INDOOR AIR QUALITY IN SCHOOLS:
AN INVESTIGATION OF THE IMPACT
OF OUTDOOR AIR QUALITY, SCHOOL
LAYOUT, AND ROOM TYPE

By
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Abstract

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Indoor air quality (IAQ) in educational facilities is a very important aspect of the educational process because it may affect the students and staff health and performance. This study was conducted during the 2012-2013 academic year in three high schools from two school districts in the North Texas region, to determine whether or not the IAQ in test schools meets Texas IAQ guidelines, investigate the impact of the outdoor quality, school layout, and room type on the IAQ of the test schools. Temperature, relative humidity, carbon monoxide (CO), carbon dioxide (CO₂), ozone (O₃), and volatile organic compounds (VOCs) were monitored for a week in four different classrooms in each school using a Direct Sense IAQ monitor (IQ-610). Outdoor air data (temperature, relative humidity, carbon monoxide and ozone) was obtained from the closest monitor sites of the Texas Commission of Environmental Quality to investigate the correlation between indoor and outdoor air quality in the test schools. The results of this study show that the test schools showed generally low levels of VOCs, CO, O₃, CO₂ within the guidelines and acceptable ranges of temperature and relative humidity. However, a few rooms meet the guideline over half percent of the time for CO₂, RH and VOCs. It is recommended that the
ventilation rate be increased to improve the IAQ in these rooms of concern. The data show weak to no correlation trends between indoor and outdoor parameters in test schools. The layout of test school facilities, evaluated using the distance of each room to the nearest school entrance, did not show an effect on the IAQ in the test schools. Different types of rooms (science room, computer room, copy room, and regular classroom) did not show different IAQ concentrations. The ANOVA test used may not have been powerful enough to detect differences.
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Chapter 1

Introduction

The primary purpose of this dissertation is to assess the indoor air quality of three schools in North Texas as well as to investigate the factors that might impact indoor air quality in the test schools, such as the outdoor air quality, school layout and room type.

1.1 Problem Statement

There is increasing evidence that indoor environmental conditions substantially affect the occupants’ health and performance (Seppanen et al., 2006). Public concern about adverse effects of indoor air quality (IAQ) has increased in recent decades, beginning with the energy crises in the 1970’s. In the 70’s “energy efficient” (tighter) buildings were designed to lower energy consumption, and synthetic building materials and furniture were increasingly used. This caused unacceptable IAQ, and occupants reported health problems associated with their buildings. According to Mendell (2004), poor IAQ has been related to acute health problems, including fatigue, headache, nausea and eye, nose, throat irritation as well as long-term health problems, including chronic respiratory diseases such as asthma, lung cancer, and heart disease. Mendell (2004) found that health problems from poor indoor environments may reduce the performance of the occupants in buildings, with potentially substantial adverse effects on workforce productivity. The US Environmental Protection Agency began using the term “Sick Building Syndrome” (SBS) to describe situations where building occupants experienced acute health and comfort effects that appear to be linked to time spent in a building. Indoor Air Quality (IAQ) refers to the air quality inside and around buildings. Regulation
and awareness of outdoor air quality and its effects on human health have been of significant concern since the mid-20th century. The United States Congress passed the US Clean Air Act in 1963, the Air Quality Act in 1967, the Clean Air Act Extension of 1970, and Clean Air Act Amendments in 1977 and 1990. IAQ has not received the same quality of regulation or attention as of yet, although people often spend more time indoors and the concentrations of certain pollutants may be significantly higher indoors than outdoors. Just before the 1973 oil embargo, the American Society of Heating, Refrigerating & Air-conditioning Engineers (ASHRAE) proposed the first major change to ventilation standards in the US. Over the past 30 years, ASHRAE has continued to revise this standard to address indoor environmental concerns.

The indoor environment of the educational facilities is particularly important for a number of reasons. As mentioned by Mendell (2005), the U.S. General Accounting Office reported in 1995 that schools, relative to other kinds of buildings, are seen as particularly likely to have environmental deficiencies because chronic shortages of funding contribute to inadequate operation and maintenance of facilities. In addition, many school facilities are constructed on tight budgets, and often their mechanical equipment does not adequately accommodate the facility need of each room, based upon the occupancy and activity level inside. Many school facilities have been designed with heating, ventilation, and air conditioning (HVAC) systems that are not capable of effectively managing space humidity. Godwin et Al. (2006) stated that schools contain a variety of spaces serving different activities, potentially different contaminant sources (e.g. classrooms, offices, science, library, cafeteria, art, gymnasiums), and many schools employ unitary air handlers that limit mixing with other spaces in school. Consequently, multiple locations should be measured to characterize IAQ parameters in schools.
According to ASHRAE 62, when HVAC systems properly align with the needs of the facility, this can prevent or fix a large number of IAQ problems by controlling the indoor relative humidity, providing adequate outdoor air ventilation on a continuous basis and providing effective particulate filtration of the outdoor air. Mendell (2005) mentioned that few states regulate indoor environmental quality (IEQ) in schools, and fewer still have minimum ventilation standards for schools.

IAQ in schools should be a major area of concern and receive more regulations and attention due to occupant density, and the fact that children have greater susceptibility to some environmental pollutants than adults, because their bodies still developing and they spend a large amount of time inside the school. Many children have chronic illnesses such as asthma, allergies, and other respiratory illnesses and, exposure to high levels of air pollutants can aggravate those conditions. Even low levels of symptomology can affect the students’ health and, in turn, their academic performance. In the case of students, not only their academic performance can be compromised, but their absences can also result in decreased government funding, effectively lowering the school’s overall budget. In the case of teachers and staff, absences can result in higher expenses due to having to pay for temporary personnel, again negatively affecting the school's budget. Wargocki (2008) mentioned that improving IAQ in schools may also lead to more time for learning and leisure, and that more difficult school work can be performed and therefore, improving IAQ would make the process of educating children more efficient.

1.2 Purpose and Scope of Study
The primary purpose of this study is to investigate the factors that might affect the IAQ and to assess the IAQ in North Texas region test schools by monitoring indoor air parameters (temperature, relative humidity (RH), carbon monoxide (CO), carbon dioxide (CO$_2$), ozone (O$_3$), total volatile organic compounds (TVOCs)) in different types of classrooms (science classroom, computer classroom, copy room and regular classroom (language, social studies, …)), to determine the factors that might affect the indoor air parameters concentration levels and to assess whether the IAQ in test schools meets the Texas Voluntary IAQ Guidelines.

1.3 Objectives of Dissertation

The focus of the proposed dissertation is to investigate the impact of the outdoor, the classroom use and the layout of the classroom on indoor air quality as well as to assess the indoor air quality in North Texas public schools.

**Objective 1:** To assess whether or not the IAQ levels in test schools meet the Texas Voluntary IAQ Guidelines (*T.V.IAQ Guidelines*).

To plot the cumulative frequency distributions for each parameter for each room in the test schools and compare it with the Texas IAQ Guidelines to determine whether or not the test schools meet the Texas Voluntary IAQ Guidelines.

H$_0$: The IAQ in test schools didn’t meet the Texas Voluntary IAQ Guidelines as set forth by Texas Department of Health.

H$_1$: The IAQ in test schools meet the Texas Voluntary IAQ Guidelines as set forth by Texas Department of Health.
Objective 2: To investigate the correlation between indoor and outdoor air quality levels in test schools in the north Texas region

Monitor selected IAQ parameters such as (temperature, relative humidity (RH), carbon monoxide (CO) and ozone (O₃)) using an automatic portable indoor air quality probe (IQ-610, Gray Wolf monitor) and collect the outdoor data for temperature, relative humidity, carbon monoxide, ozone from the Texas Commission on Environmental Quality (TCEQ) closest site to the test schools to evaluate the correlation between the indoor and outdoor air quality levels in test schools.

H0: There is no correlation between the indoor and outdoor air quality in test schools
H1: There is correlation between the indoor and outdoor air quality levels in test schools

Objective 3: To determine whether the layouts of test school facilities have an effect on the IAQ of test schools.

Compare median concentrations for the different parameters (temperature, RH, CO₂, CO, O₃, TVOCs) vs. distance to the school entrance. Compare cumulative frequency distributions for the various parameters vs. distance to school entrance.

H0: The layouts of test school facilities do not have effect on the IAQ in schools.
H1: The layouts of test school facilities have an effect on the IAQ in schools.
Objective 4: To assess whether rooms of different types have different concentration levels.

Conduct 2-way ANOVA by room and school (confidence level 0.05) to determine whether there are differences among the four different types of rooms and different schools.

H0: Rooms of different types do not have different concentration levels.

H1: Different types of rooms have different concentration levels.

1.4 Organization of Dissertation

Chapter 2 provides an overview of the existing literature related to indoor air quality in schools. Chapter 3 describes the study methodology, data collection, and data analysis procedures. Chapter 4 presents results and discusses the data analysis and interpretation. Chapter 5 summarizes conclusions and provides recommendations for future research.
Chapter 2
Review of Literature

This chapter summarizes the literature review of the factors that may impact the indoor air quality in test schools, such as the outdoor air quality and other possible factors. Additionally, the chapter includes a definition of acceptable indoor air quality according to Texas Voluntary Indoor Air Quality Guidelines for Government Buildings and the criteria for acceptable indoor air quality that have been used to assess the air quality in test schools.

2.1 Importance of Indoor Air Quality

The indoor air quality (IAQ) in classrooms is an important aspect of the learning process, and working to improve the IAQ in schools should be given as much concern as advancing teaching methods or improving the education system (Wargocki et al., 2006). Mendell (2004) mentioned that poor IAQ in schools can effect on learning directly by impairing concentration and memory during class time and indirectly by exacerbating diseases such as asthma, allergies, which can affect the occupant attendance and performance. Fisk (2000) found strong evidence that the characteristics of the building and indoor environments can significantly influence the occurrence of communicable respiratory illnesses, sick building symptoms, allergies and asthma symptoms. According to Mendell (2005), poor IAQ in schools can also have an effect on student, teacher and staff health and productivity. In the case of students, not only their academic performance compromised, their absences can also result in decreased government funding, effectively lowering the school’s overall budget. In the case of teachers and staff, absences can result in higher expenses due to having to pay for temporary personnel, again negatively affecting the school’s budget. IAQ in schools should be a major area of
concern and receive more regulation and attention due to occupant density and children having greater susceptibility to some environmental pollutants than adults, because their bodies still developing and they spend such a large amount of time inside the school.

2.2 Previous Studies of Indoor Air Quality in Schools

Table 2.1 summarizes studies of indoor air quality in schools and classrooms. Particular emphasis is given to studies of indoor air quality in Texas schools.

Torres et al. (2002) focused on identifying the parameters that can affect indoor air quality in central and south Texas elementary schools. The study had three phases: questionnaire to be completed by teachers and staff to collect general information about the classrooms use and contents, walk through in each school to obtain more information about the building’s design, and then continuous monitoring of temperature, relative humidity (RH), carbon dioxide (CO₂), carbon monoxide (CO), fungi, bacteria genera, volatile organic compounds (VOCs). Their major finding was that most of the classrooms had inadequate ventilation, which can be a major factor that affects the indoor air quality in schools.

Tortolero et al. (2002) assessed the IAQ in selected elementary schools in southeast Texas by collecting data from the environment observation checklist survey, monitoring the ventilation and collecting dust samples. They found that 86% of classrooms had CO₂ higher than the recommended level, which can indicate that the ventilation rate is less than the guideline. 69% of classrooms had relative humidity level higher than the recommended level, which can promote the growth of mold. They suggested that carpet in classrooms might contribute to mold and dust mites.

Shendell et al. (2004) examined the association between student absences and the CO₂ concentration level in 22 schools (traditional and portable classrooms) in
Washington and Idaho states. They found that when the CO$_2$ concentration level exceeded than 1000 ppm, the students absence increased relatively by 10-20%.

Petronella et al. (2005) investigated indoor air quality in a high school in Galveston, Texas by conducting a survey to identify the areas of environmental quality concern, visually inspecting those sites and then monitoring volatile organic compounds (VOCs), formaldehyde (HCHO), ozone (O$_3$), particulate matter (PM$_{10}$), mold, relative humidity (RH), and temperature. They found that the levels of VOCs, PM$_{10}$, O$_3$, HCHO were within the guidelines.

Wargocki (2006) mentioned that inadequate ventilation is one of the common problems in the schools that could affect the occupant health and performance. Wargocki (2006) examined the effect of using different ventilation rates during regular classroom work (language, math) for students ages 10-12. They found a consistent relationship between CO$_2$ concentration level and SBS symptom intensities in the classrooms and also a significant correlation between students’ performance improvement and SBS symptoms reduction.

Currie et al. (2009) examined the effect of ambient air pollution (PM$_{10}$, CO, O$_3$) on students ‘absence in 39 of the largest school districts in Texas. They found significant correlation between high levels of carbon monoxide (CO) levels, even below the federal air quality standards, and increased students’ absences as a proxy for child health.

Raysoni (2011) investigated the impact of traffic-related pollution on asthmatic children and on the air quality in four elementary schools in El Paso and the U.S. Mexico-border (two schools in high traffic zones and two in low traffic density zones). They collected the indoor air and outdoor air data of fine and coarse particulate matter (PM$_{10}$, PM$_{2.5}$), Black Carbon (BC), and nitrogen dioxide (NO$_2$). They mentioned that black carbon and nitrogen dioxide appear to be better traffic indicator than fine and coarse PM
because the BC and NO$_2$ concentrations in high traffic zones exceeded those measured in low traffic zones, and the indoor air pollution was associated with the outdoor air pollution. The study also mentioned the factors that might affect indoor/outdoor (I/O) ratios for pollutants concentrations such as the differences in building envelope tightness, building design, pollutant differential penetration, building air exchange rates, presence of central air conditioning, type of HVAC system, occupancy rates, occupants’ activities, and other indoor air pollution sources.

