Perception of Indoor Air Quality (IAQ) by Occupants of University Residence Hall Buildings

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Abstract

Four factors of indoor air quality were measured in four different areas across two different university residence hall buildings over the period of a month in order to determine differences in the building's indoor air qualities and to verify survey responses of the building occupants. The factors measured were ambient temperature, relative humidity, carbon dioxide, and air particulates ($PM_{2.5}$). The two buildings were the Margaret Loock Residence Hall and the Grohmann Tower on the Milwaukee School of Engineering (MSOE) campus, and participants of the survey were representative of the MSOE residence population. Data were taken with portable air quality devices. After data collection, the data were then compared between areas to determine any statistically significant differences through Tukey analysis. The Margaret Loock Hall had significantly lower carbon dioxide levels than the Grohmann Tower areas, indicating that buildings with tighter building envelopes require more ventilation in order to control carbon dioxide levels. The relative humidity was consistently low in all areas and buildings, verifying the occupant survey complaints of dry indoor environments. This direct correlation between the data and occupant response proves that occupant perception is accurate and should be considered more when designing indoor environments for comfort and satisfaction.

Keywords: Indoor Air Quality (IAQ), Indoor Environmental Quality (IEQ), air particulates, $PM_{2.5}$, temperature, humidity, CO_2, occupant perception, occupant comfort, occupant satisfaction, Building Use Studies Methodology (BUS), enhanced mechanical systems

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Perception of Indoor Air Quality (IAQ) by Occupants of University Residence Hall Buildings

The goal of this study was to determine if sustainable or enhanced building mechanical systems can offer more health and comfort benefits to building occupants than traditional systems. In the construction field, “greener” building solutions and enhanced systems have become a positive trend across all markets as the industry focuses more on an occupant comfort end goal. This study sought to demonstrate that enhanced heating, ventilation, and air conditioning (HVAC) systems can affect occupant health and comfort significantly, providing benefits with occupant satisfaction and productivity.

It is well known that poorly conditioned air can cause sick building syndrome, so air quality does influence occupants in any building (Bluyssen, 2009, p. 124; Tham, 2016). Sick building syndrome can cause similar symptoms as allergies in building occupants due to poor air quality (Spengler, 2001, p. 3). In this capstone project, the research goal was to measure air contaminants—including odors, particulates, and carbon dioxide (CO_2) levels—in university residence halls and confirm that sustainable infrastructure in buildings can significantly improve air quality. To further examine subject comfort, air temperature and humidity in occupied spaces were also measured to determine how noticeable indoor conditions are to occupants and to determine indoor air quality (IAQ). Indoor air quality is a factor in occupant comfort, which includes the health benefits and comfort of the indoor air conditions in a building. Residents were surveyed, and their environments monitored to correlate occupant responses to their environments and the physical measurements taken. This research seeks to support the validity of the social aspect of the Triple Bottom Line. The goal is to use the relationship between occupant perception and physical environmental data to convince building owners to invest in building systems that produce high indoor air quality. With high indoor air quality, occupant satisfaction and comfort would be ensured.

On the Milwaukee School of Engineering campus, two sites were identified for this study, one that is conditioned by enhanced systems and the other conditioned by traditional systems. The enhanced system is an air conditioning system that is more energy efficient and has better indoor temperature control than the traditional system. These two sites are the Grohmann Tower and the Margaret Loock Residence Hall, respectively. It is ideal that the residence halls provide similar services in order to prevent amenity bias in the surveys. The air quality was sampled and measured in public areas where there is high traffic of residents. Samples were taken at the beginning and end of duct runs to ensure that no data bias would affect the measurement of the air quality. The way "quality" was determined in these areas entailed looking at the concentrations and amounts of CO_2 and particulates that were in the air in the building and comparing them against each other along with health standards discussed later. In addition to these numerical comparisons, occupants were surveyed about their comfort in their environment. These results were used to determine the relationship between sustainable systems and occupant comfort. The Building Use Study (BUS) Methodology, a validated survey, was used; it is tailored to addressing occupant comfort and satisfaction (United Kingdom Green Building Council, 2013, p. 1). If an enhanced HVAC system can noticeably improve the indoor environmental quality, it can improve occupant satisfaction and comfort, motivating project owners to consider more efficient systems to better attract tenants.

Background

Regulating Bodies

Codes and Standards

Ventilation and exhaust systems are implemented in buildings in order to dilute levels of harmful particulates and contaminants, and to provide “fresh” air to building occupants (Bluyssen, 2009, p. 97). The applicable codes for the buildings studied in this capstone project include the Wisconsin Mechanical Code (Wisconsin Department of Safety and Professional Services, 2018), the International Mechanical Code (International Code Council, 2015), and the International Building Code (International Code Council, 2018). These codes dictate mechanical system parameters and performance. All buildings must conform to whichever level of code is applicable for the project and jurisdiction, as compliance with codes is mandatory (Wang, 2001).

Compliance with standards is not mandatory, but many times their use is strongly encouraged in the design of mechanical systems. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) has sections specifically referencing ventilation rates and ensuring occupant comfort (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019a). If a code references a standard, the specified content or requirements are then considered to be a mandatory implementation in a project design.

These codes and standards are briefly introduced in this report, and applicable sections are cited to get a better understanding of the considerations needed to determine ventilation and exhaust rates.

Wisconsin Mechanical Code

The Wisconsin Department of Safety and Professional Services (DSPS) is responsible for the adoption of codes (Wisconsin Department of Safety and Professional Services, 2021). The actual codes are published in the Wisconsin Administrative Code (State of Wisconsin, 2021). The state bases its state code on the International Mechanical Code and lists changes, additions, or omissions to the code in the relevant chapter. The DSPS are the responsible party that issues amendments to the code. Many times, state codes and county codes are the first ones to be applied to a building or project that exists in an area because these codes include special requirements that reflect the regional needs. Local codes are often applied where possible because they are usually more stringent than codes at the federal level.

In the Wisconsin Administrative Code, Chapter SPS 364.0401 states the requirements for ventilation in commercial buildings. The state code mainly follows the same requirements as the International Mechanical Code, with few exceptions to wording and nomenclature. SPS 364.0403 (5) (a) discusses the ventilation rate determination. The Wisconsin Code specifies "a mechanical ventilation system shall be designed to have the capacity to supply a minimum outdoor airflow rate of 7.5 cfm per person" in accordance with Table 364.0403 (Wisconsin Department of Safety and Professional Services, 2018).

SPS 364.0502 (1) also states that exhaust systems are required for any application where "equipment and processes in such areas throw off dust particles" or which emit odors, fumes, and other contaminants (Wisconsin Department of Safety and Professional Services, 2018). Aside from these exceptions, no specific requirements are needed for air quality and ventilation.

International Mechanical Code

The International Mechanical Code (IMC) is heavily referenced in the Wisconsin Mechanical Code. The most recent update for the IMC occurred in 2021 and features minor changes in exhaust terminals, dampers, and refrigerants with respect to the previous version. The IMC is mainly used in applications where local entities do not have a specified code, although states and counties often include the IMC in their code, with certain geographical exceptions to mechanical system operations.

In the IMC, Table 403.3.1.1 lists the minimum ventilation requirements for certain applications based on people and area—for residence halls, depending on the public area, the ventilation rate per person is 7.5 cubic feet per minute (cfm) (International Code Council, 2015). The IMC goes on to indicate the method for calculating the breathing zone outdoor airflow (403.3.1.1.1.1), which takes into consideration the area and the occupancy of a room. Overall, this calculation process in the international code is the most general application in determining ventilation rates in zones.

ASHRAE 62.1

The most recent update to ASHRAE 62.1 was in 2019. This standard was created by ASHRAE in collaboration with the American National Standards Institute (ANSI) (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019b). The standard was first published in 1973, and it focuses on ventilation rates and other measures that are intended to provide acceptable indoor air quality (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019b). The Wisconsin Code references this standard in an effort to provide satisfactory air quality in indoor environments.

The recent update to the standard provides three procedures for ventilation design: the indoor air quality (IAQ) procedure, the ventilation rate procedure, and the natural ventilation procedure (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019b).

ASHRAE 55

This standard's most recent update was in 2017. It focuses on specifying conditions for acceptable thermal environments and is intended for use during design, operation, and commissioning of projects (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2017). A principal goal of this standard is to reduce risk to the health and safety of occupants.

Environmental Protection Agency

The Environmental Protection Agency (EPA) was founded in 1970, and it oversees many environmental concerns, including water, air, pesticides, and public health (United States Environmental Protection Agency, 2020a). Their research into air quality over the decades has supported standards such as the Clean Air Act in attempts to lower levels of air pollution. Spanning back to 1997, the EPA already began innovating methods for measuring particulate matter (United States Environmental Protection Agency, 2020a). In 2000, they researched the cardiovascular effects of inhaling air particulates and shared their findings (United States Environmental Protection Agency, 2020a). The EPA continuously updates its standards for acceptable levels of particulate matter and air-borne contaminants.

The Clean Air Act requires the Environmental Protection Agency to set national air quality standards for select air pollutants, and particulate matter is one of these on the list (United States Environmental Protection Agency, 2020d). Listed in Table 1 are the National Ambient Air

Quality Standards, and the principal pollutants are measured in parts per million (ppm) by volume, parts per billion (ppb) by volume, and micrograms per cubic meter of air.

Table 1

National Ambient Air Quality Standards for the United States

Pollutant		Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO) www.epa.gov/co-pollution/table-historical-carbon-monoxide-co-national-ambient-air-quality-standards-naaqs		Primary	Eight (8) hours	9 ppm	Not to be exceeded more than once per year
			One (1) hour	35 ppm	
Lead (Pb) www.epa.gov/lead-air-pollution/table-historical-lead-pb-national-ambient-air-quality-standards-naaqs		Primary and secondary	Rolling three (3) month average	0.15 $\mu g/m^3$ (Note 1)	Not to be exceeded
Nitrogen Dioxide (NO_2) www.epa.gov/no2-pollution/table-historical-nitrogen-dioxide-national-ambient-air-quality-standards-naaqs		Primary	One (1) hour	100 ppb	Ninety-eighth (98th) percentile of one-hour daily maximum concentrations, averaged over three years
		Primary and secondary	One (1) year	53 ppb (Note 2)	Annual mean
Ozone (O_3) www.epa.gov/ozone-pollution/table-historical-ozone-national-ambient-air-quality-standards-naaqs		Primary and secondary	Eight (8) hours	0.070 ppm (Note 3)	Annual fourth-highest daily maximum eight-hour concentration, averaged over three years
Particle Pollution (PM) www.epa.gov/pm-pollution/table-historical-particulate-matter-pm-national-ambient-air-quality-standards-naaqs	PM2.5	Primary	One (1) year	12.0 $\mu g/m^3$	Annual mean, averaged over three years
		Secondary	One (1) year	15.0 $\mu g/m^3$	Annual mean, averaged over three years
		Primary and secondary	Twenty-four (24) hours	35 $\mu g/m^3$	Ninety-eight (98th) percentile, averaged over three years
	PM10	Primary and secondary	Twenty-four (24) hours	150 $\mu g/m^3$	Not to be exceeded more than once per year on average over three years
Sulfur Dioxide (SO_2) www.epa.gov/so2-pollution/table-historical-sulfur-dioxide-national-ambient-air-quality-standards-naaqs		Primary	One (1) hour	75 ppb (Note 4)	Ninety-ninth (99th) percentile of one-hour daily maximum concentrations, averaged over three years
		Secondary	Three (3) hours	0.5 ppm	Not to be exceeded more than once per year

