>
<th>Pasadena, CA (Zone 3B)</th>
<th>Oakland, CA (Zone 3C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRmid (0.14) to VR min (0.04)</td>
<td>83%</td>
<td>82%</td>
</tr>
<tr>
<td>VRmax (0.24) to VR min (0.04)</td>
<td>92.6%</td>
<td>92.2%</td>
</tr>
<tr>
<td></td>
<td>- 0.1%</td>
<td>- 1.1%</td>
</tr>
<tr>
<td></td>
<td>- 0.34%</td>
<td>- 2.0%</td>
</tr>
</tbody>
</table>

Table 5-15. Percent Changes in EUI for 3 Groups of U.S Retail Store Buildings relative to Reference (Benne et al. 2009)

<table>
<thead>
<tr>
<th>Reduction in ventilation rate from reference values to no minimum mechanical ventilation rate</th>
<th>Existing Stock Retail Store</th>
<th>90.1_2004</th>
<th>Max Tect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Electricity</td>
<td>Gas</td>
<td>Electricity</td>
</tr>
<tr>
<td>Turk et al 1989</td>
<td>26.9%</td>
<td>0.3%</td>
<td>/</td>
</tr>
<tr>
<td>As required by 62.1-2004</td>
<td></td>
<td>36.8%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
Chapter 6

Building Energy Performance Based on Indoor Air Set Point temperatures

6.1. Air Temperature Measurement Results

The result of every 10 minutes for total 15 temperature measurements in five locations at three levels: low level 0.1m (0.3ft) above floor, middle level 1.0 m (3.6 ft) above floor, and breathing zone level 1.7 m (5.6 ft) indicated that the vertical temperature in five locations were ranged from 17.5 °C (63.5 °F) to 26 °C (78.8°F) and from 19 °C(66.2°F) to 24.6 °C (76.28°F) in store 1 and 2 respectively and the vertical temperature differences between low level and high level were in the range of 0.5 to 1.5 in five locations for store 1 as presented in figures 6.1 to 6.5.

Figure 0-1. Vertical Air Temperature Measurement at Location_1 for Store1
Figure 6-2. Vertical Temperature Measurement at Location_2 for Store 1

Figure 6-3. Vertical Temperature Measurement at Location_3 for Store 1
Figure 6-4. Vertical Temperature Measurement at Location_4 for Store 1

Figure 6-5. Vertical Temperature Measurement at Location_5 for Store 1

For store 2 as shown in figures 6.6 to 6.10, the vertical air temperature differences were in the range of 0.1 to 1.5 in four locations with the except of the location1 the vertical temperature difference reaches to 5 because of the usage of several refrigerators and freezers to store
perishable food in this store had a potential effect on the local air temperatures. As shown in Figure 6.11.

**Figure 6-6. Vertical Temperature Measurement at Location_1 for Store 2**

**Figure 6-7. Vertical Temperature Measurement at Location_2 for Store 2**
Figure 6-8. Vertical Temperature Measurement at Location_3 for Store 2

Figure 0-9. Vertical Temperature Measurement at Location_4 for Store 2
Over all the vertical air temperature difference among the three heights provided information that both stores satisfy ASHRAE thermal comfort that the vertical Air temperature difference should in the range as presented in figure 6.12.
The Horizontal Temperature differences among five locations for three heights were in the range of 16.62°C to 26.5º and the horizontal between any two adjacent locations ranged between 0.5° C to 3° C in store 1 figures 6.13 to 6.15. For store 2 as shown in figures 6.16 to 18, around 15° C to 23.7° C were the results of the horizontal air temperature that measured among three heights and the horizontal air temperature difference between any two neighboring location in the rage of 0.2°C to 2°C except in the level 0.1 m the horizontal temperature difference between locations 1 and 5 was around 8°C.
Figure 6-13. Horizontal Air Temperature Measurements at Height 1.7 m _ Store 1

![Graph showing horizontal air temperature measurements at 1.7 m height.]

Figure 6-14. Horizontal Air Temperature Measurements at Height 1.0 m _ Store 1

![Graph showing horizontal air temperature measurements at 1.0 m height.]