Zhang (2011) examined the effect of the occupants’ activities, indoor sources and ventilation settings on the indoor air quality in five schools in South Texas (one private elementary school, one public high school, two community colleges, and one university) with ages ranging between 10 and 60 years. The study monitored PM$_{2.5}$, PM$_{10}$, ultra-fine particles (UFP), CO$_2$, temperature, and relative humidity inside and outside of each studied microenvironment simultaneously for regular school day. The studied microenvironments included classrooms, libraries, cafeterias, offices, and hallways with different room sizes (9 to 20 m$^2$). The indoor particles concentration was found to be greater than the outdoor particle concentration due to indoor sources such as classrooms activities (e.g. art activities like painting) that could elevate the UFP levels in classrooms and also due to increased total particles when the heaters started operating. They concluded that introducing more fresh air and increasing the efficiency of filters used in ventilation systems may reduce both particle and CO$_2$ concentrations and improve the air quality.

Mendell (2013) monitored the CO$_2$ concentration in classrooms and collected illness absence rates from the school district. Ventilation rates were calculated using the CO$_2$ concentrations. They found that inadequate ventilation significantly affected
absences due to illness; they suggested that meeting the IAQ guidelines could substantially improve the occupants’ health and performance.

Godwin (2006) examined 21 elementary schools, 5 middle schools and 3 high schools in southeast Michigan, to assess air quality in classrooms with different uses (art, science, office, computer, music) within and between schools. In each classroom, bio aerosols, VOCs, CO₂, RH and temperature were monitored for one work-week indoors; VOCs, bio aerosols, temperature, RH outdoors; outdoor samples were taken at rooftop locations at each school and a comprehensive walk-through survey was completed. They found that the variability of CO₂, VOC and bio aerosol concentrations within schools exceeded the variability between schools. CO₂ concentrations in most of the classrooms exceeded 1000 ppm. Low levels of VOCs and bio aerosols were found, along with acceptable ranges of temperature and RH. Bio aerosol was associated with the presence of carpeting. VOCs concentrations were the highest in science and art rooms.

Table 2.1 Previous studies of indoor air quality in schools

<table>
<thead>
<tr>
<th>Reference</th>
<th>Study Location</th>
<th>School Level</th>
<th>Parameters measured</th>
<th>Result/Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torres et al. (2002)</td>
<td>Central and south Texas Elementary</td>
<td>CO, CO₂, temperature, RH, VOCs, fungi, bacteria genera, PM₂.₅</td>
<td>Inadequate ventilation and water leakage from roofs</td>
<td></td>
</tr>
<tr>
<td>Tortolero et al. (2004)</td>
<td>Southeast Texas Elementary</td>
<td>Temperature, CO₂, RH, dust samples</td>
<td>86% of classrooms had CO₂ concentration more than 1000 ppm. 69% of</td>
<td></td>
</tr>
</tbody>
</table>
classrooms had RH more than the recommended value (30%-60%).

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Type of School</th>
<th>Parameter(s)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shendell et al. (2004)</td>
<td>Washington and Idaho</td>
<td>Elementary and secondary schools</td>
<td>CO₂ student absences</td>
<td>When the CO₂ concentration exceeded 1000 ppm, the student absences increased by 10-20%</td>
</tr>
<tr>
<td>Petronella et al. (2005)</td>
<td>Galveston, Texas</td>
<td>High school</td>
<td>VOCs, HCHO, O₃, mold, PM₁₀, temperature</td>
<td>The concentration of VOCs, PM₁₀, O₃, and HCHO were within the guidelines.</td>
</tr>
<tr>
<td>Wargocki et al. (2006)</td>
<td>Denmark</td>
<td>Elementary</td>
<td>CO₂, student performance</td>
<td>They found a significant correlation between performance improvement and decreasing the CO₂ level and SBS symptoms intensities.</td>
</tr>
<tr>
<td>Currie et al. (2009)</td>
<td>39 of the largest school districts in Texas</td>
<td>Elementary, middle and high schools</td>
<td>Ozone, CO, PM₁₀, student absences</td>
<td>They found a significant correlation between high levels of CO, even below the federal air quality standards, and increased of students’ absences.</td>
</tr>
<tr>
<td>Study (Year)</td>
<td>Location</td>
<td>Setting</td>
<td>Parameters Measured</td>
<td>Findings</td>
</tr>
<tr>
<td>-------------</td>
<td>----------</td>
<td>---------</td>
<td>---------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Raysoni et al. (2011)</td>
<td>El-Paso, Texas and US-Mexico border region</td>
<td>Elementary schools</td>
<td>PM$<em>{10}$, PM$</em>{2.5}$, BC, NO$_{2}$, indoor and outdoor.</td>
<td>IAQ was associated with outdoor air pollution. BC and NO$_{2}$ levels in high traffic zones exceeded those measured in the low traffic zones.</td>
</tr>
<tr>
<td>Zhang et al. (2011)</td>
<td>Urban and rural areas in South Texas</td>
<td>Elementary, high schools, community colleges, and university</td>
<td>PM$<em>{10}$, PM$</em>{2.5}$, UFP, CO$_{2}$, temperature, RH.</td>
<td>Increasing fresh air and the efficiency of filters may improve the air quality. Classrooms activities could elevate ultra-fine particle levels in classrooms.</td>
</tr>
<tr>
<td>Mendell et al. (2013)</td>
<td>Three school districts in California</td>
<td>Elementary</td>
<td>CO$_{2}$ and absences due to illness</td>
<td>Increasing classroom Ventilation Rates (VRs) above the state standard would substantially decrease illness absence.</td>
</tr>
<tr>
<td>Godwin et al. (2006)</td>
<td>Southeast Michigan</td>
<td>Elementary, middle and high schools</td>
<td>VOCs, CO$_{2}$, RH, temperature and bio aerosols</td>
<td>Low levels of VOCs and bio aerosol, acceptable range of temperature and RH, and often inadequate ventilation rates. Bio aerosol was associated</td>
</tr>
</tbody>
</table>
Table 2.1—Continued

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>with the presence of carpeting.</th>
</tr>
</thead>
</table>

Most of the studies listed in Table 2.1 measured air quality in a school and compared it with IAQ guidelines, assessed whether a correlation existed between student absences and indoor air quality, and/or assessed the adequacy of school ventilation rates. Only 3 of the studies looked at factors besides ventilation rates that might impact IAQ: Raysoni et al. (2011) assessed the impact of outdoor air quality due to traffic on indoor air quality, and Zhang et al. (2013) and Godwin et al. (2006) looked at the impact of classroom activities. None of the studies assessed the impact of school layout.

Most of the Texas indoor air quality studies listed in Table 2.1 were done in south and central Texas, and most involved elementary schools.

2.3 Factors that Impact Indoor Air Quality

There are many factors that can affect indoor air quality, including Zhang et al. (2011):

- The use of synthetic building materials,
- Furnishings & electronic office equipment (computers, printers, copy machines,…),
- lack of outdoor air supply to cramped spaces, inadequate ventilation, occupancy rate, insufficient exhaust airflows,
- building design,
- building envelope tightness,
- poor maintenance of heating, ventilation and air conditioning systems,
• occupants’ activities such as painting and gluing during art class, and
• Teaching supplies.

Godwin (2006) mentioned that VOCs were associated with occupants’ activities in the classrooms, and they found that art and science rooms had highest concentrations of VOCs. As investigated by Raysoni (2011), outdoor air quality level can also be a factor that affects the indoor air quality; choosing a site close to a major highway or in an industrial area may increase the indoor pollutant concentration level.

Mendell’s (2005) review of the influence of indoor environmental quality factors on occupants’ health and performance in schools mentioned that schools, relative to other kinds of buildings, are seen as particularly likely to have environmental deficiencies because chronic shortages of funding contribute to inadequate operation and maintenance of facilities. In addition, many school facilities are constructed on tight budgets, and often their mechanical equipment does not adequately accommodate the facility need of each room, based upon the occupancy and activity level inside. Many school facilities have been designed with HVAC systems that are not capable of effectively managing space humidity.

Daisey et al. (2003) mentioned that the U.S. General Accounting Office in 1995 reported in that many school districts in the United States have significant indoor environmental problems and many classrooms are inadequately ventilated. Ventilation is a very important factor that could deteriorate the indoor air quality or improve it by reducing the concentration level of the air pollution. Many studies suggested that increasing the ventilation rate with using the efficient filtration could improve the indoor air quality.
2.4 Indoor Air Quality Guidelines

Regulation and awareness of outdoor air quality and its effects on human health have been of significant concern since early in the 20th century. The United States Congress passed the US Clean Air Act in 1963, the Air Quality Act in 1967, the Clean Air act Extension of 1970, and Clean Air Act amendments in 1977 and 1990. IAQ has not received the same quality of regulation or attention as of yet, although people often spend more time indoors and the concentrations of certain pollutants may be significantly higher indoors than outdoors. As mentioned in Mendell (2005), there are few states regulating indoor environmental quality (IEQ) in schools, and fewer still have minimum ventilation standards for schools. Although there are no currently defined federal regulations covering IAQ, there are voluntary programs that have established a number of standards, guidelines and recommendations: in 1995 House Bill 2850 (HB2850) required the Texas Department of State Health Services (DSHS) to establish voluntary guidelines for IAQ in public schools. December 22, 2002 House Bill 2008 (HB2008) required DSHS to basically broaden the scope of the original guidelines to cover all government buildings, including public school buildings.

Texas Voluntary IAQ guidelines for Government Buildings (2002) define acceptable IAQ as: “the quality of air in an occupied enclosed space that is within an established temperature and humidity comfort zone, and which does not contain air contaminants in sufficient concentration to produce a negative impact on the health and comfort of the occupants”. Table 2.2 shows the Guideline values for various IAQ parameters from Texas IAQ guidelines for government buildings, 2002.
Table 2.2 Criteria for acceptable Indoor air quality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(MRL) Guidelines</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>70°F to 76°F (+/-) 2°F 20°C to 24°C (+/-) 2°C</td>
<td>ASHRAE standard 55</td>
</tr>
<tr>
<td>Relative Humidity (RH)</td>
<td>30%-60%</td>
<td>ASHRAE standard 55</td>
</tr>
<tr>
<td>Ventilation</td>
<td>15 – 60 cfm/person, depending on the space type</td>
<td>ASHRAE standard 62</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>9 ppm for 8hrs 35 ppm for 1 hr.</td>
<td>EPA (NAAQS)</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>700 ppm above the outdoor level</td>
<td>ASHRAE standard 62</td>
</tr>
<tr>
<td>Ozone (O₃)</td>
<td>Level should not exceed 0.05 ppm</td>
<td>EPA (NAAQS)</td>
</tr>
<tr>
<td>VOCs</td>
<td>Emission rate should not result in an indoor concentration levels greater than 0.5 mg/m³ of total VOCs = 165 ppb</td>
<td>Texas IAQ Guidelines, 2002</td>
</tr>
</tbody>
</table>

Further discussion of each guideline is provided below.

**Temperature**

Wyon (2004) examined the effect of temperature on the people’s comfort and productivity and suggested that (+/-) 5 °F of temperature control could increase work performance by 3% to 7%, make it easier to concentrate, and can influence workers' speed or accuracy by 2% to 20% in a task such as typewriting, learning performance,
reading and remembering words. According to ASHRAE standard 55, acceptable indoor temperatures levels range from 72°F to 76 °F in the summer and 70°F to 75°F in the winter, within a range of (+/-) 2 °F.

Relative Humidity (RH %)

Wargocki et al. (2008) mentioned that it is well documented that thermal conditions within the thermal comfort zone can reduce performance by 5% to 15%. According to (ASHRAE) standard 55, acceptable relative humidity levels range from 30% to 60% year-round. Excessively high or low relative humidity can produce discomfort. Low relative humidity can accelerate the release of spores into air, which contributes to irritation of the respiratory tract and eyes, and high relative humidity can promote the growth of mold, bacteria and dust mites, which are associated with allergies and asthma.

Ventilation

ASHRAE’s 62 standards recommended ventilation for classrooms was reduced from 30 cubic foot per minute (cfm)/person to 10 cfm/person in the 1930s, and reduced again to 5 cfm/person in 1973 due to the increase in the energy prices from the oil embargo. Due to public health concerns, they raised the minimum ventilation rate in all public buildings to 15 cfm/person (20 cfm/person in office spaces) up to 60 cfm/person in some spaces (such as smoking lounges), depending on the activities that normally occur in that space.

Carbon Monoxide (CO)

Carbon monoxide is a colorless and odorless gas resulting from incomplete oxidation of carbon in combustion processes. The main sources of CO include unvented or poorly vented indoor combustion sources, such as gas heaters and appliances, and outdoor sources from idling vehicles outside buildings. The U.S. National Ambient Air
Quality Standards for CO are 9 ppm for 8 hrs. and 35 ppm for 1 hr. At low concentrations, CO exposure symptoms include fatigue, headaches, dizziness, and nausea; at moderate concentrations, symptoms include angina, impaired vision and reduced brain function. High levels can be fatal. According to Currie et al. (2009), high concentration levels of CO, even when below the federal air quality standards, significantly increased students’ absences.