Note 1: In areas designated "nonattainment" for the Pb standards prior to the promulgation of the current (2008) standards, and for which implementation plans to attain or maintain the current (2008) standards have not been submitted and approved, the previous standards (1.5 $\mu g/m^3$ as a calendar quarter average) also remain in effect.
Note 2: The level of the annual NO_2 standard is 0.053 ppm. It is shown here in terms of ppb for the purpose of clearer comparison to the one-hour standard level.
Note 3: Final rule signed October 1, 2015, and effective December 28, 2015. The previous (2008) O_3 standards additionally remain in effect in some areas. Revocation of the previous (2008) O_3 standards and transitioning to the current (2015) standards will be addressed in the implementation rule for the current standards.
Note 4: The previous SO_2 standards (0.14 ppm 24-hour and 0.03 ppm annual) will additionally remain in effect in certain areas: (a) any area for which it is not yet one year since the effective date of designation under the current (2010) standards, and (b) any area for which an implementation plan providing for attainment of the current (2010) standard has not been submitted and approved and that is designated "nonattainment" under the previous SO_2 standards or is not meeting the requirements of an SIP call under the previous SO_2 standards (40 CFR 50.4[3). An SIP call is an EPA action requiring a state to resubmit all or part of its State Implementation Plan to demonstrate attainment of the required NAAQS.

Note. Adapted from *Ventilation for Acceptable Indoor Air Quality (62.1)* by the American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019b, p. 46.

The Clean Air Act, as seen in Table 1, identifies two types of air quality standards. Primary standards "provide public health protection, including protecting the health of "sensitive" populations" such as asthmatics, the elderly, and children (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019b, p. 45). Secondary standards protect against "decreased visibility and damage to animals, crops, vegetation, and buildings" (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2019b, p. 45). This capstone study focused on the primary air standards when analyzing air particulate measurements.

Sustainable Rating Systems

A number of building rating systems exist intended to promote more sustainable building system designs. Part of what constitutes a more sustainable building includes improved energy efficiency, indoor air quality, and indoor environmental quality (IEQ). Indoor environmental quality consists of indoor air quality, lighting quality, aesthetics, and overall comfort in the indoor environment. Organizations that administer these building rating systems have a mission to encourage and advance the practices of sustainable design, so that infrastructure in the future will be less impactful on the environment and health of people. While neither of the two residence halls in this study were certified under any sustainable rating system, it is still important to understand these systems because they provide guidelines for a healthier indoor environment and building.

LEED

LEED Rating System. LEED is the acronym for Leadership in Energy and Environmental Design and refers to a ranking system designated by the U.S. Green Building Council, created in 1993 (U.S. Green Building Council, 2020). The mission of LEED is to enable "an environmentally and socially responsible, healthy, and prosperous environment that improves the quality of life" (U.S. Green Building Council, 2020, para. 2). The LEED system focuses on savings in maintenance costs, use of less energy and water, and improvements in "indoor air quality, offering comfort to occupants", as well as creating less of an environmental burden on the surrounding community (U.S. Green Building Council, 2020, para. 3). This ranking system looks beyond economic initiatives—occupant health and comfort are a large priority in these projects.

Ranking Checklist and Progress. The process to get a building LEED certified is simple in comparison with other rating systems. There are four steps to begin the rating process: "register your project by completing key forms and submitting payment, apply for LEED certification by submitting your completed certification application and paying a fee, have LEED application reviewed, and receive the certification decision" (U.S. Green Building Council, 2017, para. 1). However, by registering, a project needs to meet minimum requirements, including items such as compliance with environmental laws—and with minimum floor and occupancy requirements.

An example of the most current LEED checklist featuring all the potential credits that a project can earn is shown in Figure 1 (U.S. Green Building Council, 2016).

Figure 1

LEED BD + C v4 Checklist

Y	?	N			
			Credit	Integrative Process	1

0	0	0	Location and Transportation		16
			Credit	LEED for Neighborhood Development Location	16
			Credit	Sensitive Land Protection	1
			Credit	High Priority Site	2
			Credit	Surrounding Density and Diverse Uses	5
			Credit	Access to Quality Transit	5
			Credit	Bicycle Facilities	1
			Credit	Reduced Parking Footprint	1
			Credit	Green Vehicles	1

0	0	0	Sustainable Sites		10
Y			Prereq	Construction Activity Pollution Prevention	Required
			Credit	Site Assessment	1
			Credit	Site Development - Protect or Restore Habitat	2
			Credit	Open Space	1
			Credit	Rainwater Management	3
			Credit	Heat Island Reduction	2
			Credit	Light Pollution Reduction	1

0	0	0	Water Efficiency		11
Y			Prereq	Outdoor Water Use Reduction	Required
Y			Prereq	Indoor Water Use Reduction	Required
Y			Prereq	Building-Level Water Metering	Required
			Credit	Outdoor Water Use Reduction	2
			Credit	Indoor Water Use Reduction	6
			Credit	Cooling Tower Water Use	2
			Credit	Water Metering	1

0	0	0	Energy and Atmosphere		33
Y			Prereq	Fundamental Commissioning and Verification	Required
Y			Prereq	Minimum Energy Performance	Required
Y			Prereq	Building-Level Energy Metering	Required
Y			Prereq	Fundamental Refrigerant Management	Required
			Credit	Enhanced Commissioning	6
			Credit	Optimize Energy Performance	18
			Credit	Advanced Energy Metering	1
			Credit	Demand Response	2
			Credit	Renewable Energy Production	3
			Credit	Enhanced Refrigerant Management	1
			Credit	Green Power and Carbon Offsets	2

0	0	0	Materials and Resources		13
Y			Prereq	Storage and Collection of Recyclables	Required
Y			Prereq	Construction and Demolition Waste Management Planning	Required
			Credit	Building Life-Cycle Impact Reduction	5
			Credit	Building Product Disclosure and Optimization - Environmental Product Declarations	2
			Credit	Building Product Disclosure and Optimization - Sourcing of Raw Materials	2
			Credit	Building Product Disclosure and Optimization - Material Ingredients	2
			Credit	Construction and Demolition Waste Management	2

0	0	0	Indoor Environmental Quality		16
Y			Prereq	Minimum Indoor Air Quality Performance	Required
Y			Prereq	Environmental Tobacco Smoke Control	Required
			Credit	Enhanced Indoor Air Quality Strategies	2
			Credit	Low-Emitting Materials	3
			Credit	Construction Indoor Air Quality Management Plan	1
			Credit	Indoor Air Quality Assessment	2
			Credit	Thermal Comfort	1
			Credit	Interior Lighting	2
			Credit	Daylight	3
			Credit	Quality Views	1
			Credit	Acoustic Performance	1

0	0	0	Innovation		6
			Credit	Innovation	5
			Credit	LEED Accredited Professional	1

0	0	0	Regional Priority		4
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1

0	0	0	TOTALS	Possible Points:	110

Certified: 40 to 49 points, **Silver:** 50 to 59 points, **Gold:** 60 to 79 points, **Platinum:** 80 to 110

Note. Adapted from the “Checklist: LEED v4 for Building Design and Construction” by the U.S. Green Building Council, 2016, para. 1 (https://www.usgbc.org/resources/leed-v4-building-design-and-construction-checklist).

There are prerequisites that need to be achieved before credits can be collected in each category. Many of these prerequisites align with the ASHRAE 55 and ASHRAE 62.1 standards; with LEED, these standards need to be followed in order to be considered for a ranking for a project. Note that the second largest section in the checklist is Indoor Environment Quality—and that not only are there several indoor air quality sections, but a prerequisite requires minimum levels of indoor air quality. Young (2018) states “the intent of the IEQ standards is to establish minimal indoor air quality performance to enhance the indoor air quality of buildings, thus contributing to the comfort and well-being of the occupants" (p.12). Occupant comfort and satisfaction can be associated with a quality indoor environment.

Greenguard

Greenguard is a certification organization that specially focuses on products used in buildings (Greenguard, 2020). In order to ensure good indoor air quality, building products must be selected that do not contribute to introducing volatile organic compounds to the building interior. Greenguard was created by SPOT, which is a product database vendor that aids consumers in finding green materials and products for their projects. They offer verification for building products and furnishings as well as the actual building environment itself. They state that good air quality is associated with tenant retention— "studies show that tenants and employees value indoor environmental quality over all other environmental or sustainability amenities offered" (Greenguard, 2020, para. 3). Especially during the recent COVID-19 pandemic, where many worked from home and have spent more time indoors than normal, indoor air quality is a large concern with occupants of a residential building.

WELL

WELL is another sustainability rating system, but it is more focused on creating more "thoughtful and intentional spaces that enhance human health and well-being" (WELL, 2020, para. 1). It was founded by the International WELL Building Institute (IWBI) in 2014. Its global movement aims to create a premier standard for buildings and "interior spaces and communities seeking to implement, validate and measure features that support and advance human health and wellness" (WELL, 2020, para. 62). This rating system focuses more on occupant benefits in environments. Figure 2 depicts the main goals of the WELL certification.

Figure 2

WELL Checklist Focuses

Note. Adapted from "WELL v2" by WELL Certified, 2021, para. 11.
(https://v2.wellcertified.com/wellv2/en/overview)

All of these factors ultimately contribute to satisfactory indoor environmental and air quality. This concern with indoor environmental quality (IEQ) and IAQ, especially with such a recent ranking system, indicates where construction and design likely will be focused in the near future.

Sustainability Achievement Benefits

Looking at these rating systems and the lengthy processes associated with certification, one might wonder why any project owner would want to achieve a certification from any of these organizations. There are many benefits in receiving a sustainable label for a building. The most notable factor is energy cost savings. While greener solutions have higher capital costs, they often save the owner money over their life cycle through greater operating efficiency and lower operating costs (Wilson, 2005).

With a certification from a system like LEED comes interested tenants and occupants. People spend "more than 90% of their time indoors" and many are taking notice of that (Wu, 2007, p. 953). As Greenguard states, many people value indoor environmental quality over other sustainable benefits, as it attracts people to a building and it is a tangible and noticeable factor (Wilson, 2005). By advertising that a building is implementing green practices, it is more likely that a building owner will see more business (Janjua et al., 2020, p. 1). Many businesses and individuals are invested in an ethical lifestyle—including being more environmentally conscious and attempting to manage their own carbon footprints. By investing in these efforts, even if no actual green rating certification is achieved, the focus of occupant comfort and safety can still be achieved and advertised.