Indoor Air Temperature °C

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/2/2012</td>
<td>15:00</td>
</tr>
<tr>
<td>4/2/2012</td>
<td>13:30</td>
</tr>
<tr>
<td>4/4/2012</td>
<td>12:00</td>
</tr>
<tr>
<td>4/4/2012</td>
<td>10:30</td>
</tr>
<tr>
<td>4/6/2012</td>
<td>09:00</td>
</tr>
<tr>
<td>4/7/2012</td>
<td>08:30</td>
</tr>
<tr>
<td>4/9/2012</td>
<td>04:30</td>
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<tr>
<td>4/10/2012</td>
<td>04:30</td>
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<td>4/11/2012</td>
<td>02:30</td>
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<td>4/12/2012</td>
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<td>4/14/2012</td>
<td>18:00</td>
</tr>
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<td>4/15/2012</td>
<td>16:30</td>
</tr>
<tr>
<td>4/16/2012</td>
<td>14:30</td>
</tr>
<tr>
<td>4/17/2012</td>
<td>12:30</td>
</tr>
<tr>
<td>4/18/2012</td>
<td>10:30</td>
</tr>
<tr>
<td>4/19/2012</td>
<td>08:30</td>
</tr>
</tbody>
</table>

Indoor Air Temperature °C

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/2/2012</td>
<td>15:00</td>
</tr>
<tr>
<td>4/2/2012</td>
<td>13:30</td>
</tr>
<tr>
<td>4/4/2012</td>
<td>12:00</td>
</tr>
<tr>
<td>4/4/2012</td>
<td>10:30</td>
</tr>
<tr>
<td>4/6/2012</td>
<td>09:00</td>
</tr>
<tr>
<td>4/7/2012</td>
<td>08:30</td>
</tr>
<tr>
<td>4/9/2012</td>
<td>04:30</td>
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<td>4/10/2012</td>
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<td>10:30</td>
</tr>
<tr>
<td>4/19/2012</td>
<td>08:30</td>
</tr>
</tbody>
</table>
Figure 6-15. Horizontal Air Temperature Measurements at Height 0.1 m, Store 1

Figure 6-16. Horizontal Air Temperature Measurements at Height 1.7 m, Store 2
Figure 6-17. Horizontal Air Temperature Measurements at Height 1.0 m_ Store 2

Figure 6-18. Horizontal Air Temperature Measurements at Height 0.1 m_ Store 2
6.2. Set Point Temperature Scenario

For the purpose of verifying how much energy could be saved using broader indoor temperature range, energy simulation models for retail stores will build using EnergyPlus software.

6.2.1 Cooling Scenarios

Scenario A: Average Measured Indoor Air Temperatures

The average measured of indoor air temperatures from the 15 sensors during the whole sampling time were 20.9°C (69.6°F) and 21.97°C (71.5°F) as shown in figures 6.19 and 6.20 for store 1 and 2 respectively.

![Figure 6-19. Average Measured Indoor Air Temperature of 15 Sensors for Two weeks in April 2012_Store 1](image-url)
Scenario B: Optimal Indoor Air Temperature for both Sedentary and Active People

The measured local air temperatures as well as the average temperatures indicate that the indoor environments in these retail stores were either below or close to the lowest acceptable indoor temperatures from the perspective of thermal comfort (ASHRAE, 2004). On one hand, based on the ASHRAE 55 thermal comfort zone diagram under 50% relative humidity, the range of summer operative temperature for sedentary people, such as cashiers in the store, the comfortable summer operative temperatures are between 23.8°C and 26.7°C. On the other hand, the range of summer operative temperature for active people, such as the customers and employees working in the store, is between 20.9°C (69.6°F) and 23.8°C as were calculated according to the empirical equations for thermal comfort adjustments due to activity level (McQuiston et al., 2005). Figure 6.21 shows the indoor temperature of 23.8°C (75°F) is the optimum temperature for cashiers people (sedentary) and customers, employees people (active) in the stores also it shows the measured air temperatures, highest and lowest acceptable air temperatures for sedentary and light activity people.

In this special case for retail stores, where the
operative temperature is almost the same as the indoor air temperature, it is possible to increases the indoor air temperature set point (Measured) to 23.8°C still maintain thermal comfort requirements for both sedentary and active People.

Figure 6-21. Measured Air Temperatures, Highest and Lowest Acceptable for Sedentary and Active Occupants
**Scenario C: Reset the optimal indoor air temperature**

Optimal indoor 23.8°C (75°F) was increased to 24.4°C (76°F) and 25°C (77°F).

**6.2.2. Heating Scenario**

**Scenario D: Reset Winter Indoor Air Temperature**

Indoor air temperature 21°C (70°F) was decreased to 20.6°C (69°F) and 20°C (68°F).

**6.2.1. Comparison of Annual Energy Consumption Results**

- Scenarios A and B

Figure 6.22 compares the annual cooling consumption for scenarios A and B for two retail store buildings. The results show that there is a significant potential for annual cooling energy savings of 48% and 22% with the temperature increasing of 2.9°C (5°F) and 1.83°C (3.5°F) for store 1 and 2 respectively.