**Carbon Dioxide (CO$_2$)**

Carbon dioxide accumulation is a surrogate of inadequate ventilation, since ventilation with sufficient outdoor air can control carbon dioxide levels. ASHRAE Standard 62 recommends an acceptable carbon dioxide level of 700 ppm above the outdoor level; the outdoor level of carbon dioxide usually ranges from 300 ppm to 400 ppm. High levels of CO$_2$ can lead to tiredness and a lack of concentration and can contribute to the symptoms of Sick Building Syndrome such as headaches, eye, nose and throat irritation, itchy skin and nausea (Texas IAQ Guideline, 2002). Daisy et al. (2003) summarized the literature on indoor air quality, ventilation, and building-related health symptoms in schools; they mentioned that adequate ventilation in classrooms should be a major focus of design because many classrooms barely meet the ASHRAE ventilation standard, which can result in an increase of carbon dioxide concentrations and symptoms in school children. According to Shendell et al. (2004), which investigated the association of student attendance, health and performance with the concentration of carbon dioxide in the classrooms, when CO$_2$ increased more than 1000 ppm above the outdoor concentration, this correlated with a relative increase (10%-20%) of the students’ absence, and the associations were statistically significant.

**Ozone (O$_3$)**
According to EPA’s National Ambient Air Quality Standard, outdoor ozone levels are not to exceed 0.075 ppm for an 8-hr average; according to Texas Voluntary IAQ Guidelines for government buildings, the acceptable level indoors is 0.05 ppm. Ozone is a respiratory irritant produced by equipment that uses high voltage electricity, for example photocopiers and ion generator air cleaners. Ozone is irritating to lung tissue, eyes, and mucous membranes. Pulmonary edema and exposure times may lead to respiratory disease (T.V.IAQ Guidelines, 2002). Reactions with ozone have the potential to be quite significant as sources of compounds that are often quite odorous and potentially damaging to both human health and materials. Apte et al. (2009) showed a clear relationship between ambient ozone concentrations and building-related health symptoms (BRS) or sick building syndrome (SBS) which can affect the occupants’ health and performance.

**Volatile organic compounds (VOCs)**

Volatile organic compounds (VOCs) are emitted from building materials, furnishings, personal care products, pesticides, tobacco smoke, air fresheners, aerosol sprays, and adhesives. Testing emissions from building materials is increasingly common and product emission rates should not result in indoor concentration levels greater than 0.5 mg/m³ of total VOCs (Texas IAQ Guidelines, 2002). Some VOCs can cause eye, nose and throat irritation; headaches; loss of coordination; nausea; and damage to the liver, kidneys, and central nervous system. A few VOCs have been linked to cancer in human (e.g., benzene). According to Daisey et al. (2003), the pollutant most commonly measured in schools are TVOCs, formaldehyde and microbiological contaminants. Formaldehyde levels in schools should be kept very low because recent research suggests that even low levels may lead to an increased risk of sensitization to allergens. Daisey et al. also mentioned that exposures to VOCs, mold and microbes generally
measured in classroom floor dust are related to asthma, SBS and other respiratory symptoms.

2.5 Recommendations for Achieving Acceptable Indoor Air Quality

Most buildings have an established ventilation rate that the HVAC unit is expected to execute. This ventilation rate is based upon building size and expected number of building occupants. An effective method to achieve good IAQ is adequate ventilation with a properly designed and operated HVAC system. Using local exhaust in areas such as copy rooms, chemical storage areas, and print shops can reduce other sources of indoor air contaminants. According to the Shendell et al. (2004), increasing ventilation rates will improve environmental satisfaction, comfort and productivity. Wargocki et al. (2000) mentioned that IAQ can be improved by selecting low polluting building and furnishing materials and electronic office equipment and/or increasing the outdoor air supply rate with an efficient filtration system.

According to Texas Voluntary IAQ Guidelines, carbon dioxide levels should be maintained less than 1,000 ppm, relative humidity between 30%-60% and temperature should be maintained within 68°F-78°F; controlling the air quality parameters within the recommended level can improve the indoor air quality and minimize the occupants' complaints. Mendell et al. (2006), suggested recommendations to improve the IAQ by maintaining indoor temperature at 72°F (+/- 2°F), providing at least minimum ventilation rates and managing moisture at building exteriors. Wargocki et al. (2007), examined the effect of outdoor air supply rate and air filter conditions in classrooms on the students' performance of school work (students 10-12 years-old). Their results show that when the outdoor air supply rate increased (from 6.4 to 18 cfm per person), the schoolwork speed
improved significantly (they performed two numerical and language-based tasks) and the average CO$_2$ concentration decreased from 1300 to 900 ppm.

2.6 How This Study Will Address Gaps in the Literature

As mentioned previously, few studies have looked at factors besides ventilation rates that might impact the indoor air quality. In addition, most of the previous Texas indoor air quality studies were done in south and central Texas, and many involved elementary schools. The primary purpose of this dissertation thus is to investigate the factors that might affect the indoor air quality in schools (outdoor air quality, classroom activities, and school layout) and to assess the air quality in test schools (high schools in North Central Texas). We monitored some indoor air parameters (temperature, RH, CO, CO$_2$, O$_3$, TVOCs) to compare these parameters with the guidelines for the acceptable indoor air.
Chapter 3
Methodology

This study was conducted during the 2012-2013 academic year in three high schools from two school districts in the North Texas Region, as listed in Table 3.1.

Table 3.1: Selected study schools from North Texas Region

<table>
<thead>
<tr>
<th>School Name and number</th>
<th>Year Built</th>
<th>Number of Students Enrolled</th>
<th>Address/ISD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Newman Smith High School</td>
<td>1973</td>
<td>2,030 students</td>
<td>Carrollton, TX/Farmer branch ISD</td>
</tr>
<tr>
<td>2. Carroll Senior High School</td>
<td>1961</td>
<td>1,281 students</td>
<td>Southlake, TX/ Carroll ISD</td>
</tr>
<tr>
<td>3. Carroll High School</td>
<td>2001</td>
<td>1,303 students</td>
<td>Southlake, TX/ Carroll ISD</td>
</tr>
</tbody>
</table>

3.1 Selection of schools and classrooms

In this study schools were selected from two participating school districts (Farmers Branch ISD and Carroll ISD) located in the North Texas Region (Dallas-Fort Worth area) by submitting a request to school districts to obtain the permission and the contact information of the schools that can participate. The Newman Smith High School location is close to the Dallas North Toll way and Interstate Highway I-35 (high traffic zones); Carroll Senior High School and Carroll High School are in residential areas (low traffic zones).

The classroom selection was based on an effort to include a variety of uses: the first room monitored was a science room, the second room was a computer classroom,
the third room was a copy room (for teacher and staff use only) except the second school
did not have copy room available to be monitored (an area between the administration
offices was monitored instead), and the fourth room was a regular classroom (language,
social studies, math,…). The regular classroom serves as a baseline. The science rooms
could potentially have elevated levels of volatile organic compounds due to use of
chemicals for experiments. The copy rooms could potentially have elevated levels of
ozone, VOCs known to be produced by some copy machines. The computer rooms could
potentially have elevated levels of ozone.

3.2 Procedure

In this study we used an industrial-based, commercially available continuous,
automatic portable indoor air quality probe (IQ-610, Gray Wolf monitor) with
specifications as shown in Table 3.2 to monitor IAQ parameters in test schools.
### Table 3.2 IQ-610 monitor specifications

<table>
<thead>
<tr>
<th>Parameter Measured</th>
<th>Measurement method</th>
<th>Range</th>
<th>Limit of Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVOCs</td>
<td>PID</td>
<td>5 to 20,000 ppb, Resolution 1ppb, L.O.D. &lt;5 ppb</td>
<td>16 ppb</td>
</tr>
<tr>
<td>CO₂</td>
<td>(NDIR)</td>
<td>0 to 10,000 ppm, Accuracy:±3% rdg±50ppm</td>
<td>181 ppm</td>
</tr>
<tr>
<td>CO</td>
<td>Electrochemical Sensor</td>
<td>0 to 500 ppm, Accuracy: ±2ppm &lt;50ppm, ±3%rdg&gt;50ppm</td>
<td>0.05 ppm</td>
</tr>
<tr>
<td>O₃</td>
<td>Electrochemical Sensor</td>
<td>0.00 to 1.00 ppm</td>
<td>0.01 ppm</td>
</tr>
<tr>
<td>Temp.</td>
<td>(Pt100)</td>
<td>-10° to 160°F (-25° to +70°C), Accuracy:±0.3°C</td>
<td>9°C</td>
</tr>
<tr>
<td>RH</td>
<td>Capacitive</td>
<td>0 to 100 %RH, Accuracy:±2%RH&lt;80%RH, (±3%RH&gt;80%RH)</td>
<td>10.2%</td>
</tr>
</tbody>
</table>

To monitor the IAQ parameters (temperature, relative humidity, carbon dioxide, total volatile organic compounds, carbon monoxide and ozone) for a week in four different classrooms in each of the test schools, we used Direct Sense IAQ (IQ-610) to obtain the results directly from the PC monitor immediately. The IQ-610 displays measurements in
real time (the monitor recorded a value every 1 minute for each measured parameter in the first school and recorded a value every 5 minutes for each parameter in the second and third school); data is logged on a PC as shown as in Figure 3.1 and can be downloaded for each classroom measurement and exported to an Excel sheet to be ready for data analysis. After collecting the data, the hourly average for each parameter was calculated in each room for indoor and outdoor comparison.

Figure 3.1 Direct sense IAQ monitor (IQ-610) (source: Gray Wolf Sensing Solution, 2007)
The monitoring unit (locked in a security case) was set up every Friday for one week to collect continuous IAQ data in one of the classrooms; we set up the monitor on a countertop about 3 ft. high close to an electricity outlet (for the IAQ monitor) and not distracting the classroom everyday work. The monitor location was changed for the following week. Since only one monitor was available, we could not monitor rooms simultaneously.

General information was collected from the administration office in the test schools regarding the building itself and the occupants, including: number of students, room area, the class period schedule, floor covering, no. of windows, no. of doors and electronic equipment. This information is summarized in Table 3.3 and Table 3.4.

The distance from each classroom to the closest exit was measured by using the measuring meter in the first and second schools (the second floor rooms were measured by adding the distance from the school entrance to the stairs and the upstairs distance from the stairs to the monitored rooms); the third school provided the measurements to determine whether the layout of the classroom affected the indoor air concentration levels.

Table 3.3 General information about the test rooms

<table>
<thead>
<tr>
<th>School #</th>
<th>Room type</th>
<th>Location</th>
<th>Area (ft²)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>School 1</td>
<td>Science classroom</td>
<td>2nd floor</td>
<td>1000 ft²</td>
<td>March 2nd - March 9th</td>
</tr>
<tr>
<td></td>
<td>Computer classroom</td>
<td>1st floor</td>
<td>1200 ft²</td>
<td>March 19th - March 26th</td>
</tr>
<tr>
<td></td>
<td>Copy room</td>
<td>1st floor</td>
<td>300 ft²</td>
<td>April 10th - April 19th</td>
</tr>
<tr>
<td></td>
<td>Math classroom</td>
<td>2nd floor</td>
<td>800 ft²</td>
<td>April 20th - April 26th</td>
</tr>
<tr>
<td>School 2</td>
<td>Science classroom</td>
<td>2nd floor</td>
<td>275 ft²</td>
<td>Oct. 15- Oct. 18</td>
</tr>
</tbody>
</table>
Table 3.3 — Continued

<table>
<thead>
<tr>
<th>School</th>
<th>Room</th>
<th>Students</th>
<th>Equipment</th>
<th>Floor type</th>
<th>Doors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (Science)</td>
<td>30-35</td>
<td>13 computers, 1 projector, 1 printer</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1 (Computer)</td>
<td>30-35</td>
<td>17 computers, 1 projector, 1 white board</td>
<td>Carpet</td>
<td>2</td>
</tr>
<tr>
<td>3 (Copy)</td>
<td>N/A</td>
<td></td>
<td>1 copy machine, 1 scanner, 1 computer</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>4 (Classroom)</td>
<td>30-35</td>
<td>2 computers, 1 projector, 1 white board</td>
<td>Carpet</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1 (Science)</td>
<td>Up to 30</td>
<td>7 computers, 1 printer, 1 projector</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1 (Computer)</td>
<td>Up to 30</td>
<td>30 computers, 2 printers, 1 projector</td>
<td>Carpet</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.4 General information about the test rooms

<table>
<thead>
<tr>
<th>School</th>
<th>Room</th>
<th>Students</th>
<th>Equipment</th>
<th>Floor type</th>
<th>Doors</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Biology classroom</td>
<td>30-35</td>
<td>13 computers, 1 projector, 1 printer</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Computer classroom</td>
<td>17 computers, 1 projector, 1 white board</td>
<td>Carpet</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4 (Copy)</td>
<td>N/A</td>
<td></td>
<td>1 copy machine, 1 scanner, 1 computer</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>4 (Classroom)</td>
<td>30-35</td>
<td>2 computers, 1 projector, 1 white board</td>
<td>Carpet</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1 (Science)</td>
<td>Up to 30</td>
<td>7 computers, 1 printer, 1 projector</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1 (Computer)</td>
<td>Up to 30</td>
<td>30 computers, 2 printers, 1 projector</td>
<td>Carpet</td>
<td>2</td>
</tr>
</tbody>
</table>
The second school did not have copy room available to be monitored; an area between the administrations offices located close to the school entrance was monitored instead.