Triple Bottom Line

The Triple Bottom Line (TBL) is referenced in many works that focus on sustainability. Sustainability is a general term that can be hard to define because "there is no widely accepted framework to help evaluate sustainability" (Papajohn et al., 2017, p. 1). The definition that best describes sustainability is a project that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Papajohn et al., 2017, p. 1). This definition can be interpreted in many ways depending on the project and owner. However, "a vague, alterable goal like sustainability can act as a boundary object, with a meaning that can shift based on context and experience" (Werkheiser & Piso, 2015, p. 1). Sustainability, though difficult to define, still holds important meaning to various organizations and clients in its own unique manner. In order to better define sustainability and to help eliminate vagueness associated with it, a concept known as the Triple Bottom Line has been developed.

The Triple Bottom Line is "an accounting framework that incorporates the three dimensions of performance: social, environmental, and financial" (Slaper & Hall, 2011, p. 1). In other words, in the sustainable construction industry, a building is evaluated and designed with three categories in mind. These categories focus on improving three distinct aspects of an operating building: such as saving money, gaining a favorable reputation, and other benefits minimizing environmental impacts. The TBL is different from traditional reporting frameworks "as it includes ecological and social measures that can be difficult to assign appropriate means of measurement" (Slaper & Hall, 2011, p. 1). Examples of these "immeasurable" effects can be occupant health and satisfaction. While the green building industry is moving towards an occupant-focused design, it is difficult to quantify human behavior and emotion in order to determine or measure the success of fulfilling the Triple Bottom Line. For decades, the financial or economic aspect of buildings was always kept in mind and was easy to compare to see the energy savings a sustainable building can provide. Now with the gradual focus on the other two parts of the triple bottom line, researchers have been attempting to accurately calculate measures of social and environmental impacts.

The economic portion of the Triple Bottom Line deals mainly with the flow of money (Slaper & Hall, 2011, p. 3). This can include income, taxes, employment, and other economic and financial measures. The goal of this portion is to be as efficient as possible with building operation to gain the maximum possible revenue. Indirect economic benefits can also be included, such as the boosting of a local economy by constructing modern buildings on sites that had little value (Janjua et al., 2020).

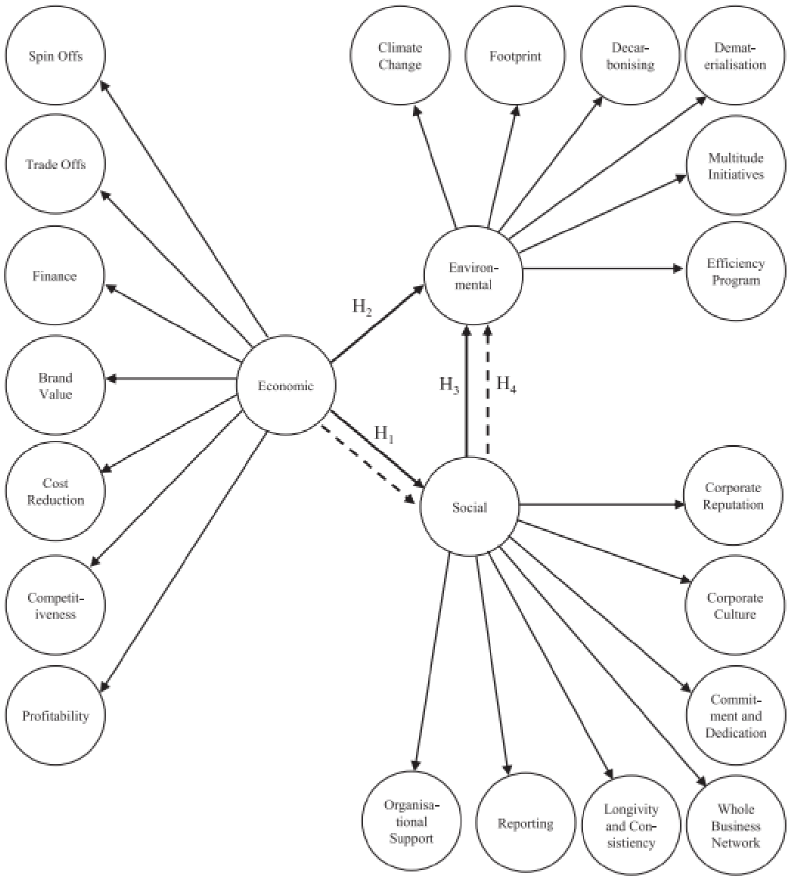
Environmental concerns are also a focal point within the TBL. While sustainable systems and buildings save money, it is important to directly take account of the environmental benefits they provide, including energy and water savings.

Finally, social concerns are evaluated within the TBL framework by considering how the building design and operation affect the comfort and health of its occupants and the surrounding community.

Figure 3 shows the relationships between each factor of the TBL (Svensson, Hogevold, Padin, Varela, & Sarstedt, 2018, p. 981).

Figure 3

Triple Bottom Line Relationships



Note. Adapted from “Framing the Triple Bottom Line Approach: Direct and Mediation Effects Between Economic, Social and Environmental Elements” by G. Svensson, C. Ferro, N. Høgevold, C. Padin, J. Varela, and M. Sarstedt, 2018, *Journal of Cleaner Production, 197*, p. 981 (https://doi.org/10.1016/j.jclepro.2018.06.226).

Some of the factors the environmental sector addresses are climate change—and related to climate change—the building’s carbon footprint. By having a smaller carbon and energy footprint due to the increased operating efficiency of the building, the building has less of a negative impact on climate change. However, as previously stated, these factors also affect the cost, and can affect occupant satisfaction as well. Overall, the three aspects of the TBL are interconnected, and while this study is focused on the social benefits, it also considers how economic and environmental factors indirectly influence or affect the social domain.

The social aspect of the Triple Bottom Line is often discredited or ignored because it typically does not benefit the owner upfront, and because the social dimension does not provide direct benefits to the other two dimensions. It has empirically been known that "social sustainability is one of the weakest sustainability dimensions" (Wang et al., 2018, p. 1). However, social sustainability has gained attention in recent years (Kelly et al., 2017, p. 17). "The social dimension is related to the qualities of human beings, like skills, dedication, and experience, covering both the internal and external environment of the company" (Machado et al., 2015, p. 3). According to Machado et al. (2015), not only is the social dimension linked "to the influences which social actions are taken" by a building, it also includes "sustainability that focuses on the benefits to society as whole" (p. 3). So the effects of a sustainable building not only heavily influence the operation of the building itself, but the surrounding community and markets as well.

Air Pollutants

One large focus in sustainable design is the air quality. Air quality negatively affects occupants when it is poor and is an example of how the three elements of the TBL tie together. An example of this is the term "sick building syndrome"—if the air quality is poor, this disease can cause "headache, dizziness, nausea, coughing and sneezing, irritation of eyes, throat and nose" and irritated skin (Vafaeenasab et al., 2015, p. 247). The human health effects of outdoor pollutants are well established and are used to set health-based standards for outdoor air, but indoor levels have the potential to exceed these outdoor levels and constraints (United States Environmental Protection Agency, 2020a).

Carbon Dioxide

Concentrations of carbon dioxide in indoor spaces are higher than levels in outdoor spaces since occupants are exhaling the substance in a contained space. Because of this effect, design of air conditioning systems needs to provide adequate ventilation to minimize and eliminate any negative side effects of high carbon dioxide levels.

Side Effects. Greiner (1991) reports that “at concentrations of 2,500 ppm to 5,000 ppm carbon dioxide can cause headaches. At extremely high levels of 100,000 ppm (10 percent) people lose consciousness in ten minutes, and at 200,000 ppm (20 percent) CO_2 causes partial or complete closure of the glottis” (para. 2). Typically, carbon dioxide levels never reach the high levels that produce the more serious of these side effects because modern buildings are well ventilated. The need for better ventilation today is because modern buildings are designed to have less air infiltration through the building envelope in order to improve energy efficiency and because many of the materials used in modern buildings off-gas harmful chemical substances. Ventilation designed to address these issues also keep carbon dioxide levels in check. Carbon dioxide levels are not an issue if proper ventilation rates are maintained (Greiner, 1991).

Acceptable Levels. Under ASHRAE standards, the acceptable levels of carbon dioxide allowed in buildings range from 300 to 1,000 ppm (particles per million). In Milwaukee, the outdoor concentration is around 405 ppm. In this study, the acceptable range was established at 400 to 1,000 ppm.

Sources of Carbon Dioxide. The main source of carbon dioxide in indoor environments is the occupants themselves. Foggin (2010) reports that “Human metabolism alone can lead to CO_2 levels in excess of 3,000 ppm” (para. 3). The levels of carbon dioxide depend on how active the occupants are in the area—workout rooms will have higher levels than seating areas, for example. Lastly, appliances such as gas stoves can also increase carbon dioxide levels in indoor environments.

Air Particulates

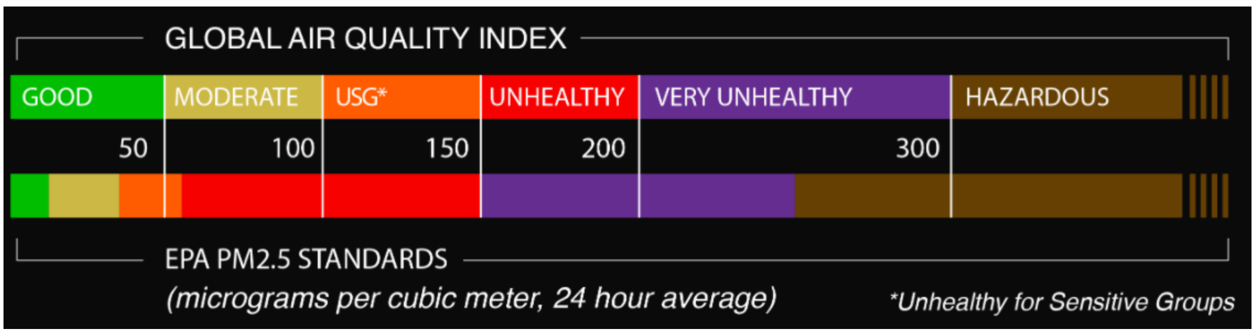
Particulate matter (PM) is a mixture of solid and liquid particles in the air. They can vary in shape, size, and composition. The particulates that were measured in this study are $PM_{2.5}$, which is of special concern to the Environmental Protection Agency. $PM_{2.5}$ are particles less than 10 micrometers in diameter. They are at risk of being inhaled, and the “particles can affect the lungs and, in some cases, cause serious health effects” (United States Environmental Protection Agency, 2020a, para. 1). While particulates are not incredibly harmful immediately, over time they can cause extensive symptoms (Enomoto, Tierney, & Nozaki, 2008). The World Health Organization (WHO) “estimates that particulate matter (PM) air pollution contributes to approximately 800,000 premature deaths each year, ranking it the 13th leading cause of mortality worldwide” (Anderson, Thundiyil, & Stolbach, 2012, p. 1).