![Optimum Vs Measured](image)

**Figure 6-22. Electrical Cooling Consumption for Scenario A and B**
- **Scenario C:**

   The electrical energy cooling savings were around 42% and 19% for store 1 and 2 respectively as presented in figure 6.23 when the indoor set point temperature increased for 1.8°C up to 25.6 °C(78°F).

![Graph showing electrical cooling consumption for Scenario C](image)

Figure 6-23. Electrical Cooling Energy Savings of Scenario C for Store 1 and 2

- **Scenarios D:**

   When the indoor set point temperatures decreased by 1°C (2°F), the annual natural gas heating savings for 2011 were around 9% and 13% for store 1 and 2 respectively. Figure 6.24 shows these results.
6.3. Optimization between Setpoint Temperature and Ventilation Rate

On one hand, the different ventilation rate scenarios had a negligible impact on electrical cooling consumption. However, by resetting the indoor cooling has a potential effect on electrical cooling consumption. For example when the indoor cooling temperature increased by 1.2°C (2°F) from 23.8°C (75°F) to 25°C (77°F), the energy saving were around 29% and 13% for store 1 and 2 respectively. On the hand, both the ventilation rates and the set point had a great impact on natural gas heating consumption. For example as indicated in figures 6.25 and 6.25 when the ventilation rates with indoor air temperature decreased from measured ventilation rates 1.08 m³/h.m² (0.099cfm/ft²) with indoor set point temperatures 21°C (70°F) to Molhave limit 0.395 m³/h.m² (0.22Cfm/ft²) and 20°C (68°F) for store 1 and 2.4 m³/h.m² (0.1312 cfm/ft²) with indoor setpoint temperature 21°C (70°F) to Molhave limit 1.868 m³/h.m² (0.102cfm/ft²) and indoor store temperature 20°C, the heating gas savings were around 8% and 13% respectively.
Figure 6-25. Optimization of Ventilation Rates with Indoor set point Temperatures _ Store 1

Figure 6-26. Optimization of Ventilation Rates with Indoor Set point Temperatures_ Store
In previous section regarding the occupancy numbers in the stores, the results concluded that most of the time retail stores worked with a low rate of people numbers in majority hours of the day in a week. In addition, ASHRAE Project_RP1596, an investigation of ventilation rate measurements revealed that even though half of the retail stores tested met or exceeded VRP, these ventilation rates were not sufficient to keep all contaminants below guidelines limits. Zaatari et al., announced that there is no documentation of the adequacy of VRP maintaining an acceptable indoor quality in retail building that were investigated in ASHARE _PR 1596.

Based on these results, this study suggests using demand control ventilation (DCV) that is often based on CO$_2$ concentrations in other words to vary the amount of outdoor air based on occupancy in retail stores. The potential energy savings through CO$_2$ based DCV in retail buildings can be significant.
Chapter 7

Conclusions and Recommendations for Future Work

7.1. Conclusions

The main purpose of this chapter is to summarize the main dissertation findings in order to improve the existing knowledge related to examining a novel idea of energy savings strategies for retail store environments. These strategies included reducing ventilation rates required based on two procedures (VRP and IAQP of ASHRAE Standard 62.1_2010), and resetting indoor air temperatures in summer and winter. Measurements were made in two stores in Central Pennsylvania in order to approach the two objectives of this dissertation.

7.1.1 Objective 1: Modification of Ventilation Rates

The actual number of occupants was measured using people counter sensors in store 1 and store administrators provided the hourly transaction number, which were recorded by each store’s computer system. Four hour average VOC concentrations were measured using Summa Canisters as a mobile collection device. Simultaneously, the TVOC and formaldehyde concentrations were measured with photoionization detectors (PID) and real-time formaldehyde monitors, respectively. PID TVOC concentrations were not directly correlated with TVOC concentration calculated by summing the separated VOC concentrations collected by Summa Canisters. In this study, the summation of individual VOC concentrations was used for TVOC concentrations. In addition, the Formaldehyde monitors (FMM) results were strongly correlated with DNPH tube results. The major finding from this objective can be summarized as followings:
The maximum daily occupant number for one week was approximately 40% and 30% lower than that called by ASHRAE Standard 62.1 (Maximum) for store 1 and 2, respectively, so that the maximum occupant density was 6 people/100m² (5 people/1000 ft²) and 5 people/100m² (4 people/1000ft²), respectively. In addition and for different seasons, the average occupant numbers were approximately 300 in five days of September 2011 and 225 in two days in January 2012 for store 2.