Outdoor Air Quality (OAQ) measurement data (Temperature, Relative Humidity, Carbon monoxide, Ozone) was obtained from the closest monitor sites of Texas Commission of Environmental quality (TCEQ) to the test schools. For the first school we collected the outdoor data (Temperature, relative humidity, ozone) from the Dallas North site monitor (C63), and carbon monoxide from Dallas Hinton St. Site (C401). The second and third schools are located close to each other: temperature, RH and O3 were collected from the Grapevine Fairway site (C70) and carbon monoxide from the north Ft. Worth northwest site (C13). The outdoor air data site information is shown in Table 3.5 Locations of schools and outdoor monitoring sites are shown in Figures 3.2, 3.3 and 3.4. As mentioned by Currie (2009), individual monitors for each pollutant are set up all over the

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3 (Hallway)</td>
<td>N/A</td>
<td>A hallway between the administration offices</td>
<td>Carpet</td>
<td>1</td>
</tr>
<tr>
<td>4 (Classroom)</td>
<td>Up to 30</td>
<td>1 computer, 1 projector, 1 lab top, 2 boards</td>
<td>Carpet</td>
<td>1</td>
</tr>
<tr>
<td>3 (Science)</td>
<td>14-24</td>
<td>1 computer, 1 printer, 1 projector</td>
<td>Vinyl</td>
<td>2</td>
</tr>
<tr>
<td>2 (Computer)</td>
<td>28</td>
<td>29 computers, black board</td>
<td>Carpet</td>
<td>1</td>
</tr>
<tr>
<td>3 (Copy)</td>
<td>N/A</td>
<td>1 Xerox big copy machine</td>
<td>Vinyl</td>
<td>1</td>
</tr>
<tr>
<td>4 (Classroom)</td>
<td>22-30</td>
<td>1 computer, 1 projector, white board</td>
<td>Carpet</td>
<td>1</td>
</tr>
</tbody>
</table>
state and take hourly reading of the pollutant levels at each location. Carbon monoxide data were collected from different sites because there are only five sites in the Dallas-Fort Worth area for carbon monoxide data.

Interpolating parameter values from several regional monitors to estimate a value at each school location was considered. The interpolation may, however, introduce additional uncertainty, and data is not available to determine whether the interpolated values would be closer to actual outdoor values at the schools than the values from the closest monitor. Thus, the decision was made to simply use the outdoor parameter values from the closest monitor.

Table 3.5 Summary of the outdoor air quality monitoring site information

<table>
<thead>
<tr>
<th>School # and Address</th>
<th>Parameters</th>
<th>TCEQ monitoring site</th>
</tr>
</thead>
<tbody>
<tr>
<td>School (1) Newman Smith High School 2335 North Josey lane Carrollton TX.75006</td>
<td>RH, ( \text{O}_3 ), temperature</td>
<td>Dallas North # 2 (C_63) 12532 ½ Nuestra Drive</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>Dallas Hinton (C_401) 1415 Hinton street</td>
</tr>
<tr>
<td>School (2) Carroll Senior High School 1501 W. Southlake Grapevine, TX.76092</td>
<td>RH, ( \text{O}_3 ), temperature</td>
<td>Grapevine Fairway (C_70) 4100 Fairway Dr.</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>Ft. Worth North West (C_13) 3317 Ross Ave.</td>
</tr>
<tr>
<td>School (3) Carroll High School 800 N. Whitechapel Blvd South lake, TX.76092</td>
<td>RH, ( \text{O}_3 ), temperature</td>
<td>Grapevine Fairway (C_70) 4100 Fairway Dr.</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>Ft. Worth North West (C_13) 3317 Ross Ave.</td>
</tr>
</tbody>
</table>
Figure 3.2 Locations of the TCEQ outdoor monitoring sites and school 1

Figure 3.3 Locations of the TCEQ outdoor monitoring sites and school 2
3.3 Data Analysis

Table 3.6 summarizes the data analysis approaches.

Table 3.6 Summary of research objectives and data analysis strategies

<table>
<thead>
<tr>
<th>Research questions</th>
<th>Data type</th>
<th>Statistical analysis approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do IAQ levels in test schools meet the Texas Voluntary IAQ Guidelines?</td>
<td>Temperature, RH, CO, CO₂, O₃, VOCs</td>
<td>Plot the cumulative frequency distributions for each pollutant for each room using the mean of the data collected at 1-minute or 5-minute intervals, and determine the percent of time that the Texas IAQ Guidelines are attained.</td>
</tr>
<tr>
<td>Question</td>
<td>Parameter</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Is there a correlation between indoor and outdoor air quality levels in test schools?</td>
<td>Temperature, RH, O₃, CO</td>
<td>Plot the hourly average of each parameter for each room indoor vs. the outdoor value for that parameter for that hour. Determine whether there is a correlation (there is a strong correlation $R \geq 0.7$ or a no correlation if $R &lt; 0.7$). Also, plot indoor vs. outdoor values with 1-hour time-lag ($t-1$) and ($t-2$).</td>
</tr>
<tr>
<td>Do the layouts of test school facilities have an effect on the IAQ?</td>
<td>Temperature, RH, CO₂, O₃, CO₂, CO, O₃, TVOCs</td>
<td>Compare median concentrations for the different parameters (temperature, RH, CO₂, CO, O₃, TVOCs) vs. distance to the school entrance. Compare cumulative frequency distributions of the various parameters for each room vs. distance to school entrance (school layout).</td>
</tr>
<tr>
<td>Do rooms of different types have different concentrations?</td>
<td>Temperature, RH, CO₂, O₃, VOCs</td>
<td>Conduct 2-way ANOVA by room (confidence level 0.05) to determine whether there are a significant difference of the IAQ concentration among the four different types of rooms at each school, for each pollutant.</td>
</tr>
</tbody>
</table>
Chapter 4
Presentation and Analysis of Data

This chapter presents descriptions and explanations of the study results and findings. The results are organized in accordance with the research questions as mentioned below: whether the IAQ in test schools meet the Texas Voluntary IAQ Guidelines for public school buildings and the factors that might affect the indoor air quality of selected Texas public high schools.

Research Question 1: Do the IAQ levels in test schools meet the Texas Voluntary IAQ Guidelines?

Research Question 2: Is there a correlation between indoor and outdoor air quality levels in test schools?

Research Question 3: Do the layouts of test school facilities have an effect on the IAQ?

Research Question 4: Do rooms of different types have different concentrations?

Figures 4.1 to 4.72 show the hourly average concentration levels of IAQ parameters (temperature, CO₂, RH%, TVOCs, CO, O₃) of the four rooms in each test school.
Figure 4.1 Relative humidity vs. time for first school in science room

Figure 4.2 Relative humidity vs. time for first school in computer room
Figure 4.3 Relative humidity vs. time for first school in copy room

Figure 4.4 Relative humidity vs. time for first school in general classroom
Figure 4.5 Temperature vs. time for first school in science room

Figure 4.6 Temperature vs. time for first school in computer room
Figure 4.7 Temperature vs. time for first School in copy room

Figure 4.8 Temperature vs. time for first school in general classroom
Figure 4.9 Volatile organic compounds concentration vs. time for first school in science room

Figure 4.10 Volatile organic compounds concentration vs. time for first school in computer room
Figure 4.11 Volatile organic compounds concentration vs. time for first school in copy room

Figure 4.12 Volatile organic compound concentration vs. time for first school in general classroom
Figure 4.13 Carbon monoxide concentration vs. time for first school in science room

Figure 4.14 Carbon monoxide concentration vs. time for first school in computer classroom
Figure 4.15 Carbon monoxide concentration vs. time for first school in copy room

Figure 4.16 Carbon monoxide concentration vs. time for first school in general classroom
Figure 4.17 Ozone concentration vs. time for first school in science room

Figure 4.18 Ozone concentration vs. time for first school in computer room
Figure 4.19 Ozone concentration vs. time for first school in copy room

Figure 4.20 Ozone concentration vs. time for first school in general classroom
Figure 4.21 Carbon dioxide concentration vs. time for first school in science room

Figure 4.22 Carbon dioxide concentration vs. time for first school in computer room
Figure 4.23 Carbon dioxide concentration vs. time for first school in copy room

Figure 4.24 Carbon dioxide concentration vs. time for first school in general classroom
Figure 4.25 Relative humidity vs. time for second school in science room

Figure 4.26 Relative humidity vs. time for second school in computer room
Figure 4.27 Relative humidity vs. time for second school in copy room

Figure 4.28 Relative humidity vs. time for second school in general classroom
Figure 4.29 Temperature vs. time for second school in science room

Figure 4.30 Temperature vs. time for second school in computer room
Figure 4.31 Temperature vs. time for second school in copy room

Figure 4.32 Temperature vs. time for second school in general classroom
Figure 4.33 Volatile organic compounds concentration vs. time for second school in science room

Figure 4.34 Volatile organic compounds concentration vs. time for second school in computer room
Figure 4.35 Volatile organic compounds concentration vs. time for second school in copy room

Figure 4.36 Volatile organic compounds concentration vs. time for second school in general classroom
Figure 4.37 Carbon monoxide concentration vs. time for second school in science room

Figure 4.38 Carbon monoxide concentration vs. time for second school in computer room
Figure 4.39 Carbon monoxide concentration vs. time for second school in copy room

Figure 4.40 Carbon monoxide concentration vs. time for second school in general classroom
Figure 4.41 Ozone concentration vs. time for second school in science room

Figure 4.42 Ozone concentration vs. time for second school in computer room
Figure 4.43 Ozone concentration vs. time for second school in copy room

Figure 4.44 Ozone concentration vs. time for second school in general classroom
Figure 4.45 Carbon dioxide concentration vs. time for second school in science room

Figure 4.46 Carbon dioxide concentration vs. time for second school in computer room
Figure 4.47 Carbon dioxide concentration vs. time for second school in copy room

Figure 4.48 Carbon dioxide concentration vs. time for second school in general classroom
Figure 4.49 Relative humidity vs. time for third school in science room

Figure 4.50 Relative humidity vs. time for third school in computer room
Figure 4.51 Relative humidity vs. time for third school in copy room

Figure 4.52 Relative humidity vs. time for third school in general classroom
Figure 4.53 Temperature vs. time for third school in science room

Figure 4.54 Temperature vs. time for third school in computer room
Figure 4.55 Temperature vs. time for third school in copy room

Figure 4.56 Temperature vs. time for third school in general classroom
Figure 4.57 Volatile organic compounds concentration vs. time for third school in science room

Figure 4.58 Volatile organic compounds concentration vs. time for third school in computer room
Figure 4.59 Volatile organic compounds concentration vs. time for third school in copy room

Figure 4.60 Volatile organic compounds concentration vs. time for third school in general classroom
Figure 4.61 Carbon monoxide concentration vs. time for third school in science room

Figure 4.62 Carbon monoxide concentration vs. time for third school in computer room
Figure 4.63 Carbon monoxide concentration vs. time for third school in copy room

Figure 4.64 Carbon monoxide concentration vs. time for third school in general classroom
Figure 4.65 Ozone concentration vs. time for third school in science room

Figure 4.66 Ozone concentration vs. time for third school in computer room
Figure 4.67 Ozone concentration vs. time for third school in copy room

Figure 4.68 Ozone concentration vs. time for third school in general classroom
Figure 4.69 Carbon dioxide concentration vs. time for third school in science room

Figure 4.70 Carbon dioxide concentration vs. time for third school in computer room
Figure 4.71 Carbon dioxide concentration vs. time for third school in copy room

Figure 4.72 Carbon dioxide concentration vs. time for third school in general classroom
Hourly average values of relative humidity for school 1 remained within the 30-60% recommended range. For school 2, all 4 rooms fell below 30% relative humidity for some hours, as did 2 of the 4 rooms for school 3.

Hourly average values of temperatures for the schools generally stayed within the range of 20-25 °C (generally within the 20-24°C indoor air quality guidelines as well be discussed in more detail later). Temperature for school 1 tended to be cooler during the day within this range, possibly due to setting the climate control at a lower temperature while children are in school, and slightly higher in the evening and at night, when the climate control may be set at a higher temperature to save energy. The temperature for the other 2 schools were more constant with time, likely due to the climate control being set at a constant temperature. The temperature in School 1 Room 3 showed very anomalous behavior on April 17, dropping to 12-13°C during the night. The electricity may have been off during this time.

TVOCs for all 3 schools tended to fall to a background value, probably due to external VOC sources, during the night and on weekends. This background was around 100 ppb for school 1 and 2, but higher (100-200 ppb) for school 3. School 3 is in a residential area; perhaps vegetation surrounding the school increased the outdoor VOC levels, due to emissions, for example, of isoprene from pine trees.

TVOCs showed more spikes (1-hour large peaks) than the other species. Several of these occurred when the monitor was first turned on: School 1, Room 3, 4/18 (after a period with no data collected, when the monitor may have been off); School 2, Room 1, 10/15; School 3, Room 4, 12/3. These spikes may have been due to the monitor not being warmed up. However, a number of VOC spikes occurred when the monitor had already been measuring emissions for hours or days (School 1, Room 3, 4/19; School 1, Room 4, 4/20; School 2, Room 1, 10/15; School 3, Room 3, 11/27 and 11/29). None of
these spikes occurred in any of the schools in Room 2 (Computer Room); 4 occurred in Room 3 (Copy Room) – 2 for School 1 and 2 for School 3. These peaks may have been due to staff running large numbers of copies.

CO hourly averages for School 1 were higher during the day (9 a.m. to 7 p.m.) when the school was occupied and fell to zero at night. CO levels often peaked at 9 a.m. and continued to drop until 7 p.m. large spikes occurred in Room 3 on 4/11 and Room 4 on 4/20. VOC levels also spiked in Room 4 on 4/20. Room 4 was a regular classroom; it is unclear what may have caused CO and VOCs to spikes on 4/20.