Side Effects. Some health effects of inhalable particles are: “irritation of the eyes, nose, and throat, aggravation of coronary and respiratory disease symptoms, and premature death in people with heart or lung disease” (United States Environmental Protection Agency, 2020a, para. 2). Coughing and sneezing can also be side effects and with continued exposure to these particles, can worsen (Government of West Australia, 2020).

Acceptable Levels. The United States Environmental Protection Agency established $PM_{2.5}$ standards beginning in 1987. In 2012, an update was made to the National Ambient Air Quality Standard, which lowered the annual maximum level of $PM_{2.5}$ from 15 μg/m^3 to 12 μg/m^3 (United States Environmental Protection Agency, 2019). The annual level was introduced earlier in the Clean Air Act. Figure 4 displays the PPM ranges of $PM_{2.5}$ and the dangers that can be associated with the ranges.

Figure 4

PM 2.5 Hazard Levels



Note. Adapted from "The Weight of Numbers: Air Pollution and PM2.5" by AirVIsual, 2020, para. 8 (https://undark.org/breathtaking/).

Overall, if the measurement of $PM_{2.5}$ is under 50 μg/m^3, most of the population will not be affected, including those more prone to health issues (AirVisual, 2020). The $PM_{2.5}$ hazard categories are the bottom bars in Figure 4—the top features the general global standards.

Sources of Particulates. While most of inhalable air particulates come from outdoor air, there are some indoor sources. Indoor particles can be generated through cooking, smoking, and combustion activities such as usage of fireplaces (United States Environmental Protection Agency, 2020a). However, mitigation of these particles is possible by utilizing vented stoves, fireplaces, and space heaters, using appropriate wood for stoves and fireplaces, and venting all appropriate areas.

Air Comfort Parameters

Temperature

Thermal comfort is difficult to achieve, because every single individual has their own preference. However, it is often defined as when "a person feels neither too cold nor too warm" (Green Education Foundation, 2018, para. 1). The perception of indoor environments can vary from person to person. The general rule of thumb is to deliver air to rooms at "around 69 to 73 degrees F" (Green Education Foundation, 2018, para. 3). However, ASHRAE 55 comfort parameters display that a more appropriate range would be around 71 to 82 degrees Fahrenheit, depending on the activity and clothing levels of the occupants (American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2017). If the temperature goes beyond these parameters, occupants can become stressed, feel lethargic, and be distracted from their work (Xiong et al., 2015). The temperature is based on the system effectiveness but can also be affected by solar radiation effects—occupants near windows exposed to direct sunlight may feel warmer than occupants sitting in the center of the building. Overall, the thermal environment directly affects productivity levels and human health (Charalampopoulos, 2019).

Humidity

Humidity control is not only important for occupant comfort, but occupant health as well (Razjouyan et al., 2020). If there is too much humidity, occupants can report the air "feeling stuffy" (Green Education Foundation, 2018). In general, inhalation of air "will cause a cooling of the mucous membranes in the upper respiratory tract", so when there is high humidity this cooling of the membranes does not occur, leading occupants to perceive the air as "stuffy"

(Toftum & Fanger, 1999, p. 643). But high humidity levels can also encourage the growth of bacteria and fungi, which in large amounts can affect the health of occupants if exposed. On the other hand, low humidity levels are heavily associated with dry sinuses, dry skin, and dry throats. It also causes an increase in static discharge when people touch surfaces (Green Education Foundation, 2018). These symptoms are more noticeable because they directly affect an occupant's wellbeing.

Occupant Comfort

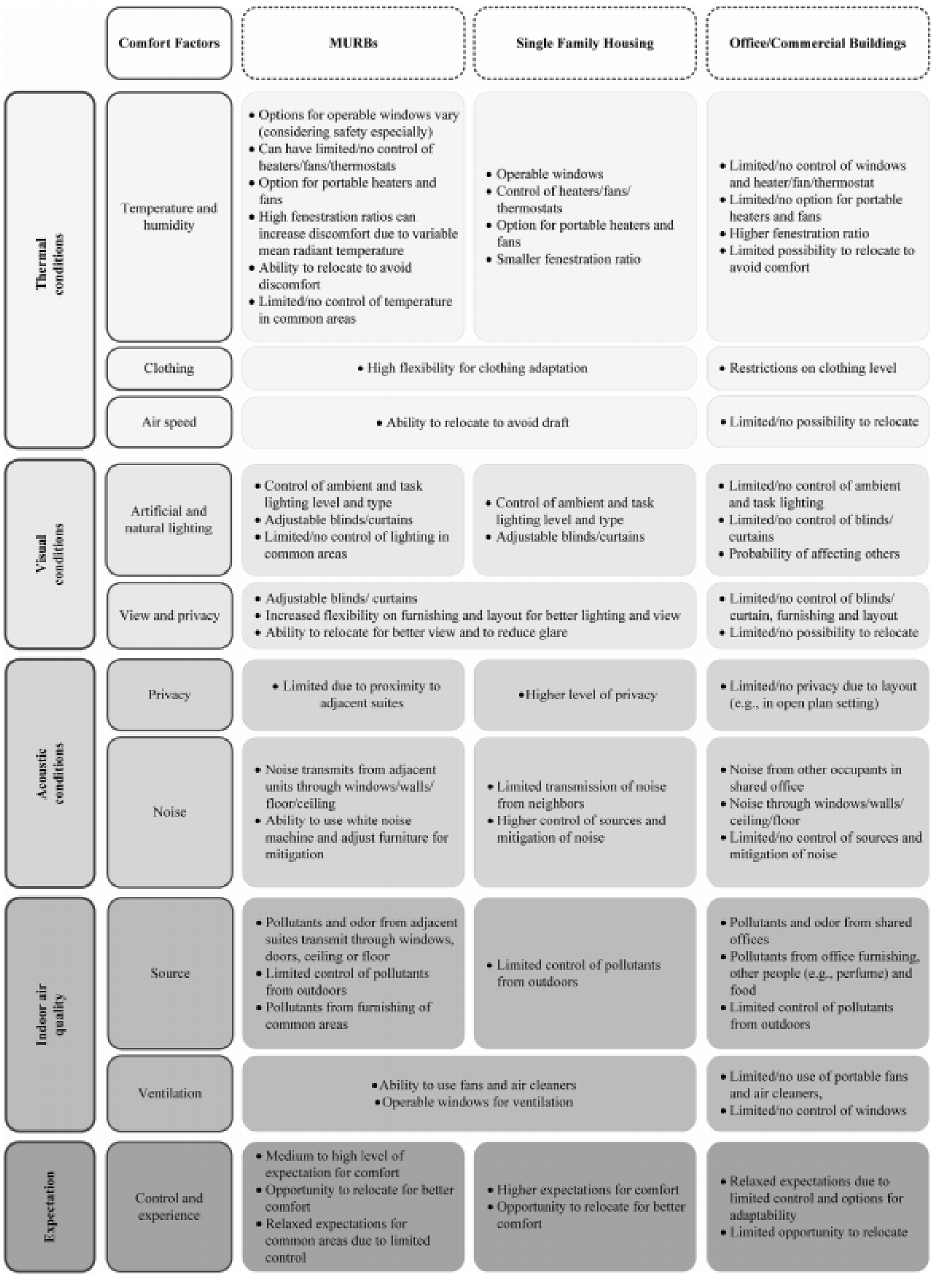
Comfort in Residential Buildings

Designers have become more aware of the importance of indoor environmental quality, but studies often have only looked at commercial buildings or single-family homes, which are accompanied by more control over one's indoor environment. However, multi-unit residential buildings have not been studied as much, which is surprising considering they have "several distinctive design and control features that differentiate from single-family homes with regards to comfort" (Andargie et al., 2019, p. 1). A recent study by Asif et al. (2018) did investigate indoor temperature, relative humidity, and carbon dioxide levels in academic buildings with different systems. Asif et al. (2018) observe that "educational institutes are the places where students and teachers spend more time as compared to any other indoor environment after homes making them the most important indoor environment to be studied" (p. 84). However, one main concern with multi-unit buildings is the indoor temperature difference the stack effect can have on certain units in the building. In colder seasons, warm air may rise more to the top units and bring with it odors and contaminants from lower units. This travel of contaminants is nearly impossible to contain in multi-unit buildings, as hallways easily can be infiltrated whenever an occupant opens their apartment door (Andargie et al., 2019, p. 2). Along with acoustic comfort and overall unit size, it is clear that in multi-unit residential buildings, it is difficult to maintain good indoor air and environmental quality.

A comparison of the expected amenities and functions relating to a building type is shown in Figure 5. Figure 5 shows the difference in comfort factors for each application and further highlights why commercial building studies cannot be applied directly to multi-unit residences.

Figure 5

IAQ Factors for Different Occupancies



	Comfort Factors	MURBs	Single Family Housing	Office/Commercial Buildings
Thermal conditions	Temperature and humidity	• Options for operable windows vary (considering safety especially) • Can have limited/no control of heaters/fans/thermostats • Option for portable heaters and fans • High fenestration ratios can increase discomfort due to variable mean radiant temperature • Ability to relocate to avoid discomfort • Limited/no control of temperature in common areas	• Operable windows • Control of heaters/fans/ thermostats • Option for portable heaters and fans • Smaller fenestration ratio	• Limited/no control of windows and heater/fan/thermostat • Limited/no option for portable heaters and fans • Higher fenestration ratio • Limited possibility to relocate to avoid comfort
	Clothing	• High flexibility for clothing adaptation		• Restrictions on clothing level
	Air speed	• Ability to relocate to avoid draft		• Limited/no possibility to relocate
Visual conditions	Artificial and natural lighting	• Control of ambient and task lighting level and type • Adjustable blinds/curtains • Limited/no control of lighting in common areas	• Control of ambient and task lighting level and type • Adjustable blinds/curtains	• Limited/no control of ambient and task lighting • Limited/no control of blinds/ curtains • Probability of affecting others
	View and privacy	• Adjustable blinds/ curtains • Increased flexibility on furnishing and layout for better lighting and view • Ability to relocate for better view and to reduce glare		• Limited/no control of blinds/ curtain, furnishing and layout • Limited/no possibility to relocate
Acoustic conditions	Privacy	• Limited due to proximity to adjacent suites	• Higher level of privacy	• Limited/no privacy due to layout (e.g., in open plan setting)
	Noise	• Noise transmits from adjacent units through windows/walls/ floor/ceiling • Ability to use white noise machine and adjust furniture for mitigation	• Limited transmission of noise from neighbors • Higher control of sources and mitigation of noise	• Noise from other occupants in shared office • Noise through windows/walls/ ceiling/floor • Limited/no control of sources and mitigation of noise
Indoor air quality	Source	• Pollutants and odor from adjacent suites transmit through windows, doors, ceiling or floor • Limited control of pollutants from outdoors • Pollutants from furnishing of common areas	• Limited control of pollutants from outdoors	• Pollutants and odor from shared offices • Pollutants from office furnishing, other people (e.g., perfume) and food • Limited control of pollutants from outdoors
	Ventilation	• Ability to use fans and air cleaners • Operable windows for ventilation		• Limited/no use of portable fans and air cleaners, • Limited/no control of windows
Expectation	Control and experience	• Medium to high level of expectation for comfort • Opportunity to relocate for better comfort • Relaxed expectations for common areas due to limited control	• Higher expectations for comfort • Opportunity to relocate for better comfort	• Relaxed expectations due to limited control and options for adaptability • Limited opportunity to relocate

Note. Adapted from "A Review of Factors Affecting Occupant Comfort in Multi-Unit Residential Buildings" by M. Andargie, M. Touchie, and W. O'Brien, 2019, *Building and Environment, 160,* p. 3 (https://doi.org/10.1016/j.buildenv.2019.106182).