Based on occupant numbers and using the VRP during the whole week, the retail stores were ventilated by the minimum ventilation rate required by floor component for most hours of the day, except 5 hours a day (13:00-18:00 pm) when the stores were ventilated with the approximate amount of up to 30% and 22% above the minimum ventilation rate required by floor component respectively.

Based on contaminants of concern and by using IAQP, the formaldehyde was the most important VOC of concern in retail stores. Both studied stores exceeded the most important conservative health guideline for formaldehyde, which is 7.3 ppb OEHHA TWA REL. This finding motivated an exploration of strategies to reduce exposure to formaldehyde in retail store buildings with energy penalty and increasing of operation cost of filter material and also motivated an effort exploring strategies with a minimal energy penalty. Those strategies can be concluded in the followings:

- Increase ventilation rates required to approximately 16% and 38% for store 1 and (lower than the maximum ventilation rates required by ASHRAE Standard 62.1), or increase the measured, and the minimum ventilation rates by approximately 53% and 12%, and by 43% and 21% in the stores 1 and 2, respectively.
- Apply air clean filter to Purafil selected media to completely eliminate formaldehyde concentrations. The filtration media will cost around $490 and $704 per month for store 1 and 2 respectively so that the operation cost will be increased dramatically.

- Reduce whole-building emission rates to have a potential effect on reducing formaldehyde in stores below 7.3 ppm by approximately 50% and 29% respectively.

- Isolate sources of formaldehyde such as insulation materials and furniture

Another finding of this study was that the Total Volatile Compound was at low concentrations in both stores. This finding motivated an effort to explore different ventilation strategies to reduce energy consumption. Energy Natural gas heating savings of approximately 19% and 15%, and 6% and 9% could be achieved when the ventilation rates in store 1 and 2 (respectively) were reduced from ASHRAE minimum (VRmin) and measured ventilation (VRmea) rates to Mohave guideline (1700 µg/m²) and approximately by 16% and 16% to Bridges reference (1000 µg/m²).

Another important finding of this dissertation that can contribute to the understanding of the impact of ventilation rates on electrical energy consumption is that the electrical cooling energy consumption was not significantly sensitive to different ventilation rates. Generally, the results show that by reducing the ventilation rates, the electrical cooling consumption slightly increased in the range of 0.4% to 4% for both stores.

7.1.2 Objective 2: Resetting Indoor Air Temperatures

The indoor air temperature measurements revealed that vertical indoor air temperature differences were stratified and in the range of 0.5º C to 3.0º C between sensors most of the time,
which is also within the limit of the ASHRAE thermal comfort requirements. Horizontal indoor air temperature measurement difference results show well mixed air in the stores. These differences were only from 0.5º C to 4 ºC among sensors most of the time.

Interestingly, the temperature of 23.8 ºC (75º F), which is the lowest value of thermal comfort (ASHRAE 55-2004), was the optimum temperature for sedentary people, such as cashiers and for active people, such as customers and employees working in the store.

The measured indoor temperatures in the theses buildings were at the lower limit or below the ASHRAE thermal comfort requirements, around 20.7ºC (70ºF) and 21.79º C (71.5ºF), so that by increasing this temperature to the optimum temperature, the electrical cooling energy savings were approximately 48% and 22% for store 1 and 2, respectively. With respect to the heating findings, the energy savings were approximately 9% and 13%, 1ºC less in store 1 and 2, respectively.

7.1.2 Optimization between Ventilation Rate Reductions and set point Indoor Air Temperatures

Study findings concluded that ventilation rate reductions had negligible effects on the electrical cooling consumption. However, increasing indoor air temperatures by approximately 3ºC in summer had a significant effect on the energy savings. In winter, both energy saving strategies, ventilation reduction and decrease in temperature set points, had a significant effect on the natural gas consumption.
7.2. Recommendations for Future Studies

To assess the impact of different ventilation rates on electrical cooling consumption, site measurements needed to be performed.
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### Appendix A

#### Air Conditioning System _ Store 1

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Appendix B

Indoor CO₂ concentration based on averaged five measurements at different locations in retail space
Appendix C

VOLATILE ORGANIC COMPOUNDS IN FOURTEEN U.S. RETAIL STORES (Nirlo, et al., 2014)

Table 3 Indoor categorized VOC concentrations (ppb) found by Summa canisters for all test visits.