For school 2, CO levels tended to be high at the beginning of the school day (around 9 a.m.), but then dropped to zero during the day. For 2 of the rooms (science room and computer room), CO levels increased again in the evening, for reasons that are not clear. For school 3, CO levels for Rooms 2, 3, and 4, were 0 all the time.

Ozone hourly average concentrations for the 3 schools generally ranged between 0.03 and 0.04 ppm, with the exception of School 3, which showed levels down to 0.02 and up to 0.05 ppm. Concentrations generally fell below the 0.05 ppm indoor air quality guideline, as will be discussed in more detail later. For School 1 Room 1 and 4, ozone concentrations tended to increase in the evening and be higher overnight, for reasons that are not clear.

Carbon dioxide generally for the 3 schools was higher during hours that the school was occupied, as would be expected, since people exhale CO₂. CO₂ levels generally peaked around 2 p.m., noon, and 3 p.m. for schools 1, 2, and 3, respectively, at levels between 1000 ppm and 1500 ppm. At night, CO₂ would fall to background levels of 500 ppm, presumably the outdoor level; School 1, Room 4; School 2, Room 4; and School 3 Room 1, however, consistently for weekdays showed peak concentrations in
excess of 2000 ppm. This was likely due to inadequate ventilation, as will be discussed later.

4.1 The mean value of IAQ concentration levels in test schools and the Texas Voluntary IAQ Guidelines

Figures 4.73 to 4.178 show the cumulative frequency distributions of the indoor data for the science room in the first school, using the frequency distributions for comparison to recommended standards and show percent of time that concentrations are below a certain value. A normal distribution is also shown on each figure. The discrete values/stair step shape of the ozone and carbon monoxide cumulative frequency distributions are due to the monitor reporting discrete values (0.02, 0.03 and 0.04) for ozone and (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1) for carbon monoxide. The cumulative frequency distributions of the indoor data for the other rooms in test schools are provided in the appendix.

Figure 4.73 Cumulative frequency distribution of VOCs in School 1, Science room
Figure 4.74 Cumulative frequency distribution of CO$_2$ in School 1, Science room

Figure 4.75 Cumulative frequency distribution of ozone in School 1, Science room
Figure 4.76 Cumulative frequency distribution of carbon monoxide in School 1, Science room

Figure 4.77 Cumulative frequency distribution of temperature in School 1, Science room
Table 4.1 compares the first school's values of indoor air parameters (VOCs, CO₂, O₃, CO, temperature and RH) over the period tested with the IAQ guidelines. It is not clear whether a 1-hour average, daily average, weekly average, or annual average should be compared to the guidelines, since no averaging time is specified. The VOC 1-minute readings comply with the Texas IAQ guideline from 45 to 95% of the time. The low level of compliance in the copy room (50%) could have been due to equipment operation (use of ink and organic toner), but the reason for the high VOC level in the classroom (45% compliance) was not clear; it could be from using office materials such as (markers, pens, glue, sanitizer, air freshener) contain chemicals during the classroom time, which could elevate VOCs level.
The carbon dioxide guideline is met 80% of the time in the copy room, which would be anticipated to contain few students, but only 35% of the time in the general classroom. This indicates that the ventilation rate is inadequate in that classroom and an increase in the ventilation rate (increase in the amount of fresh outdoor air) is required to reduce the CO₂ concentration level. Increasing the ventilation rate for all rooms would be beneficial.

The 1-minute values of ozone measured for all the rooms fell within the recommended guideline (0.05 ppm) 100% of the time. The 1-minute values of carbon monoxide measured for all the four rooms fell below the Texas IAQ Standard for outdoor air (9 ppm - 8hrs) 100% of the time. Maximum concentrations averaged over longer time-periods are lesser than maximum concentrations averaged over shorter time periods. Since the 1-minute average CO readings met the 9 ppm standard, the readings averaged over 8-hour time frames would also meet the 9 ppm standard, with lower maximum average values.

The 1-minute values of temperature measured for all four rooms fell within the Texas IAQ standard (20°C to 24°C (+/-2)). The mean values of the relative humidity measured for all four rooms (ranging from 36% to 43%) fell within the Texas IAQ guideline (30%-60%) at least 90% of the time.

Figures 4.79 to 4.84 show the mean and standard deviation for the four rooms of the first school.
Table 4.1 IAQ parameters of school 1 (Newman Smith High School) compared to Texas IAQ guidelines

<table>
<thead>
<tr>
<th>Air Quality (S1)</th>
<th>Room</th>
<th>MIN 1-minute</th>
<th>MAX 1-minute</th>
<th>MEAN (St. Dev.)</th>
<th>MRL Guidelines</th>
<th>% of time that readings met guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVOCs (ppb)</td>
<td>1 (Science)</td>
<td>73</td>
<td>331</td>
<td>126 (31)</td>
<td>0.5 mg/m³ or 165 ppb</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>32</td>
<td>225</td>
<td>112 (23)</td>
<td></td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>90</td>
<td>1639</td>
<td>152 (112)</td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>99</td>
<td>1079</td>
<td>172 (83)</td>
<td></td>
<td>45%</td>
</tr>
<tr>
<td>CO₂ (ppm)</td>
<td>1 (Science)</td>
<td>421</td>
<td>1362</td>
<td>730 (293)</td>
<td>700 ppm above outdoor level</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>415</td>
<td>1736</td>
<td>792 (315)</td>
<td></td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>437</td>
<td>1626</td>
<td>790 (226)</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>413</td>
<td>3114</td>
<td>1420 (634)</td>
<td></td>
<td>35%</td>
</tr>
<tr>
<td>O₃ (ppm)</td>
<td>1 (Science)</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03 (0)</td>
<td>0.05 ppm</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.035 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.037 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>1 (Science)</td>
<td>0</td>
<td>0.4</td>
<td>+0.06 (0.1)</td>
<td>9 ppm - 8 hours</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>0</td>
<td>0.8</td>
<td>+0.09 (0.2)</td>
<td>35 ppm - 1 hour</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>0</td>
<td>7.7</td>
<td>+0.06 (0.2)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>0</td>
<td>1.2</td>
<td>+0.2 (0.2)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>1 (Science)</td>
<td>19</td>
<td>24</td>
<td>22 (0.7)</td>
<td>20-24°C (+/-2)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>21</td>
<td>25</td>
<td>23 (0.7)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>21</td>
<td>25</td>
<td>24 (0.7)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>18</td>
<td>26</td>
<td>22 (2)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>%RH</td>
<td>1 (Science)</td>
<td>27</td>
<td>54</td>
<td>36 (5)</td>
<td>30-60%</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>35</td>
<td>52</td>
<td>42 (2)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>31</td>
<td>51</td>
<td>37 (4)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>31</td>
<td>61</td>
<td>43 (4)</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

*Since the 1-minute average CO readings met the 9 ppm standard, the readings averaged over 8-hour time frames would also meet the 9 ppm standard.
Figure 4.79 Mean and S.D. of VOCs in rooms 1-4 of School 1

Figure 4.80 Mean and S.D. of CO₂ in rooms 1-4 of School 1

Figure 4.81 Mean and S.D. of O₃ in rooms 1-4 of School 1
Figure 4.82 Mean and S.D. of CO in rooms 1-4 of School 1

Figure 4.83 Mean and S.D. of temperature in rooms 1-4 of School 1

Figure 4.84 Mean and S.D. of RH in rooms 1-4 of School 1
Table 4.2 compares the second school’s values of indoor air parameters (VOCs, CO₂, O₃, CO, temperature and RH) and the IAQ guidelines. The 5-minutes VOC values for all the rooms compiled with the guideline from 75-100% of the time. Interestingly, for this school, the copy room complied with the VOC levels 100% of the time, unlike School 1, for which the copy room complied only 50% of the time. This could be due to use of a different kind of toner. Interestingly, classroom compliance for this school was 95%, compared to 45% for the first school. The reason for this is unclear.

The carbon dioxide was met 75-85% of the time for the four rooms. Increasing the ventilation rate for all classrooms would be beneficial.

The 5-minutes values of ozone measured for all the rooms fell within the recommended guideline (0.05 ppm) 100% of the time. The 5-minutes values of carbon monoxide measured for all the four rooms fell below the Texas IAQ guideline (9 ppm-8hrs) 100% of the time.

The 5-minutes values of temperature measured for all four rooms fell within the Texas IAQ guideline (20°C to 24°C (+/-2)) 100% of the time. The 5-minutes values of relative humidity measured for all four rooms, however, fell within the Texas IAQ guideline (30%-60%) only 70-90% of the time.

Figures 4.85 to 4.90 show the mean and standard deviation for the four rooms of the second school.
Table 4.2 IAQ parameters of School 2 (Carroll Senior High School) compared to Texas IAQ guidelines

<table>
<thead>
<tr>
<th>Air Quality (S2)</th>
<th>Room</th>
<th>MIN 5-minutes</th>
<th>MAX 5-minutes</th>
<th>MEAN (St. Dev)</th>
<th>MRL guidelines</th>
<th>% of time that readings met guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TVOCs (ppb)</strong></td>
<td>1 (Science)</td>
<td>99</td>
<td>583</td>
<td>160 (62)</td>
<td>0.5 mg/m³ or 165 ppb</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>118</td>
<td>384</td>
<td>159 (34)</td>
<td></td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>92</td>
<td>195</td>
<td>105 (12)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>97</td>
<td>266</td>
<td>115 (16)</td>
<td></td>
<td>95%</td>
</tr>
<tr>
<td><strong>CO₂ (ppm)</strong></td>
<td>1 (Science)</td>
<td>391</td>
<td>1732</td>
<td>719 (394)</td>
<td>700 ppm above outdoor level.</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>424</td>
<td>1209</td>
<td>743 (226)</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>361</td>
<td>1665</td>
<td>633 (297)</td>
<td></td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>387</td>
<td>2834</td>
<td>664 (434)</td>
<td></td>
<td>85%</td>
</tr>
<tr>
<td><strong>O₃ (ppm)</strong></td>
<td>1 (Science)</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03 (0)</td>
<td>0.05 ppm</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.039 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.0368 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>0.02</td>
<td>0.04</td>
<td>0.035 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td><strong>CO (ppm)</strong></td>
<td>1 (Science)</td>
<td>0</td>
<td>0.5</td>
<td>^0.029 (0)</td>
<td>9 ppm-8 hours 35 ppm-1 hour</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>0</td>
<td>0.03</td>
<td>^0.036 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>0</td>
<td>0.8</td>
<td>^0.021 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>0</td>
<td>0.4</td>
<td>^0.002 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td><strong>Temp. (°C)</strong></td>
<td>1 (Science)</td>
<td>21.8</td>
<td>25</td>
<td>24 (0.9)</td>
<td>20-24°C(+/-2)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>22.7</td>
<td>25.7</td>
<td>25 (0.3)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>20.1</td>
<td>24.5</td>
<td>23 (1)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>19.8</td>
<td>24.3</td>
<td>23 (0.7)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td><strong>RH%</strong></td>
<td>1 (Science)</td>
<td>22.6</td>
<td>68.7</td>
<td>44 (10)</td>
<td>30-60%</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>2 (Computer)</td>
<td>23.4</td>
<td>53</td>
<td>38 (7)</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>3 (Copy)</td>
<td>20.4</td>
<td>44.2</td>
<td>32 (6)</td>
<td></td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td>4 (Classroom)</td>
<td>26.1</td>
<td>56</td>
<td>39 (7)</td>
<td></td>
<td>90%</td>
</tr>
</tbody>
</table>

*Since the 5-minutes average CO readings met the 9 ppm standard, the readings averaged over 8-hour time frames would also meet the 9 ppm standard.
Figure 4.85 Mean and S.D. of VOCs in rooms 1-4 of School 2

Figure 4.86 Mean and S.D. of CO₂ in rooms 1-4 of the School 2

Figure 4.87 Mean and S.D. of O₃ in rooms 1-4 of School 2
Figure 4.88 Mean and S.D. of CO in rooms 1-4 of School 2

Figure 4.89 Mean and S.D. of temperature in rooms 1-4 of School 2

Figure 4.90 Mean and S.D. of RH in rooms 1-4 of School 2
Table 4.3 compares the third school’s values of indoor air parameters (VOCs, CO₂, O₃, CO, temperature and RH) with the IAQ guidelines. The 5-minutes VOC values complied with the guideline 80-90% of the time for the computer, copy and general classrooms but it did not meet the guideline for the science room at all. The high VOC level in the science room could be due to the use of chemicals.

The carbon dioxide guideline was met only 35% of the time in the science room; the ventilation rate in this room should be increased. The CO₂ guideline was met 80-95% of the time in the other 3 rooms. Increasing ventilation rates in these rooms would also be beneficial.

The 5-minutes values of ozone measured for all the rooms fell within the recommended guideline (0.05 ppm) 100% of the time. The 5-minutes values of carbon monoxide measured for all the four rooms fell below the Texas IAQ (9 ppm-8hrs) 100% of the time.

The 5-minutes values of temperature measured for all the four rooms fell within the Texas IAQ standard (20°C to 24°C (+/-2)) 100% of the time. The 5-minutes values of relative humidity measured for all four rooms fell within the Texas IAQ guideline (30%-60%) 35-95% of the time.