The four factors that contribute to overall comfort that are highlighted in this study are thermal comfort, visual comfort, acoustic comfort, and IAQ satisfaction (Andargie et al., 2019, p. 4). Most studies often focus on just one of these factors, but multifactor studies produce the best results.

Overall, the need for additional multiunit residential building indoor environmental quality studies is great. Andargie et al. (2019) state that “IEQ in residential buildings can also affect the productivity of occupants who do not work from home. Some studies have found out that poor indoor environmental conditions can impact sleep quality”, which in turn can affect their performance at their job (p. 5). There is a demand for quality environments not only in workplaces, but in homes and dwellings—the lack of IAQ studies on multiunit buildings shows a need for additional research (Mendell et al., 2002).

Methodology

Buildings Studied

Margaret Loock Hall

Location. Margaret Loock Hall is located on the Milwaukee School of Engineering campus at 324 E. Juneau Avenue. It is located in Milwaukee, Wisconsin, and is in the 53202 zip code area. Each floor can house up to 40 students, with 10 dormitory floors. The twelfth floor is a community lounge, and the first floor has study areas and meeting rooms.

Basis of Design. The area where the measurements were taken is located on the ground floor of the building. There is a small community and study area near the entrance, and it offers a printing station and seating for students. The area was selected because it is the only community area in the building for occupants currently available. The other community area in the building is the twelfth floor longue, however that floor has been temporarily converted into a

COVID-19 isolation floor. Community areas were selected in order to respect the privacy and identity of building occupants, and to prevent exposure to COVID-19 when taking measurements. There are operable windows in this area, and a number of times when air quality measurements were being taken, it was noted that occupants had left windows in the area open.

The building HVAC system is simple—the temperature is controlled entirely by a condenser unit that is located directly outside of the building when cooling is required in the area. No adjustments were made to the system for COVID-19. There are no variable air volume (VAV) dampers in the system, just constant air whenever the setpoint is changed on the thermostat. Because of this design, the control of the room temperature may be more difficult to achieve and hold. Constant air means that the rate of air coming into the space cannot be adjusted, and so the control is more difficult to achieve ideal temperatures. For heating, the ground floor has hydronic baseboard heating around the area. There is no humidity control within the system, which can be a comfort issue. The system does have MERV (minimum efficiency reporting value) filters, which are changed out on a regular basis by building maintenance. The MERV filters are uniform throughout all of the campus buildings and are intended to reduce the amount of air particulates in the indoor environment. The MERV filter rating utilized is a MERV-8, typical of residence buildings. Theoretically, the MERV filters utilized in the building can remove up to 90% of air particulates that come in through the outdoor air being brought into the building (United States Environmental Protection Agency, 2021).

Grohmann Tower

Location. The Grohmann Tower is located on the Milwaukee School of Engineering campus at 233 E. Juneau Avenue. It is located in Milwaukee, Wisconsin, and is in the 53202 zip code area. This building offers studio, one-bedroom, and two-bedroom apartments for students.

The fourth floor is a community lounge, with conference rooms and study areas throughout. The first three floors house a parking garage. The fourth floor was selected because it is the only community area in the building for occupants. Community areas were selected in order to respect the privacy and identity of building occupants, and to prevent exposure to COVID-19 when taking measurements.

Basis of Design. The areas the measurements were taken are located on the fourth floor of the building. This floor has general study areas for the students, along with several conference rooms that host events. The conference rooms are also used for classes and by students for a study area. This floor does not have operable windows, but there is an exit leading to an outside patio.

The floor is served by a small air handling unit, which is located in a mechanical room on the same floor. There are variable air volume boxes (VAVs) located throughout the floor to provide secondary heating. These VAV boxes are heated through electrical coils rather than hot water. Each conference room has its own VAV box, while the study area is served by multiple boxes. This allows for more user control over the indoor environment without disrupting conditions in other areas. There is no humidity control within the system, which can be a comfort issue. No adjustments were made to the system for COVID-19. The system does have MERV (minimum efficiency reporting value) filters, which are changed out on a regular basis by building maintenance. The MERV filters are uniform throughout all of the campus buildings and are intended to reduce the amount of air particulates in the indoor environment. The MERV filter rating utilized is a MERV-8, typical of residence buildings. Theoretically, the MERV filters utilized in the building can remove up to 90% of air particulates that come in through the outdoor air being brought into the building (United States Environmental Protection Agency, 2021).

Data Collection

Times

The times that the field measurements were taken ranged from noon to early afternoon—no measurements were taken in the early morning or at night. This time range was determined by visiting each building before taking measurements and noting when the most people and traffic occurred in the areas. Because this study occurred during the COVID-19 pandemic, there were not as many people occupying community spaces as there would be without restrictions, but nevertheless, there were always several people in each area when measurements were taken. Occupants were seated most times so the activity level was mainly low, but oftentimes, there would be foot traffic through the areas as well.

Areas

The areas that measurements were taken are shown in Appendix A. Because of the size of the public space, the Grohmann Tower had three separate areas, while Margaret Loock Hall only had one. The meter when sampling was placed on tables or on seating to best represent a breathing zone of a building occupant. Meters also were not placed directly next to any air terminals to ensure that the space conditions were not influenced by these possible contaminations (Fernald, 2017, p. 43). All data measurements taken from each area are in Appendix D.

Outdoor Weather

The study took place in the winter of 2020-2021. On average, the outdoor air temperature was between 10-to-30-degrees Fahrenheit.

Equipment

Particulate Meter. The meter utilized to measure the $PM_{2.5}$ levels was the HoldPeak PM2.5 Tester (HP-5800D). It is a portable device that measures particulates changes in indoor environments. The device has preset hazard levels to indicate a healthy environment or not. The Holdpeak measures both $PM_{2.5}$ and PM_{10} in units of $\mu g/m^3$. Throughout the entire study, the level never reached one that qualified as a health concern (HoldPeak, 2018).

Temperature, Relative Humidity, and Carbon Dioxide Meter. The device utilized to measure the room temperature, relative humidity, and carbon dioxide levels was the AZ Instrument Corporation 77597 CO2, CO, Temperature and Relative Humidity Recorder (AZ Instrumental Corporation, 2017). It also can measure carbon monoxide as well, but that was not within the scope of the study. The device automatically warms up for a period of 30 seconds after initial power-on. The precision for the CO_2 levels recorded on the meter are 1 ppm, while the precision for relative humidity is 0.1% (Fernald, 2017, p. 44).

Survey

Participant Selection

The participant demographic consisted of residents of either Margaret Loock Hall or Grohmann Tower. Anybody who fit this description was asked to participate in the survey because the goal was to get an accurate representation of MSOE student residents. The only restriction was that any resident under the age of eighteen or any resident who could not consent on their own behalf would not be asked to participate. The reason for this restriction was because of policies established by the Milwaukee School of Engineering’s Institutional Review Board (IRB) (Milwaukee School of Engineering, 2020). IRB approval was required before surveys could be distributed to residents. Resident participation was entirely voluntary.

Survey Selection

To adhere to MSOE IRB policies, the survey selected was a validated, licensed survey from a recognized third-party organization. As mentioned earlier, the BUS Methodology survey was used. The BUS Methodology survey measures how building occupants perceive the indoor environmental quality in a building. It asks about how the temperature, humidity, and particulates in rooms affect their behavior. It also asks how general items pertaining to air and environmental quality affect occupant satisfaction. The BUS Methodology survey is validated to not contain leading questions—questions that may lead participants towards a certain, biased answer. Each question is general, allowing for it to be applied to many building applications. Because of this, it ensures that the resident responses to the MSOE residence hall survey are not skewed.

Because of the BUS license, the text of the survey cannot be shared within this capstone study, so general explanations will be provided. The survey questions all attempted to determine the occupant satisfaction within the buildings. These questions covered aspects such as “thermal comfort, ventilation, indoor air quality, lighting, personal control, noise, space, design, and image” (United Kingdom Green Building Council, 2013). Thermal comfort included perceived temperature, humidity, and stuffiness. Questions pertaining to thermal comfort asked the same questions for both the hot and cold season. Personal control included perceived control of temperature (e.g., available thermostats), lighting, ventilation, and noise. Any questions about noise asked about the disturbance of noise from outside of the building and from neighbors within the vicinity. The space, design, and image questions specifically asked about the aesthetics of the building, both inside and outside. This collection of variables and aspects associated with the BUS Methodology allows researchers to qualitatively determine the occupant satisfaction with both IAQ and IEQ.

Survey Distribution and Collection

Before the survey was distributed to participants, an initial email was sent to residents of Margaret Loock Hall and Grohman Tower, asking if they would be interested in participating in a voluntary survey. The text of the email distributed to residents is included in Appendix B. The initial email was sent out by the principal investigator of this study, Nora Ureche, a graduate student, rather than by MSOE residence hall administrators, in accordance with MSOE IRB policy. If a professor or administrator contacted any resident about the survey, it might have been perceived that participation was mandated because of the imbalance of power between students and MSOE officials. By having the author of this report, a student, engage the interest of participants, nobody felt coerced to participate.

There were thirty-five participants who were interested in participating based on the responses to the first email that was sent out. A second email with access to the survey on-line link was then sent out to those who responded, again from the author of this report. The second email distributed to interested participants is included in Appendix C. Twenty-seven students participated fully, and two students partially filled out the survey. Of the partial answers, only the first few questions were filled out, giving almost no data, and so the responses from these two participants were ignored.

In accordance with the IRB policies, volunteer anonymity was protected. The online survey program Qualtrics was utilized to distribute the survey, which has an anonymous link option. The only person who viewed the initial interest emails was the author of this report—however, she was unaware of who actually took the survey. There are no means of tracking answers to specific individuals. In summary, the survey was virtually distributed to interested participants in an anonymous manner.

Data Analysis

Normality, Randomness, Independence

In order to accurately analyze data statistically, the data sets need to be determined first to be normal, random, and independent. In this project, the data sets feature measurement data for temperature, relative humidity, carbon dioxide, and particulate matter in Margaret Loock Hall and in Grohmann Tower. It is important to determine the type of data before testing because certain tests can be violated if assumptions of data are not met. This capstone features an analysis of parametric data, which “provide more accurate findings than the nonparametric tests, but they are based upon one common assumption of normality” (Verma & Abdel-Salam, 2019, p. 1). By plotting the data, normal distribution can be confirmed. Randomness and independence are also important in ensuring that the data points are not skewed or biased. Randomness ensures that the data has been taken from a random sample (Verma & Abdel-Salam, 2019, p. 74). Lastly, various parametric tests require independence in the data set, which assumes that no single data point has influence over another data point in the set (Verma, 2019, p. 82). These parametric assumptions, if fulfilled, create more robust statistical analysis results. To display the data sets fulfilling these assumptions in this capstone study, plots were created with the Minitab program and are in the Appendix.