| VOC Category     | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe | HaFe |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Ethanol          | 250  | 194  | <DL  | <DL  | 840  | 484  | 436  | 637  | 10.9 | 51.4 | 149  | 400  | 71.6 | 31.4 | 4.9  | 40.2 | 212  | 13.8 | <DL  |
| Non-halogenated alkenes | 183  | 461  | 14.1 | 13.2 | 13.2 | 39.4 | 43.7 | 84.2 | <DL  | 195  | 18.1 | 165  | 10.5 | 8.8  | 231  | 15.6 | 9.0  | 45.7 | 117  | 16.4 | 18.8 | 150  | 22.4 |
| Acetone          | 370  | 122  | 108  | 34.7 | 17.5 | 21.0 | 24.4 | 99.6 | 7.2  | 22.7 | 25.9 | 15.1 | 17.3 | 6.3  | 3.5  | 192  | 5.1  | 13.9 | 13.1 | 12.2 | 27.4 | 16.3 | 16.0 |
| Total impurities | 348  | 287  | 19.9 | 6.5  | 6.5  | 3.9  | 4.2  | 8.2  | 18.7 | 5.4  | 2.5  | 2.2  | <DL  | <DL  | <DL  | 5.5  | <DL  | 21.2 | 5.4  | 7.3  | 8.3  | 133  | 21.5 | 5.6  | 2.8  |
| Acetonitrile     | 55.2 | 4.3  | <DL  | <DL  | <DL  | 0.7  | 6.5  | 0.6  | 5.2  | 4.1  | <DL  | 0.55 | 1.04 | <DL  | 50.6 | 24.4 | <DL  | 21.4 | 5.6  | 9.6  | 3.5  | 7.7  | 2.0  |
| Isopropenol      | 18.0 | 105  | 15.9 | 10.6 | 6.5  | 6.9  | 13.6 | 68.8 | 25.6 | 4.9  | 20.3 | 7.7  | 5.7  | 5.3  | 3.3  | 0.3  | 5.7  | 18.7 | 6.9  | 12.2 | 12.6 | 9.8  | 10.1 | 0.6  | 1.8  |
| Chlorinated acids | 47.8 | 50.3 | 3.7  | 1.6  | 2.3  | 0.8  | 11.6 | 0.7  | <DL  | <DL  | 4.1  | 1.18 | 5.8  | 11.5 | 1.3  | <DL  | 11.4 | 4.5  | 0.5  | 7.0  | 9.7  | 9.3  | 3.4  | 10.4 | 7.0  |
| STES              | 55.5 | 34.5 | 14.2 | 3.3  | 2.7  | 0.4  | 3.3  | 0.6  | 2.3  | 1.7  | 22.0 | 1.8  | 1.5  | 1.3  | 21.7 | 8.9  | 3.7  | 10.1 | 1.6  | 0.7  | 1.3  | 5.0  | 2.0  | 5.3  |
| Halogenated alkenes | 0.1  | 15.5 | 3.7  | 13.9 | 14.6 | 7.2  | 15.4 | 5.1  | 2.7  | 45.0 | 34.7 | 7.9  | 3.4  | 2.5  | 0.7  | <DL  | 0.5  | 0.5  | 5.5  | 8.5  | 6.8  | 6.7  | 9.7  |
| Non-TiSS4 aromatic | 6.8  | 0.4  | <DL  | <DL  | <DL  | 0.7  | 1.8  | 2.4  | <DL  | <DL  | 0.5  | 0.6  | 0.6  | 0.6  | 0.6  | 0.6  | <DL  | <DL  | <DL  | <DL  | <DL  | <DL  | <DL  | 50.2 |
| Other             | 93.1 | 101  | 114  | <DL  | <DL  | <DL  | 10.0 | 7.5  | 25.8 | 2.9  | <DL  | 19.6 | 2.4  | 1.8  | 14.5 | <DL  | 7.4  | <DL  | <DL  | 11.2 | <DL  | 2.7  | 14.7 |

*a Detection limit (DL) = 0.5 ppb for most compounds.
*b The first letter identifies the store type (H for home improvement, M for general merchandise, E for electronics, O for office supply, F for furniture, G for grocery (mid-size) and S for small grocery); the second letter differentiates the brand of the store; and the third letter the location of the store (P for Pennsylvania and T for Texas). At stores where multiple visits occurred, sampling events are identified with a four-character code composed of the store code and a number (1–4) referring to the test visit considered.
Appendix D

VOC category concentrations by site, as sampled indoors by Summa Canisters.
Appendix E

Formaldehyde concentration by site, as sampled indoors by DNPH tubes ASHEAR RP 1596
VITA

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Education

-B.Sc in Mechanical and Industrial Engineering, Tripoli University in Libya
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Work on projects

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