Figures 4.91 to 4.96 show the mean and standard deviation for the four rooms of the third school.
Table 4.3 IAQ parameters of School 3 (Carroll High School) compared to Texas IAQ guidelines

<table>
<thead>
<tr>
<th>Air Quality (S3)</th>
<th>Room</th>
<th>MIN 5-minutes</th>
<th>MAX 5-minutes</th>
<th>MEAN (St. Dev.)</th>
<th>MRL guidelines</th>
<th>% of time that readings met guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVOCs (ppb)</td>
<td>1(Science)</td>
<td>167</td>
<td>354</td>
<td>238 (30)</td>
<td>0.5 mg/m³, or 165 ppb</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>2(Computer)</td>
<td>124</td>
<td>222</td>
<td>143 (14)</td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>3(Copy)</td>
<td>102</td>
<td>571</td>
<td>154 (47)</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>4(Classroom)</td>
<td>104</td>
<td>687</td>
<td>140 (33)</td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>CO₂ (ppm)</td>
<td>1(Science)</td>
<td>539</td>
<td>2239</td>
<td>1221 (435)</td>
<td>700 ppm above outdoor level.</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>2(Computer)</td>
<td>390</td>
<td>2643</td>
<td>560 (277)</td>
<td></td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>3(Copy)</td>
<td>393</td>
<td>2174</td>
<td>737 (271)</td>
<td></td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>4(Classroom)</td>
<td>395</td>
<td>2874</td>
<td>687 (315)</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>O₃ (ppm)</td>
<td>1(Science)</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03 (0)</td>
<td>0.05 ppm.</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2(Computer)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3(Copy)</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4(Classroom)</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>1(Science)</td>
<td>0</td>
<td>0.2</td>
<td>*0.01 (0)</td>
<td>9 ppm-8hours</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2(Computer)</td>
<td>0</td>
<td>0</td>
<td>*0 (0)</td>
<td>35 ppm-1hour.</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3(Copy)</td>
<td>0</td>
<td>0</td>
<td>*0 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4(Classroom)</td>
<td>0</td>
<td>0</td>
<td>*0 (0)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>1(Science)</td>
<td>20.6</td>
<td>23.5</td>
<td>22 (0.55)</td>
<td>20-24°C (+/-2)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2(Computer)</td>
<td>20.9</td>
<td>25.1</td>
<td>24 (0.55)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>3(Copy)</td>
<td>22.4</td>
<td>25.6</td>
<td>23 (0.66)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>4(Classroom)</td>
<td>20.6</td>
<td>24.9</td>
<td>23 (0.8)</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>RH%</td>
<td>1(Science)</td>
<td>27.3</td>
<td>53.2</td>
<td>35 (6)</td>
<td>30-60%</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>2(Computer)</td>
<td>20.5</td>
<td>39.9</td>
<td>29 (5)</td>
<td></td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>3(Copy)</td>
<td>21.7</td>
<td>46.2</td>
<td>28 (4)</td>
<td></td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>4(Classroom)</td>
<td>24.4</td>
<td>58.8</td>
<td>38 (4)</td>
<td></td>
<td>95%</td>
</tr>
</tbody>
</table>

*Since the 5-minutes average CO readings met the 9 ppm standard, the readings averaged over 8-hour time frames would also meet the 9 ppm standard.
Figure 4.91 Mean and S.D. of VOCs in rooms 1-4 School 3

Figure 4.92 Mean and S.D. of CO₂ in rooms 1-4 of School 3

Figure 4.93 Mean and S.D. of O₃ in rooms 1-4 of School 3
Figure 4.94 Mean and S.D. of CO in rooms 1-4 of School 3

Figure 4.95 Mean and S.D. of temperature in rooms 1-4 of School 3

Figure 4.96 Mean and S.D. of RH in rooms 1-4 of School 3
For the first research question we can reject the null hypothesis (H0: The IAQ in test schools do not meet the Texas Voluntary IAQ Guidelines as set forth by Texas Department of Health) for ozone, carbon monoxide, and temperature because the classrooms sampled met the guidelines 100% of the time. For VOCs, CO₂ and relative humidity, we accept the null hypothesis; rooms met these guidelines 0-100%, 35-95% and 35-100% of the time, respectively, meaning that some rooms did not meet the guidelines over half of the time.

4.2 The correlation between indoor and outdoor air quality levels in test schools

Figures 4.97 through 4.144 are cumulative frequency distributions of the hourly outdoor data from regional monitors, to which the measured indoor data will be compared. The outdoor values vary for the different rooms in a given school, because the indoor data was collected on different days. The outdoor data for each room was chosen to correspond to the days and hours of indoor data collection.

A normal distribution is also shown on each plot for comparison. From visual observation, the measured data generally closely follow a normal distribution, with slight deviation. The most typical deviation is like that of Figure 4.95: compared to the normal distribution, the measured data fewer very high values, more intermediate values, and fewer very low values. The stair step shape of the carbon monoxide cumulative frequency distributions being due to the discrete values (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1) of the outdoor data for carbon monoxide.
Figure 4.97 Cumulative frequency distribution of outdoor ozone for School 1, Science room

Figure 4.98 Cumulative frequency distribution of outdoor RH for School 1, Science room
Figure 4.99 Cumulative frequency distribution of outdoor temperature for School 1, Science room.

Figure 4.100 Cumulative frequency distribution of outdoor CO for School 1, Science room.
Figure 4.101 Cumulative frequency distribution of outdoor ozone for School 1, Computer room

Figure 4.102 Cumulative frequency distribution of outdoor temperature for School 1, Computer room
Figure 4.103 Cumulative frequency distribution of outdoor RH for School 1, Computer room

Figure 4.104 Cumulative frequency distribution of outdoor CO for School 1, Computer room
Figure 4.105 Cumulative frequency distribution of outdoor ozone for School 1, Copy room

Figure 4.106 Cumulative frequency distribution of outdoor temperature for School 1, Copy room
Figure 4.107 Cumulative frequency distribution of outdoor RH for School 1, Copy room

Figure 4.108 Cumulative frequency distribution of outdoor CO for School 1, Copy room
Figure 4.109 Cumulative frequency distribution of outdoor O\textsubscript{3} for School 1, Regular classroom

Figure 4.110 Cumulative frequency distribution of outdoor temperature for School 1, Regular classroom
Figure 4.111 Cumulative frequency distribution of outdoor RH for School 1, Regular classroom

Figure 4.112 Cumulative frequency distribution of outdoor CO for School 1, Regular classroom
Figure 4.113 Cumulative frequency distribution of outdoor Ozone for School 2, Science room

Figure 4.114 Cumulative frequency distribution of outdoor temperature for School 2, Science room
Figure 4.115 Cumulative frequency distribution of outdoor RH for School 2, Science room

Figure 4.116 Cumulative frequency distribution of outdoor CO for School 2, Science room
Figure 4.117 Cumulative frequency distribution of outdoor Ozone for School 2, Computer room

Figure 4.118 Cumulative frequency distribution of outdoor temperature for School 2, Computer room
Figure 4.119 Cumulative frequency distribution of outdoor RH for School 2, Computer room

Figure 4.120 Cumulative frequency distribution of outdoor CO for School 2, Computer room
Figure 4.121 Cumulative frequency distribution of outdoor Ozone for School 2, Copy room

Figure 4.122 Cumulative frequency distribution of outdoor temperature for School 2, Copy room
Figure 4.123 Cumulative frequency distribution of outdoor RH for School 2, Copy room

Figure 4.124 Cumulative frequency distribution of outdoor CO for School 2, Copy room
Figure 4.125 Cumulative frequency distribution of outdoor ozone for School 2, Regular classroom

Figure 4.126 Cumulative frequency distribution of outdoor temperature for School 2, Regular classroom
Figure 4.127 Cumulative frequency distribution of outdoor RH for School 2, Regular classroom

Figure 4.128 Cumulative frequency distribution of outdoor CO for School 2, Regular classroom
Figure 4.129 Cumulative frequency distribution of outdoor ozone for School 3, Science room

Figure 4.130 Cumulative frequency distribution of outdoor temperature for School 3, Science room
Figure 4.131 Cumulative frequency distribution of outdoor RH for School 3, Science room

Figure 4.132 Cumulative frequency distribution of outdoor CO for School 3, Science room
Figure 4.133 Cumulative frequency distribution of outdoor ozone for School 3, Computer room

Figure 4.134 Cumulative frequency distribution of outdoor temperature for School 3, Computer room
Figure 4.135 Cumulative frequency distribution of outdoor RH for School 3, Computer room

Figure 4.136 Cumulative frequency distribution of outdoor CO for School 3, Computer room
Figure 4.137 Cumulative frequency distribution of outdoor ozone for School 3, Copy room

Figure 4.138 Cumulative frequency distribution of outdoor temperature for School 3, Copy room
Figure 4.139 Cumulative frequency distribution of outdoor RH for School 3, Copy room

Figure 4.140 Cumulative frequency distribution of outdoor CO for School 3, Copy room
Figure 4.141 Cumulative frequency distribution of outdoor ozone for School 3, Regular classroom

Figure 4.142 Cumulative frequency distribution of outdoor temperature for School 3, Regular classroom
Figure 4.143 Cumulative frequency distribution of outdoor RH for School 3, Regular classroom

Figure 4.144 Cumulative frequency distribution of outdoor CO for School 3, Regular classroom
Figures 4.145 to 4.176 show the hourly average parameter values for the first school, indoor vs. outdoor to determine whether there is a correlation. The first plot shows the outdoor parameter values at time t-2 vs. the indoor parameter values at time t and the second plot shows the outdoor parameter values at time t-1 vs. the indoor parameter values at time t. Since some time is required for the outdoor air to enter the school (ventilation rates may be 3-4 air changes per hour), the measured indoor values may correlate better with the outdoor values for the previous hour or (t-2). The third plot shows indoor parameter value at time t vs. outdoor parameter value at time t. A regression line is fit to the data in each plot. The correlation coefficient R value for the line are shown on each plot. A negative coefficient in front of the R value indicates negative correlation between indoor and outdoor concentrations. The second and third school plots are provided in the appendix. Cumulative frequency distributions of the difference of the indoor and outdoor air quality values are also plotted for each parameter in each room for School 1.
Figure 4.145 Hourly values of indoor vs. outdoor temperature for School 1, Science room
Figure 4.146 Cumulative frequency distribution of (IA-OA) temperature for School 1, Science room
Figure 4.147 Hourly values of indoor vs. outdoor temperature for School 1, Computer room
Figure 4.148 Cumulative frequency distribution of (IA-OA) temperature for School 1, Computer room
Figure 4.149 Hourly values of indoor vs. outdoor temperature for School 1, Copy room
Figure 4.150 Cumulative frequency distribution of (IA-OA) temperature for School 1, Copy room
Figure 4.151 Hourly values of indoor vs. outdoor temperature for School 1, Regular classroom
Figure 4.152 Cumulative frequency distribution of (IA-OA) temperature for School 1, Regular classroom
Figure 4.153 Hourly values of indoor vs. outdoor relative humidity for School 1, Science room
Figure 4.154 Cumulative frequency distribution of (IA-OA) RH for School 1, Science room
Figure 4.155 Hourly values of indoor vs. outdoor relative humidity for School 1, Computer room
Figure 4.156 Cumulative frequency distribution of (IA-OA) RH for School 1, Computer room
Figure 4.157 Hourly values of indoor vs. outdoor relative humidity for School 1, Copy room
Figure 4.158 Cumulative frequency distribution of (IA-OA) RH for School 1, Copy room
Figure 4.159 Hourly values of indoor vs. outdoor relative humidity for School 1, Regular classroom
Figure 4.160 Cumulative frequency distribution of (IA-OA) RH for School 1, Regular classroom
Figure 4.161 Hourly values of indoor vs. outdoor carbon monoxide for School 1, Science room
Figure 4.162 Cumulative frequency distribution of (IA-OA) CO for School 1, Science room
Figure 4.163 Hourly values of indoor vs. outdoor carbon monoxide for School 1, Computer room.
Figure 4.164 Cumulative frequency distribution of (IA-OA) CO for School 1, Computer room
Figure 4.165 Hourly values of indoor vs. outdoor carbon monoxide for School 1, Copy room
Figure 4.166 Cumulative frequency distribution of (IA-OA) CO for School 1, Copy room
Figure 4.167 Hourly values of indoor vs. outdoor carbon monoxide for School 1, Regular classroom
Figure 4.168 Cumulative frequency distribution of (IA-OA) CO for School 1, Regular classroom
Figure 4.169 Hourly values of indoor vs. outdoor ozone for School 1, Science room
Figure 4.170 Cumulative frequency distribution of (IA-OA) ozone for School 1, Science room
Figure 4.171 Hourly values of indoor vs. outdoor ozone for School 1, Computer room
Figure 4.172 Cumulative frequency distribution of (IA-OA) ozone for School 1, Computer classroom
Figure 4.173 Hourly values of indoor vs. outdoor ozone for School 1, Copy room
Figure 4.174 Cumulative frequency distribution of (IA-OA) ozone for School 1, Copy room
Figure 4.175 Hourly values of indoor vs. outdoor ozone for School 1, Regular classroom
Figure 4.176 Cumulative frequency distribution of (IA-OA) ozone for School 1, Regular classroom
Table 4.4 summarize the correlation trends of the indoor and outdoor air quality for the three schools. Trends could not be evaluated for VOCs, CO2 because the outdoor monitors did not measure these pollutants. The correlation coefficients R for the third school rooms 2, 3 and 4 were N/D because all the indoor carbon monoxide values for these rooms were zeroes.