Tukey’s Test

Tukey’s Multiple Comparison Test allows for multiple samples to be compared all at the same time. The procedure “allows the simultaneous formation of prespecified confidence intervals for all paired comparisons using the Student t-distribution” (Reddy, 2011, p. 118).

Instead of doing individual hypothesis tests between all sample sets, the Tukey test allows all comparisons to be made within one statistical analysis. It also provides more information than an ANOVA test, which allows for multiple sample testing as well; however, when the null hypothesis is rejected in ANOVA, the exact cause for that result is not identified (Reddy, 2011, p. 118). The Minitab program was utilized for this analysis, with a Tukey test performed for temperature in all areas, relative humidity in all areas, carbon dioxide in all areas, and particulate levels in all areas. The results of these analyses are in the Appendix (see Appendices E through N for all statistical analysis associated with this project).

Hypothesis Test

A hypothesis test of two independent samples allows for a statistical analysis of the comparisons between the two sample sets. It determines whether or not sample means are statistically significant in their differences or not. This capstone study utilized the Minitab program for this test and the results can be seen in the Appendix. The samples tested were the carbon dioxide levels in Margaret Loock Residence Hall compared to the three areas in Grohmann Tower.

Data Formatting

In the survey results, participants selected neutral answers if they were unsure of their response or did not know how to respond to the question. An example of this occurring was when participants were asked to rate the comfort levels of the indoor areas in the summertime; many participants did not reside in the buildings during the summer and thus had no accurate perceptions of the indoor environment. These replies were taken into consideration and the questions that pertained to the summer season were not considered in the results of this capstone study to avoid noise in the data that would hide the significance of the winter responses. Further data formatting was then applied to the field measurements to create a better statistical analysis.

There was a total of 50 field measurements taken in each area for the IAQ data. In the statistical analysis, there are only 22 data points in each sample set because of repetition. These repeating data points were averaged into one data point to prevent skew in the normal distribution of data. Repeating data points were taken in the first place to minimize the variance in the data set. There also is a gap between the collection dates from February 4th to February 15th due to the principal investigator not being within accessible distance to the campus during this time.

Results and Discussion

Tukey Tests

The Tukey temperature results concluded that the only significant difference in the mean temperatures measured in the test areas was between the mean temperature of Grohmann Tower Area 1 (GR1) and Grohmann Tower Area 2 (GR2). For a visual of the proximity of these areas, refer to Appendix A for the floor plans. Both did not share a letter in the analysis, indicating significant difference. The lettering method Minitab outputs to determine this significance is based on the 95% confidence intervals between sets of data. Those with a simultaneous 95% confidence interval that contains the numerical value zero will then share a letter, which indicates similarity. Those that do not have zero contained are considered significantly different from each other. This proves that areas that are within the interior of a floor have much different temperature requirements and factors than areas exposed to glass curtains. GR1 was, on average, three whole degrees cooler than GR2. Considering the times the measurements were taken, it can be safely assumed that GR2 was more difficult to cool because of excessive solar heat from the glass curtain during the middle of the day.

The Tukey relative humidity results concluded that there were no significant differences between any of the areas. All areas shared the same letter in the analysis, indicating no significant differences. The relative humidity means ranged from 13 to 15 percent relative humidity, which is very low when considering comfort levels for occupants. Margaret Loock Hall (MLH) had the highest average at 15.61%.

The Tukey carbon dioxide results concluded that there was a significant difference between MLH's mean carbon dioxide levels and all areas of the Grohmann Tower. MLH had a letter that was not shared by the other areas, indicating significant difference. Once again, these letters are based on the simultaneous 95% confidence intervals between each area, and those that share a letter have a confidence interval that contains the numerical value of zero. See Appendix L for the "Tukey Simultaneous 95% CIs" graph that visually displays this result. The means of GR1, GR2, and the Grohmann Tower Conference Room (GRC) all were around the 490 ppm to 515 ppm range. MLH had a mean carbon dioxide level of only 438.54 ppm. There is a difference of almost 50 ppm between buildings, though all areas had similar amounts of occupants in the space during measurement. MLH has operable windows, and it was noted during measurements that they would be open on occasion. The main entrance to the building is also located near the MLH area. Meanwhile, all areas measured in Grohmann Tower were on the fourth floor, away from any main entrances. Grohmann Tower is also a more modern building, with a tighter building envelope. This carbon dioxide analysis proved that with tighter building envelopes comes a greater need to have robust ventilation systems. MLH's natural ventilation through the building envelope allows it to have lower levels of carbon dioxide.

The Tukey air particulate results concluded that there were no significant differences between any of the areas. All areas shared the same letter in the analysis, indicating no significant differences. Air particulate levels ranged from 2.8 $\mu g/m^3$ to 3.5 $\mu g/m^3$, both very low and healthy levels of particulates. MLH did have the highest average at 3.469 $\mu g/m^3$.

Hypothesis Tests

To verify and further support the Tukey carbon dioxide test results, two sample hypothesis tests were conducted between MLH and each Grohmann Tower area individually.

The null hypothesis for the first test is that the mean values of MLH and GR1 are the same—this is the default hypothesis that would be accepted if the significance value (i.e., p-value) exceeds 0.05. The alternative hypothesis proposed is that MLH and GR1 have significantly different carbon dioxide levels. Since the test output a p-value of less than 0.05, the alternative hypothesis is accepted and confirms that MLH carbon dioxide levels differ significantly from those in GR1.

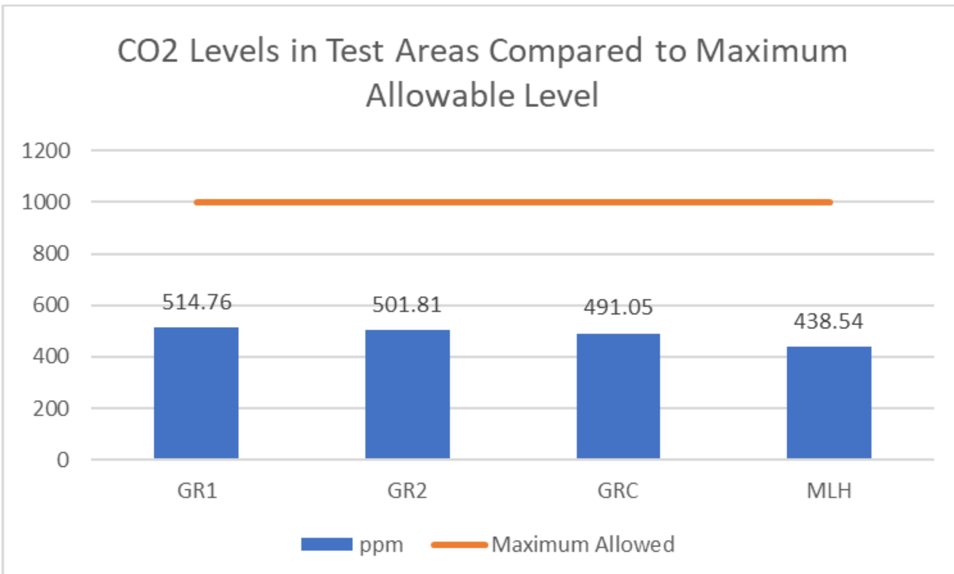
The null hypothesis for the second test is that the means of MLH and GR2 are the same. The alternative hypothesis proposed is that MLH and GR2 have significantly different carbon dioxide levels. Since the test output a p-value of less than 0.05, the alternative hypothesis is accepted and confirms that MLH carbon dioxide level do differ significantly from those at GR2.

Lastly, the null hypothesis for the third test is that the means of MLH and GRC are the same. The alternative hypothesis proposed is that MLH and GRC have significantly different carbon dioxide levels. Since the test output a p-value of less than 0.05, the alternative hypothesis is accepted and confirms that MLH carbon dioxide levels do differ significantly from those in GRC.

These tests were performed to further support the Tukey results, but they also indicate that taken out of a group analysis on an individual level, the carbon dioxide levels are still significantly different and worth noting. Figure 6 displays the CO_2 data for each location, with respect to the maximum safe level.

Figure 6

Comparison of Measured Carbon Dioxide Levels to ASHRAE Standards



Note. Figure 6 depicts the average carbon dioxide levels of each test area in comparison to the maximum allowable level of 1000 ppm.

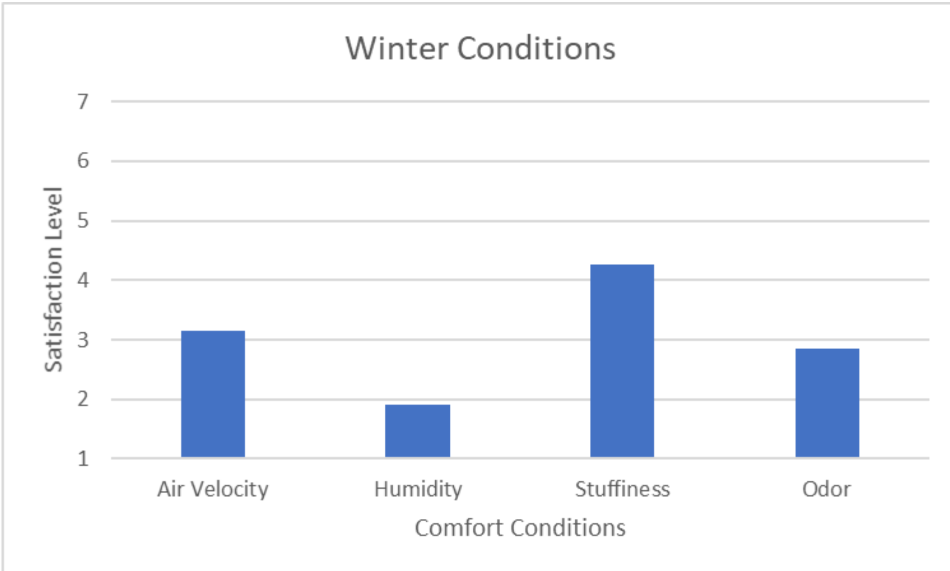
Figure 6 shows the mean values of carbon dioxide at the measured locations in relation to the cutoff for healthy levels (1000 ppm) discussed earlier. Neither building reached an unhealthy range of carbon dioxide levels, but it is important to note how the carbon dioxide levels in Grohmann Tower are significantly higher than those in Margaret Loock. Also noted earlier was that because of the COVID-19 pandemic, occupancy levels were already less than typical. The question these data pose is: if occupancy in the Grohmann Tower is at a normal range, would the carbon dioxide levels approach the unhealthy range? This capstone study's scope cannot provide an answer to this question; further research after the pandemic is recommended. Since Grohmann Tower is a modern building with a tight building envelope, carbon dioxide levels present in the common areas under conditions of normal occupancy should be tested at some future point.