As shown in Table 4.4, the highest R values were 0.7 (temperature); 0.78, 0.71, 0.8, 0.74, 0.78, 0.8 (relative humidity); and 0.72 (ozone). 3 of the strong correlations were for indoor concentration at time t vs. outdoor concentration at time t; 2 were for indoor concentration at time t vs. outdoor concentration at time t-1; and 3 were for indoor concentration at time t vs. outdoor concentration at time t-2. This indicates that including the time lag did not improve the indoor/outdoor correlation. For School 1, the temperature correlations are negative, meaning that as the outdoor temperature increases, the indoor temperature decreases. This could be due to increased running of the air conditioner as the outdoor temperature increases. The relative humidity correlations are all positive for the first and second schools but there are two rooms with negative correlations for third school. The carbon monoxide correlations are positive, with the exception of one room for each of the second and third schools. Ozone shows two rooms with negative correlations in the first school and one in the third school. The reason for the negative correlations is not clear.

According to Table 4.4, for both indoor vs. outdoor both at time t and for indoor at time t, and outdoor at time t-1, t-2, the schools show weak to no correlation between indoor and outdoor air quality, with the exception of one room for temperature, 3 rooms for relative humidity, and one room for ozone (strong correlation R ≥ 0.7 or weak to no correlation R < 0.7). The rooms that show a strong correlation for one parameter do not
show a strong correlation for the other parameters, interestingly enough. The overall lack of correlations is likely due to the air-tightness of the building envelopes.
Table 4.4 Correlation coefficients (R) for indoor vs. outdoor parameter values for the test schools

<table>
<thead>
<tr>
<th>School</th>
<th>Room</th>
<th>Temp. vs. (t)</th>
<th>Temp. vs. (t-1)</th>
<th>%RH vs. (t)</th>
<th>%RH vs. (t-1)</th>
<th>CO (ppm) vs. (t)</th>
<th>CO (ppm) vs. (t-1)</th>
<th>O₃ (ppm) vs. (t)</th>
<th>O₃ (ppm) vs. (t-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.05 (-)</td>
<td>0.02 (-)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.0</td>
<td>0.1</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tr>
<tr>
<td>2</td>
<td>0.45</td>
<td>0.32 (-)</td>
<td>0.12 (-)</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.0</td>
<td>0.1</td>
<td>0.28</td>
</tr>
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</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.08 (-)</td>
<td>0.03 (-)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.38</td>
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<tr>
<td>4</td>
<td>0.12</td>
<td>0.04 (-)</td>
<td>0.13 (-)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
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<tr>
<td>2</td>
<td>1</td>
<td>0.41 (-)</td>
<td>0.23 (-)</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.0</td>
<td>0.1</td>
<td>0.26</td>
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<tr>
<td>3</td>
<td>0.7</td>
<td>0.66 (-)</td>
<td>0.63 (-)</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.0</td>
<td>0.53</td>
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</tr>
<tr>
<td>4</td>
<td>0.62</td>
<td>0.64 (-)</td>
<td>0.64 (-)</td>
<td>0.1</td>
<td>0.3</td>
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<td>0.3</td>
<td>0.0</td>
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</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.18 (-)</td>
<td>0.14 (-)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.26</td>
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</tr>
<tr>
<td>2</td>
<td>0.14</td>
<td>0.13 (-)</td>
<td>0.13 (-)</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>N/D</td>
<td>N/D</td>
<td>N/D</td>
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<td>0.36</td>
<td>0.37 (-)</td>
<td>0.33 (-)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>N/D</td>
<td>N/D</td>
<td>N/D</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>0.52</td>
<td>0.49 (-)</td>
<td>0.42 (-)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>N/D</td>
<td>N/D</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Yellow indicates that the correlation for indoor vs. outdoor is a good fit.
For the second research question, we fail to reject the null hypothesis ($H_0$: There is no correlation between the indoor and outdoor air quality in test schools) because more than 85% of the results for that research question show weak to no correlation trends between the indoor and outdoor in the test schools.

4.3 The School Facilities Layout and the IAQ Parameter Levels

Figures 4.177 to 4.194 are box and whisker plots that show median and quartile values of the IAQ parameters. The box and whisker plots are ordered so that the plot for the room with the closest distance to the school entrance (layout) is shown at the bottom of the plot. The distance from the school entrance increases as one moves up toward the top of the plot.

Figure 4.177 VOCs (for each room) vs. distance from the school entrance in the first school
Figure 4.178 Average concentration of CO₂ (for each room) vs. the distance from school entrance in the first school.

Figure 4.179 Average concentration of ozone (for each room) vs. the distance from school entrance in the first school.
Figure 4.180 Average concentration of CO (for each room) vs. the distance from school entrance in the first school

Figure 4.181 Average temperature (for each room) vs. the distance from school entrance in the first school
From visual inspection of the plots for the first school, there does not appear to be a relationship between distance to the nearest entrance and pollutant concentration. Such a relationship would be anticipated if there were a relationship between indoor and outdoor concentrations. Given that no correlation between indoor and outdoor air was observed in Research Question 2, it is not surprising that there is no apparent relationship between distance to the nearest entrance and pollutant concentration. Instead, classroom levels appear to be influenced more by indoor sources. Room 4 in particular seems anomalous in concentrations of VOCs, CO₂, and CO, with concentrations higher than the other rooms. For the four rooms (room 2 (60 ft.), room 3 (70 ft.), room 4 (150 ft.) and room 1 (250 ft.)), the median of VOCs are (116, 135, 161, 118 ppb), CO₂ (849, 984, 1743, 791 ppm) CO (0.03, 0.01, 0.26, 0.069 ppm), O₃ (0.035, 0.03, 0.029, 0.03 ppm), temperature (24, 24, 21, 22 °C) and RH (43, 34, 42, 40%).
Figure 4.183 Average concentration of VOCs (for each room) vs. the distance from school entrance in the second school.

Figure 4.184 Average concentration of CO₂ (for each room) vs. the distance from school entrance in the second school.
Figure 4.185 Average concentration of $O_3$ (for each room) vs. the distance from school entrance in the second school.

Figure 4.186 Average concentration of CO (for each room) vs. the distance from school entrance in the second school.
Figure 4.187 Average temperature (for each room) vs. the distance from school entrance in the second school

Figure 4.188 Average RH (for each room) vs. the distance from school entrance in the second school
For the second school, from visual observation of the plots, there does not appear to be a relationship between distance to the entrance and concentration, with the possible exception of carbon dioxide, which decreases slightly with distance from the entrance. For the four rooms (room 2 (48 ft.), room 4 (120 ft.), room 1 (141 ft.) and room 3 (173 ft.)) the median of VOCs are (155, 116, 139, 94 ppb), CO₂ are (823, 667, 521, 521 ppm), CO (0, 0, 0, 0 ppm), O₃ (0.04, 0, 0.035, 0.039 ppm), temperature (25, 23, 23, 24 °C) and RH (42, 35, 44, 34%).

![Graph showing average concentration of VOCs (for each room) vs. the distance from school entrance in the third school](image)

Figure 4.189 Average concentration of VOCs (for each room) vs. the distance from school entrance in the third school
Figure 4.190 Average concentration of CO₂ (for each room) vs. the distance from school entrance in the third school.

Figure 4.191 Average concentration of O₃ (for each room) vs. the distance from school entrance in the third school.
Figure 4.192 Average concentration of CO (for each room) vs. the distance from school entrance in the third school

Figure 4.193 Average temperature (for each room) vs. the distance from school entrance in the third school
For the third school, from visual observation of the plots, there does not appear to be a relationship between distance to the entrance and concentration. For the four rooms (room 3 (37 ft.), room 1 (41 ft.), room 4 (85 ft.) and room 2 (95 ft.)), the medians of VOCs are (140, 237, 136, 154 ppb), CO₂ are (825, 1262, 900, 469 ppm), CO are (0, 0, 0, 0 ppm), O₃ are (0.04, 0.03, 0.03, 0.04 ppm), temperature are (24, 23, 23, 25 °C) and RH are (28, 30, 38, 35%).

Figures 4.195 to 4.212 show the comparison of the cumulative frequency distribution of the IAQ parameters for the four rooms in each school.
Figure 4.195 Cumulative frequency distributions of CO$_2$ for each room in the first school

Figure 4.196 Cumulative frequency distributions of CO for each room in the first school
Figure 4.197 Cumulative frequency distributions of ozone for each room in the first school

Figure 4.198 Cumulative frequency distributions of RH for each room in the first school
Figure 4.199 Cumulative frequency distribution of temperature for each room in the first school

Figure 4.200 Cumulative frequency distribution of VOCs for each room in the first school
Figure 4.201 Cumulative frequency distribution of CO$_2$ for each room in the second school

Figure 4.202 Cumulative frequency distribution of CO for each room in the second school
Figure 4.203 Cumulative frequency distribution of $O_3$ for each room in the second school

Figure 4.204 Cumulative frequency distribution of RH for each room in the second school
Figure 4.205 Cumulative frequency distribution of temperature for each room in the second school

Figure 4.206 Cumulative frequency distribution of VOCs for each room in the second school
Figure 4.207 Cumulative frequency distribution of CO₂ for each room in the third school

Figure 4.208 Cumulative frequency distribution of CO for each room in the third school
Figure 4.209 Cumulative frequency distribution of O$_3$ for each room in the third school

Figure 4.210 Cumulative frequency distribution of RH for each room in the third school
Figure 4.211 Cumulative frequency distribution of temperature for each room in the third school

Figure 4.212 Cumulative frequency distribution of VOCs for each room in the third school
Similar to the median box and whisker plots, the cumulative frequency distribution plots show no consistent relationship between the distance from the school entrance (school layout) and IAQ concentration in the test schools.

For the third question, we fail to reject the null hypothesis (H0: The layouts of test schools facilities do not have an effect on the IAQ in schools), because plots show no apparent relationship.

4.4 The IAQ concentration levels of different room types

Figures 4.213 to 4.224 show sample plots for the air quality parameters in one school for two days. 1-hour average concentration for all four rooms are shown on the same plot for comparison. Since the data in different rooms was collected during different weeks, the difference among rooms could reflect differences due to week of data collection (and differing influences of outdoor air quality, for example).

![Figure 4.213 Friday hourly average indoor temperature in School 1, Rooms 1-4](image)

Figure 4.213 Friday hourly average indoor temperature in School 1, Rooms 1-4
Figure 4.214 Tuesday hourly average indoor temperature in School 1, Rooms 1-4

Figure 4.215 Friday hourly average indoor carbon dioxide in School 1, Rooms 1-4
Figure 4.216 Tuesday hourly average indoor carbon dioxide in School 1, Rooms 1-4

Figure 4.217 Friday hourly average indoor relative humidity in School 1, Rooms 1-4
Figure 4.218 Tuesday hourly average indoor relative humidity in School 1, Rooms 1-4

Figure 4.219 Friday hourly average indoor volatile organic compounds in School 1, Rooms 1-4
Figure 4.220 Tuesday hourly average indoor volatile organic compounds in School 1, Rooms 1-4

Figure 4.221 Friday hourly average indoor carbon monoxide in School 1, Rooms 1-4
Figure 4.222 Tuesday hourly average indoor carbon monoxide in School 1, Rooms 1-4

Figure 4.223 Friday hourly average indoor ozone in School 1, Rooms 1-4
Figure 4.224 Tuesday hourly average indoor ozone in School 1, Rooms 1-4

Figures 4.225 to 4.248 show the comparison of the cumulative frequency distributions for the same room of various parameters in the test schools.

Figure 4.225 Cumulative frequency distribution of VOCs for Science room in schools (1-3)
Figure 4.226 Cumulative frequency distribution of VOCs for Computer room in schools (1-3)

Figure 4.227 Cumulative frequency distribution of VOCs for Copy room in schools (1-3)
Figure 4.228 Cumulative frequency distribution of VOCs for Regular classroom in schools (1-3)

Figure 4.229 Cumulative frequency distribution of temperature for Science room in schools (1-3)
Figure 4.230 Cumulative frequency distribution of temperature for Computer room in schools (1-3)

Figure 4.231 Cumulative frequency distribution of temperature for Copy room in schools (1-3)
Figure 4.232 Cumulative frequency distribution of temperature for Regular classroom in schools (1-3)

Figure 4.233 Cumulative frequency distribution of RH for Science room in schools (1-3)
Figure 4.234 Cumulative frequency distribution of RH for Computer room in schools (1-3)

Figure 4.235 Cumulative frequency distribution of RH for Copy room in schools (1-3)
Figure 4.236 Cumulative frequency distribution of RH for Regular classroom in schools (1-3)

Figure 4.237 Cumulative frequency distribution of ozone for Science room in schools (1-3)
Figure 4.238 Cumulative frequency distribution of ozone for Computer room in schools (1-3)

Figure 4.239 Cumulative frequency distribution of ozone for Copy room in schools (1-3)
Figure 4.240 Cumulative frequency distribution of ozone for Regular classroom in schools (1-3)

Figure 4.241 Cumulative frequency distribution of CO$_2$ for Science room in schools (1-3)
Figure 4.242 Cumulative frequency distribution of CO\textsubscript{2} for Computer room in schools (1-3)

Figure 4.243 Cumulative frequency distribution of CO\textsubscript{2} for Copy room in schools (1-3)
Figure 4.244 Cumulative frequency distribution of CO$_2$ for Regular classroom in schools (1-3)

Figure 4.245 Cumulative frequency distribution of CO for Science room in schools (1-3)
Figure 4.246 Cumulative frequency distribution of CO for Computer room in schools (1-3)

Figure 4.247 Cumulative frequency distribution of CO for Copy room in schools (1-3)
A two-way ANOVA was conducted to determine whether the IAQ parameters differ among room types and/or between schools. Tables 4.5 to 4.8 show the averages of CO, CO₂, O₃ and VOCs from the two-way ANOVA test and Table 4.9 summarizes the ANOVA results.