Survey Results

While the questions that came from the BUS Methodology survey cannot be included in this capstone study, the results of certain questions are in Appendix O, without including the original question. Questions that were added on in addition to the licensed survey are also included. Overall, occupants were comfortable in both of the residence halls. Most of the participants spent their time studying in each of the respective areas, as well, indicating that these participants had lots of experience with the studied indoor environments. Figure 7 shows general satisfaction levels concerning comfort.

Figure 7

General Satisfactory Levels of Winter Indoor Conditions

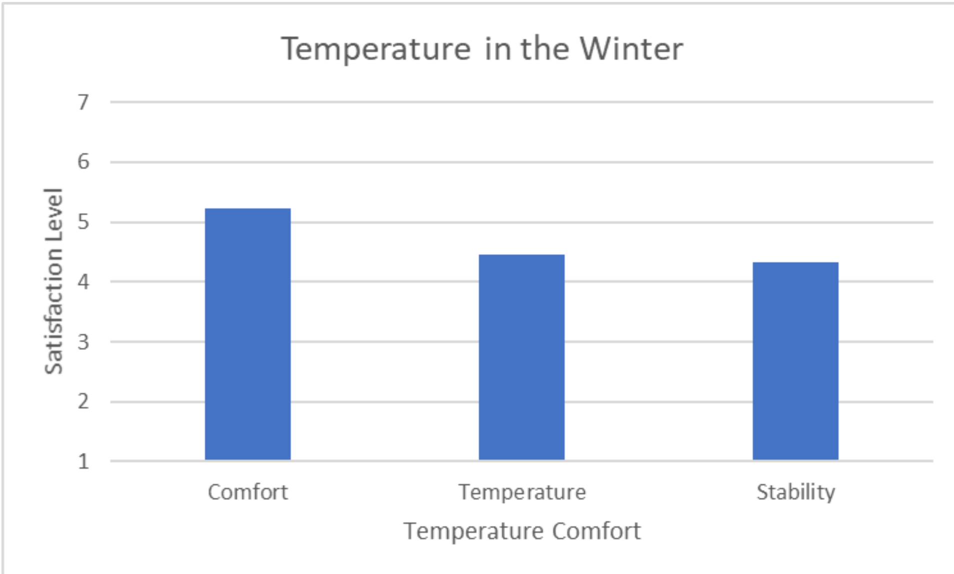


Note. Figure 7 depicts the average responses of participants when asked if these indoor air quality aspects were unsatisfactory (a score of 1) or satisfactory (a score of 7). The average satisfaction level for adequate humidity was 1.90.

The temperature conditions and general air conditions in the winter season were found to be satisfactory on all accounts aside from relative humidity. As seen in Figure 7, the humidity had a mean satisfaction score of only 1.90 on a scale of 1 to 7. Occupants complained about the air in both buildings being noticeably dry. Some even commented about this issue, stating that they would often have dry throats and even bloody noses in more severe cases. This was the main negative issue occupants identified. Figure 8 shows other satisfaction levels with the indoor temperature during the winter season, and satisfaction was high, further stressing an issue specifically with relative humidity.

Figure 8

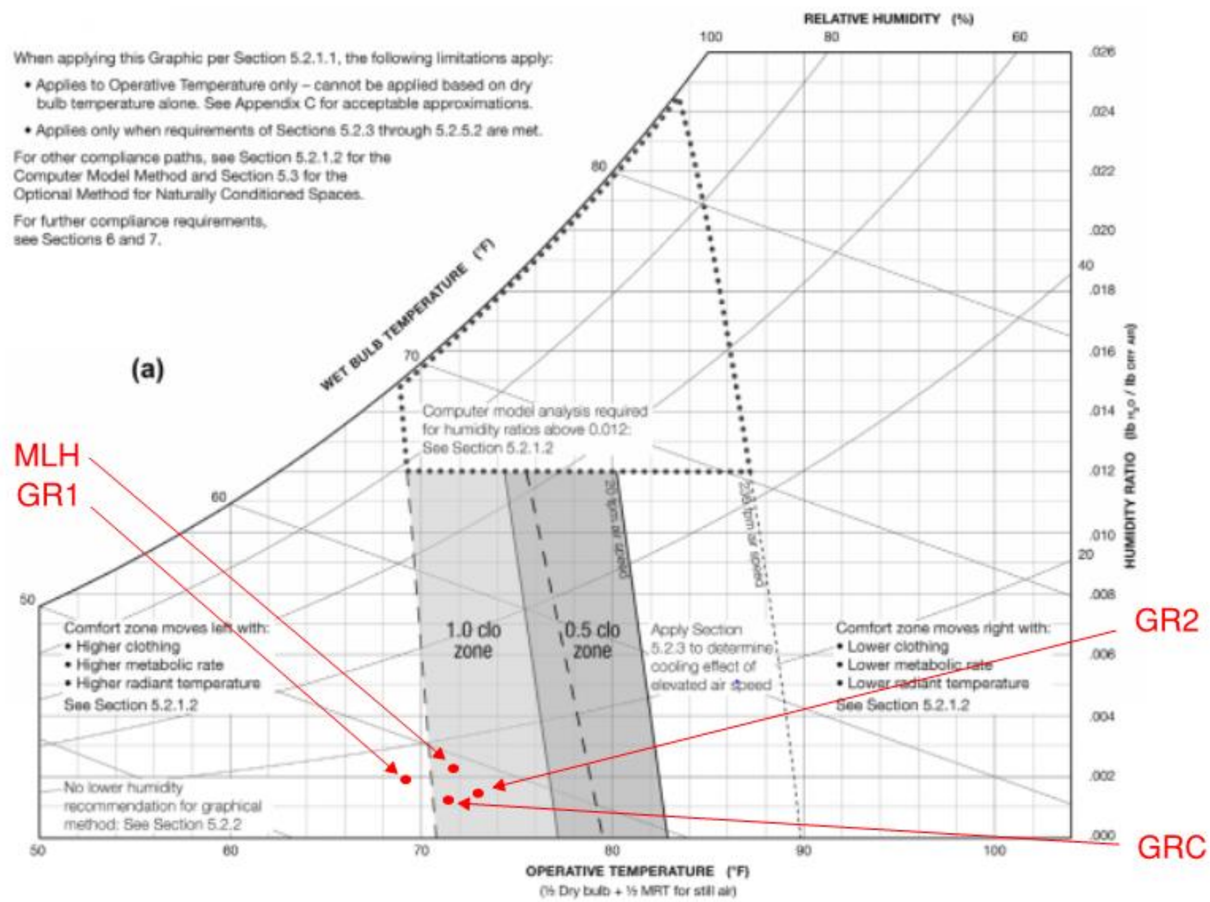
Satisfactory Levels of Indoor Air Temperature in the Winter



Note. Figure 8 displays the satisfaction levels of the overall comfort with respect to temperature, the actual temperature itself, and how stable the temperature stayed in the indoor environment.

Figure 9

Thermal Comfort Parameters ASHRAE 55 with Test Area Averages Plotted



Note. Adapted from "Standard 55 thermal environmental conditions for human occupancy" by The American Society of Heating, Refrigeration, and Air Conditioning Engineers, 2017, p. 6 (https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy).

Figure 9 depicts the thermal and humidity comfort standards from ASHRAE 55. While the operative temperature is the mean temperature between the wet and dry bulb temperature, for this visual it was assumed to be dry bulb temperature. The only concern where this would be an inaccurate representation of the comfort levels would be in areas where there is excessive solar heat gain. The averages of temperature and relative humidity from each test area were plotted over Figure 9. The highest relative humidity of the test areas was only 15%, which as seen in Figure 9, further confirms the uncomfortably low levels occupants acknowledged. While there is no minimum relative humidity assigned by ASHRAE 55, these combinations of temperatures and relative humidity levels are close to entering an area where occupant comfort is not achieved, with one area (GR1) being outside of the ideal parameters.

Conclusion and Recommendations

It is apparent that the occupants of either residence hall are aware of the indoor environment when it does not meet expected standards. The complaints about dry air in the survey are validated through the measured relative humidity levels, only peaking at a mean of 15 percent. The minimum level for relative humidity in the winter should be around 30 percent to maintain occupant comfort as a rule of thumb. Even when occupants are not educated and specialized in building design and operation, air quality factors can still be accurately perceived. Both clients and designers should approach projects with the end results in mind—more specifically, occupant comfort and satisfaction, as perception by occupants is accurate and consistent.

Tighter building envelopes will require more ventilation, as carbon dioxide levels were consistently higher in the Grohmann Tower than in the Margaret Loock Residence Hall. Ventilation systems should be carefully considered and designed if building envelopes are tight in order to successfully filter out carbon dioxide emissions. The rest of the air quality factors (temperature, relative humidity, and air particulates) showed no differentiating data regarding the building envelope. However, further research should go into these data relationships—while MLH did have the lowest carbon dioxide levels, it also had the highest relative humidity and air particulate levels. Whether these factors are tested for interrelationships between each other or are compared between different constructed buildings, further research into this can aid with understanding and further defining air quality. This odd trend with the MLH area may be correlation without causation concerning the relative humidity and air particulates, but the strength of its carbon dioxide level significance cannot be ignored. Looking further into this question may provide more insight into how or if air quality parameters correlate.

Air particulates in either building did not differentiate, nor did they reach a level that would be considered a public health hazard. MERV filters are an effective solution for filtering out $PM_{2.5}$ from outdoor air introduced into the building mechanical system.

It is important to anticipate solar heat gain in areas with lots of exposure, such as glass curtains or windows. Grohmann Tower Area 2 had a mean temperature three degrees higher than Area 1, the areas being separated by mere feet. While there are manual curtains located in this area, for future operation, automated daylighting shades can be installed to minimize solar heat gain without sacrificing any advantages of the natural light.

While this capstone study has developed several conclusions, it still had a small set of data and the collection process can be improved upon. Data points and repeating data points could have been taken more frequently than once a day, and further research can explore other times during the day and investigate the effects of time of day on air quality. There are many parameters in this capstone study that affect air quality that can be studied—location, season, time, frequency, etc. Any research exploring these variables can aid with further defining recommended practices for good air quality. If a future study like this were to be conducted, it is recommended that the data collection process be altered. If the building has a building automation system, or if there is better equipment that can continuously monitor an environment's air quality, these should be utilized to collect field measurements. This procedure would obtain more data points and repeating data points, creating a more accurate set of data, and the equipment would be more precise than the instantaneous handheld equipment utilized in this capstone study. To obtain the most representative data for an air quality study, buildings that are largely occupied by occupants daily should be considered for a more accurate representative study; this capstone study was restricted because of the COVID-19 pandemic and the associated restrictions put in place. However, further research can be put into contaminants, such as airborne viruses and bacteria, moving forward, instead of just analyzing comfort parameters, as this is a large public health issue related to air quality with little research.