**Table 4.5 Averages of CO**

<table>
<thead>
<tr>
<th>Room</th>
<th>Room1 (Science)</th>
<th>Room 2 (Computer)</th>
<th>Room3 (Copy)</th>
<th>Room4 (General)</th>
<th>School average</th>
</tr>
</thead>
<tbody>
<tr>
<td>School 1</td>
<td>0.07</td>
<td>0.09</td>
<td>0.06</td>
<td>0.2</td>
<td>0.105</td>
</tr>
<tr>
<td>School 2</td>
<td>0.029</td>
<td>0.036</td>
<td>0.021</td>
<td>0.002</td>
<td>0.022</td>
</tr>
<tr>
<td>School 3</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0025</td>
</tr>
<tr>
<td>Room average</td>
<td>0.03633</td>
<td>0.042</td>
<td>0.027</td>
<td>0.0673</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.248 Cumulative frequency distribution of CO for Regular classroom in schools (1-3)
Table 4.6 Averages of CO₂

<table>
<thead>
<tr>
<th></th>
<th>Room1</th>
<th>Room2</th>
<th>Room3</th>
<th>Room4</th>
<th>School average</th>
</tr>
</thead>
<tbody>
<tr>
<td>School1</td>
<td>730</td>
<td>792</td>
<td>790</td>
<td>1420</td>
<td>933</td>
</tr>
<tr>
<td>School2</td>
<td>719</td>
<td>743</td>
<td>633</td>
<td>664</td>
<td>690</td>
</tr>
<tr>
<td>School3</td>
<td>1221</td>
<td>560</td>
<td>737</td>
<td>687</td>
<td>801</td>
</tr>
<tr>
<td>Room average</td>
<td>890</td>
<td>698</td>
<td>720</td>
<td>924</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7 Averages of O₃

<table>
<thead>
<tr>
<th></th>
<th>Room1</th>
<th>Room2</th>
<th>Room3</th>
<th>Room4</th>
<th>School average</th>
</tr>
</thead>
<tbody>
<tr>
<td>School1</td>
<td>0.035</td>
<td>0.035</td>
<td>0.037</td>
<td>0.03</td>
<td>0.03425</td>
</tr>
<tr>
<td>School2</td>
<td>0.03</td>
<td>0.039</td>
<td>0.0368</td>
<td>0.0352</td>
<td>0.03525</td>
</tr>
<tr>
<td>School3</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.0325</td>
</tr>
<tr>
<td>Room average</td>
<td>0.031667</td>
<td>0.034667</td>
<td>0.037933</td>
<td>0.031667</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.8 Averages of VOCs

<table>
<thead>
<tr>
<th></th>
<th>Room1</th>
<th>Room 2</th>
<th>Room3</th>
<th>Room4</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td>School 1</td>
<td>126</td>
<td>112</td>
<td>152</td>
<td>172</td>
<td>141</td>
</tr>
<tr>
<td>School 2</td>
<td>160</td>
<td>159</td>
<td>105</td>
<td>115</td>
<td>135</td>
</tr>
<tr>
<td>School 3</td>
<td>238</td>
<td>143</td>
<td>154</td>
<td>140</td>
<td>169</td>
</tr>
<tr>
<td>Room average</td>
<td>175</td>
<td>138</td>
<td>137</td>
<td>142</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.9 Two-way ANOVA for the test schools

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source of variation</th>
<th>F-actual</th>
<th>F-critical</th>
<th>P-value</th>
<th>df</th>
<th>Is difference in means significance?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>Rows (Rooms)</td>
<td>0.50857</td>
<td>4.757063</td>
<td>0.690761</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Columns (Schools)</td>
<td>6.745494</td>
<td>5.143253</td>
<td>0.029171</td>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>Rows (Rooms)</td>
<td>0.52209</td>
<td>4.757063</td>
<td>0.682733</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Columns (Schools)</td>
<td>0.776553</td>
<td>5.143253</td>
<td>0.501276</td>
<td>2</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>O₃</td>
<td>Rows (Rooms)</td>
<td>2.45827</td>
<td>4.757063</td>
<td>0.16054</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Columns (Schools)</td>
<td>0.688169</td>
<td>5.143253</td>
<td>0.538185</td>
<td>2</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>TVOCs</td>
<td>Rows (Rooms)</td>
<td>0.700587</td>
<td>4.75063</td>
<td>0.585209</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Columns (Schools)</td>
<td>0.962541</td>
<td>5.1432253</td>
<td>0.433953</td>
<td>2</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

The results of the two-way ANOVA test show that: for the carbon monoxide concentration there is no significant difference (P>0.05) between the rooms’ average concentrations are (0.036, 0.042, 0.027, 0.067 ppm) for the four different types of rooms;
however, there is a significant difference (P<0.05) between the average concentrations of test schools are (0.105, 0.022 and 0.0025 ppm). For the VOCs there is no significant difference (P>0.05) between the room average concentrations are (175, 138, 137 and 142 ppb) for the four different use rooms and there is no significant difference (P>0.05) between the schools average concentrations are (141, 135 and 169 ppb). For carbon dioxide there is no significant difference (P>0.05) between the rooms’ average concentrations are (890, 698, 720 and 924 ppm) and there is no significant difference (P>0.05) between schools average concentrations are (933, 690 and 801 ppm). For the ozone there is no significant difference (P>0.05) between the rooms average concentrations are (0.032, 0.035, 0.038, 0.032 ppm) for the four different types of rooms and there is no significant different between the average concentration of test schools are (0.034, 0.035 and 0.033 ppm).

The results of the ANOVA test were not expected: we expected that the science rooms could have elevated levels of volatile organic compounds, the computer rooms to have elevated level of ozone and copy room have elevated level of VOCs that could be produced by some equipment operation. The ANOVA test used may not have been powerful enough to detect differences.

For the fourth research question, we cannot reject the null hypothesis (H0: Rooms of different types do not have different concentration level) because all the results of the two-way ANOVA test show no significant difference between all the rooms concentration levels in the test schools.
Chapter 5
Conclusions and Recommendations

5.1 Summary

This chapter includes a discussion of the general conclusions from this dissertation, along with recommendations for future research.

For the first research question, the data show that all the test schools have acceptable levels of ozone, carbon monoxide, temperature and RH that meet Texas IAQ guidelines and low levels of VOCs, CO$_2$ within the guidelines. Levels of VOCs and CO$_2$ for the fourth room (regular classroom) in the first school met the guidelines only 45% and 35% of the time, respectively, likely due to inadequate ventilation. The first room (science room) of the third school also showed high concentration VOCs and CO$_2$ as well; this room complied with the VOC and CO$_2$ guidelines 0% and 35% of the time, respectively, which could be due to the use of some chemicals during the classroom and inadequate ventilation as well.

For the second research question, from measuring the correlations between indoor and outdoor parameters, more than 85% of the results show weak to no correlation trends between the indoor and outdoor in the test schools, which could be strongly influenced by the building air tightness.

For the third question, median parameters of the four different types of rooms in box plots and cumulative frequency distributions of the four rooms vs. the distance from the school entrance were compared. All plots show no apparent relationship, which can indicate that the layout of the school facilities does not have an effect on the IAQ in test schools.

For the fourth research question, by conducting a two-way ANOVA test to determine whether the IAQ parameters differ among room types and/or among schools,
the results show a significant difference (P<0.05) between the mean value of the indoor air quality among CO levels in the different schools, but not among various types of rooms.

The main recommendation of this study is to mitigate the ventilation rate to meet the Texas IAQ Guidelines in all the test schools, which will be beneficial to improve the indoor air quality and reduce the VOCs and CO\textsubscript{2} concentrations in the rooms exceeded the Texas IAQ guidelines.

5.2 Recommendations for Future Research

Schools serve different activities, potentially could produce different pollutants (e.g. classrooms, offices, science, library, cafeteria, art, gymnasiums), perceived acceptable air quality, should be considered as priorities to ensure healthy environment for learner and educators. This study had limitations due to the lack of funds: using only one monitor limited the ability to collect data in different classrooms at the same time on the same days. If such data had been able to be collected, then a multiple linear regression model could have been built to estimate indoor air quality parameters (pollutant concentrations), considering predictor variables such as time of day, outdoor air quality parameter values, the room’s use, distance from the school entrance. Since the data had to be collected one room at a time, time series correlation issues meant that such a model could not be built via traditional methods.

Replicating the data in different seasons and monitoring the same school in two different seasons is important to evaluate the seasonal effects and will be more beneficial in measuring the correlation between indoor and outdoor air quality as well. Conducting the same study in more than two school districts could make the data more representative.
Including other potential contaminants in the monitoring instrument, like formaldehyde and particulate matter, which are very common pollutants in schools as mentioned in the literature, would be an important additional step.
Appendix A

Cumulative frequency distribution of indoor air parameters in test schools
School 1, Room 2
Normal Distribution

School 1, Room 2
Normal Distribution
School 1, Room 2

Normal Distribution

% frequency

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.00 0.01 0.02 0.03 0.04 0.05

O3(ppm)

% frequency

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.2 0.4 0.6 0.8 1.0

CO(ppm)

School 1, Room 2
Normal Distribution
VOCs (ppb)

- School 1, Room 3
- Normal Distribution

CO₂ (ppm)

- School 1, Room 3
- Normal Distribution
School 1, Room 3
Normal Distribution

School 1, Room 3
Normal Distribution
School 1, Room 4
Normal Distribution

School 1, Room 4
Normal Distribution
VOCs(ppb)

% frequency

School 2, Room 1
Normal Distribution

CO₂(ppm)

% frequency

School 2, Room 1
Normal Distribution
School 2, Room 1
Normal Distribution

%frequency vs. CO(ppm)

%frequency vs. CO(ppm)
VOCs (ppb)

School 2, Room 2
Normal Distribution

CO₂ (ppm)

School 2, Room 2
Normal Distribution
School 2, Room 2 Normal Distribution

School 2, Room 2 Normal Distribution
School 2, Room 3

Normal Distribution
School 2, Room 4

Normal Distribution
School 2, Room 4
Normal Distribution
School 3, Room 1

Normal Distribution

VOCs (ppb)

CO2 (ppm)
Graph 1: %frequency vs. VOCs (ppb)

Graph 2: %frequency vs. CO₂ (ppm)

- Blue line: School 3, Room 2
- Red line: Normal Distribution
School 3, Room 2
Normal Distribution
School 3, Room 3
Normal Distribution

School 3, Room 3
Normal Distribution
School 3, Room 3
Normal Distribution

%frequency vs. Temperature°C

%frequency vs. %RH
School 3, Room 4

Normal Distribution

VOCs (ppb)

% frequency

0 200 400 600 800

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

CO₂ (ppm)

% frequency

0 1000 2000 3000 4000

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
School 3, Room 4

Normal Distribution
Appendix B

The correlation between indoor and outdoor in test schools.
School 2, Science room (R=-0.40797)
Linear (School 2, Science room (R=-0.40797))

School 2, Computer room (R=0.111723)
Linear (School 2, Computer room (R=0.111723))
IA. Temperature °C vs OA. Temperature °C

School 2, Copy room (R=0.700932)

School 2, Regular classroom (R=0.621641)
School 2, Science room (R=0.599242)

Linear (School 2, Science room (R=0.599242))

School 2, Computer room (R=0.782326)

Linear (School 2, Computer room (R=0.782326))
School 2, Copy room 
(R=0.394989)

Linear (School 2, Copy room (R=0.394989))

School 2, Regular classroom
(R=0.187717)

Linear (School 2, Regular classroom (R=0.187717))
School 2, Science room
(R=-0.01103)

Linear (School 2, Science room (R=-0.01103))

School 2, Computer room (R=0.012461)

Linear (School 2, Computer room (R=0.012461))

School 2, Copy room (R=0.405224)

Linear (School 2, Copy room (R=0.405224))
School 2, Regular classroom (R=0.350215)

Linear (School 2, Regular classroom (R=0.350215))

School 2, Science room (R=0.104224)

Linear (School 2, Science room (R=0.104224))
School 2, Computer room (R=0.08266)

Linear (School 2, Computer room (R=0.08266))

School 2, Copy room (R=0.525208)

Linear (School 2, Copy room (R=0.525208))
School 2, Regular classroom (R=0.396655)

Linear (School 2, Regular classroom (R=0.396655))

School 3, Science room (R=0.175928)

Linear (School 3, Science room (R=0.175928))
School 3, Computer room (R=0.136284)
Linear (School 3, Computer room (R=0.136284))

School 3, Copy room (R=0.355408)
Linear (School 3, Copy room (R=0.355408))

School 3, Regular classroom (R=0.520676)
Linear (School 3, Regular classroom (R=0.520676))
School 3, Science room (R=0.014004)

Linear (School 3, Science room (R=0.014004))

School 3, Computer room (R=0.385177)

Linear (School 3, Computer room (R=0.385177))
School 3, Copy room (R= -0.02835)

Linear (School 3, Copy room (R= -0.02835))

School 3, Regular classroom (R= -0.07549)

Linear (School 3, Regular classroom (R= -0.07549))

School 3, Science room (R= -0.24317)

Linear (School 3, Science room (R= -0.24317))
School 3, Science room (R=0.263043)

Linear (School 3, Science room (R=0.263043))

School 3, Computer room (R=-0.00292)

Linear (School 3, Computer room (R=-0.00292))
School 3, Copy room (R=0.389567)

School 3, Regular classroom (R=0.722163)
References

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