References

AirVisual. (2020). *The weight of numbers: Air pollution and PM2.5*. https://undark.org/breathtaking/

American Society of Heating, Refrigeration, and Air Conditioning Engineers. (2017). Standard 55 thermal environmental conditions for human occupancy. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

American Society of Heating, Refrigeration, and Air Conditioning Engineers. (2019a). Standards 61.1 and 62.2. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

American Society of Heating, Refrigeration, and Air Conditioning Engineers. (2019b). *Ventilation for acceptable indoor air quality (62.1).*

Andargie, M.S., Touchie, M., & O'Brien, W. (2019). A review of factors affecting occupant comfort in multi-unit residential buildings. *Building and Environment*, *160*, 1-14. https://doi.org/10.1016/j.buildenv.2019.106182

Anderson, J.O., Thundiyil, J.G., & Stelbach, A. (2012). Clearing the air: A review of the effects of particulate matter air pollution on human health. *Journal of Medical Toxicology*, *8*, 166-175. https://doi.org/10.1007/s13181-011-0203-1

Asif, A., Zeeshan, M., & Jahanzaib, M. (2018). Indoor temperature, relative humidity and CO2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems. *Building and Environment*, *133*, 83-90. https://doi.org/10.1016/j.buildenv.2018.01.042

AZ Instrumental Corporation. (2017). *CO2 & CO & temp. & RH recorder*. https://www.az-instrument.com.tw/en/product-616376/CO2-CO-Temp-RH-Recorder-77597-AZ.html

Bluyssen, P. (2009). *The indoor environment handbook: How to make buildings healthy and comfortable.* Routledge.

Charalampopoulos, I. (2019). A comparative sensitivity analysis of human thermal comfort indices with generalized additive models. *Theoretical and Applied Climatology, 137,* 1605-1622. https://doi.org/10.1007/s00704-019-02900-1

Enomoto, M., Tierney, W., & Nozaki, K. (2008). Risk of human health by particulate matter as a source of air pollution. *Journal of Toxicological Sciences, 33,* 251-267. https://doi.org/10.2131/jts.33.251

Fernald, H. (2017). *Relationship analysis between select indoor and outdoor pollutants in Milwaukee area offices.* [Master's thesis, Milwaukee School of Engineering]. MSOE Library Electronic Publications at MSOE. https://milwaukee.ent.sirsi.net/client/en_US/search/asset/362/0

Foggin, T. (2010). *Carbon dioxide in indoor air*. https://ncceh.ca/documents/practice-scenario/carbon-dioxide-indoor-air#:~:text=Indoor%20levels%20are%20usually%20higher,also%20increase%20CO2%20levels.

Government of Western Australia, Department of Health. (2020). *Health effects of dust*. https://www.healthywa.wa.gov.au/Articles/F_I/Health-effects-of-dust

Green Education Foundation. (2018). *Thermal comfort*. http://www.greeneducationfoundation.org/green-building-program-sub/learn-about-green-building/1239-thermal-comfort.html#:~:text=A%20lack%20of%20thermal%20comfort,with%20more%20than%20the%20temperature.

Greenguard. (2020). *SPOT solutions*. https://spot.ul.com/greenguard/

Greiner, T. (1991). *Indoor air quality: Carbon monoxide and carbon dioxide (AEN-125).* https://www.abe.iastate.edu/extension-and-outreach/indoor-air-quality-carbon-monoxide-and-carbon-dioxide-aen-125/

HoldPeak. (2018). *PM2.5 tester, digital portable air quality tester for PM2.5 HP-5800D.* https://www.holdpeak.com/pm2-5-tester-digital-portable-air-quality-tester-for-pm2-5-hp-5800d

International Code Council. (2015). *2015 IMC: International mechanical code.* Country Club Hills, IL: International Code Council.

International Code Council. (2018). *International building code.*

Janjua, S.Y., Sarker, P.K., & Biswas, W.K. (2020). Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings. *Journal of Environmental Management*, *264*. 1-13. https://doi.org/10.1016/j.jenvman.2020.110476

Kelly, W.E., Luke, B., & Wright, R.N. (Eds.) (2017). *Engineering for sustainable communities: Principles and practices*. ASCE.

Machado, C.M.L., Scarvarda, A., Vaccaro, G., Korzenowski, A.L., & Batista, E. (2015). Analysis of hospital's sustainability: Economical, environmental, and social lenses. Proceedings of the *2015 Industrial and Systems Engineering Research Conference*, 1-9. https://www.researchgate.net/profile/Catia_Lopes16/publication/309416372_Analysis_of_hospital's_sustainability_Economical_environmental_and_social_lenses/links/580f789108aef2ef97afe599/Analysis-of-hospitals-sustainability-Economical-environmental-and-soci

Mendell, M.J., Fisk, W.J., Kreiss, K., Levin, H., Alexander, D., Cain, W.S., Girman, J.R., Hines, C.J., Jensen, P.A., Milton, D.K., Rexroat, L.P., & Wallingford, K.M. (2002). Improving the health of workers in indoor environments: Priority research needs for a national occupational research agenda. *Public Health Matters, 92*, 1430-1440. https://doi.org/10.2105/ajph.92.9.1430

Milwaukee School of Engineering. (2020). *MSOE institutional review board (IRB).* https://libguides.msoe.edu/irb

Papajohn, D., Brinker, C., & El Asmar, M. (2017). MARS: Metaframework for assessing ratings of sustainability for buildings and infrastructure. *Journal of Management in Engineering, 33,* 04016026-1-04016026-21. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000478

Razjouyan, J., Lee, H., Gilligan, B., Lindberg, C., Nguyen, H., Canada, K., Burton, A., Sharafkhaneh, A., Srinivasan, K., Currim, F., Ram, S., Mehl, M., Goebel, N., Lunden, M., Bhangar, S., Heerwagen, J., Kampschroer, K., Sternberg, E.M., & Najafi, B. (2020). Wellbuilt for wellbeing: Controlling relative humidity in the workplace matters for our health. *Indoor Air, 30*, 167-179. https://doi.org/10.1111/ina.12618

Reddy, T. A. (2011). *Applied data analysis and modeling for energy engineers and scientists.* Springer Science and Business Media. https://doi.org/10.1007/978-1-4419-9613-8

Slaper, T.F. & Hall, T.J. (2011). *The triple bottom line: What is it and how does it work?* https://web.mit.edu/2.813/www/readings/TripleBottomLine.pdf

Spengler, J. (2001). Sick building syndrome studies and the compilation of normative and comparative values. *Indoor air quality handbook.* McGraw-Hill.

State of Wisconsin. (2021). *Administrative code*. https://docs.legis.wisconsin.gov/code

Svensson, G., Hogevold, N., Padin, C., Varela, J.C., & Sarstedt, M. (2018). Framing the triple bottom line approach: Direct and mediation effects between economic, social, and environmental elements. *Journal of Cleaner Production, 197*, 972-991. https://doi.org/10.1016/j.jclepro.2018.06.226

Tham, K. (2016). Indoor air quality and its effects on humans--a review of challenges and developments in the last 30 years. *Energy and Buildings, 130*, 637-650. https://doi.org/10.1016/j.enbuild.2016.08.071

Toftum, J., & Fanger, O. (1999). Air humidity requirements for human comfort (SE-99-5-1). *ASHRAE Transactions, 105*, 641-647.

United Kingdom Green Building Council. (2013). *Pinpointing: BUS methodology*. https://www.ukgbc.org/sites/default/files/Pinpointing_BUS_methodology.pdf

United States Environmental Protection Agency. (2019). *What are the air quality standards for PM*. https://www3.epa.gov/region1/airquality/pm-aq-standards.html

United States Environmental Protection Agency. (2020a). *Indoor particulate matter*. https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter

United States Environmental Protection Agency. (2020b). *Milestones in EPA's air quality research history*. https://www.epa.gov/research/milestones-epas-air-quality-research-history

United States Environmental Protection Agency. (2020c). *Our mission and what we do*. https://www.epa.gov/aboutepa/our-mission-and-what-we-do#:~:text=The%20mission%20of%20EPA%20is%20to%20protect%20human%20health%20and%20the%20environment.

United States Environmental Protection Agency. (2020d). *Summary of the clean air act*. https://www.epa.gov/laws-regulations/summary-clean-air-act

United States Environmental Protection Agency. (2021). *What is a MERV rating?* https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1

U.S. Green Building Council. (2016). *Checklist: LEED v4 for building design and construction*. https://www.usgbc.org/resources/leed-v4-building-design-and-construction-checklist

U.S. Green Building Council. (2017). *Guide to LEED certification: Commercial: U.S. green building council*. https://www.usgbc.org/tools/leed-certification/commercial

U.S. Green Building Council. (2020). *Values, mission and vision*. https://www.usgbc.org/about/brand

Vafaeenasab, M.R., Morowatisharifabad, M.A., Ghaneian, M.T., Hajhosseini, M., & Ehrampoush, M.H. (2015). Assessment of sick building syndrome and its associating factors amoung nurses in the educational hospitals of Shahid Sadoughi University of Medical Sciences, Yazd, Iran. *Global Journal of Health Science, 7,* 247-253. https://doi.org/10.5539/gjhs.v7n2p247

Verma, J. & Abdel-Salam, G. (2019). *Testing statistical assumptions in research.* John Wiley & Sons Incorporated.

Wang, H. Z., Zhang, X., & Lu, W. (2018). Improving social sustainability in construction: Conceptual framework based on social network analysis. *Journal of Management in Engineering, 34,* 05018012-1-050:8012-9. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000607

Wang, S. (2001). *Handbook of air conditioning and refrigeration.* New York: McGraw-Hill.

WELL. (2020). *About us*. https://www.wellcertified.com/about-iwbi/

WELL. (2021). *WELL v2*. https://v2.wellcertified.com/wellv2/en/overview

Werkheiser, I.P., & Piso, Z. (2015). People work to sustain systems: A framework for understanding sustainability. *Journal of Water Resources Planning and Management, 141,* A4015002-1-A4015002-7. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000526

Wilson, A. (2005, April). Making the case for green building. *Environmental Building News, 14(4)*, 10-15. https://www.buildinggreen.com/feature/making-case-green-building

Wisconsin Department of Safety and Professional Services. (2018). *Chapter SPS 364: Heating, ventilating, and air conditioning.* https://docs.legis.wisconsin.gov/code/admin_code/sps/safety_and_buildings_and_environment/361_366/364

Wisconsin Department of Safety and Professional Services. (2021). *Protecting the public, promoting progress*. https://dsps.wi.gov/pages/Home.aspx

Wu, F. (2007). Improving indoor environmental quality for public health: Impediments and policy recommendations. *Environmental Health Perspectives, 115*, 953-964. https://doi.org/10.1289/ehp.8986

Xiong, J., Lian, Z., Zhou, X., You, J., & Lin, Y. (2015). Effects of temperature steps on human health and thermal comfort. *Building and Environment, 94*, 144-154. https://doi.org/10.1016/j.buildenv.2015.07.032

Young, W. (2018). *A study of student comfort and satisfaction within green residence halls.* (Publication No. 2053996682) [Master's thesis, Purdue University]. Proquest Dissertations and Thesis Global Database.

Appendix A – Floor Plans and Labelled Areas

Figure A1

Grohmann Tower Floor Plan

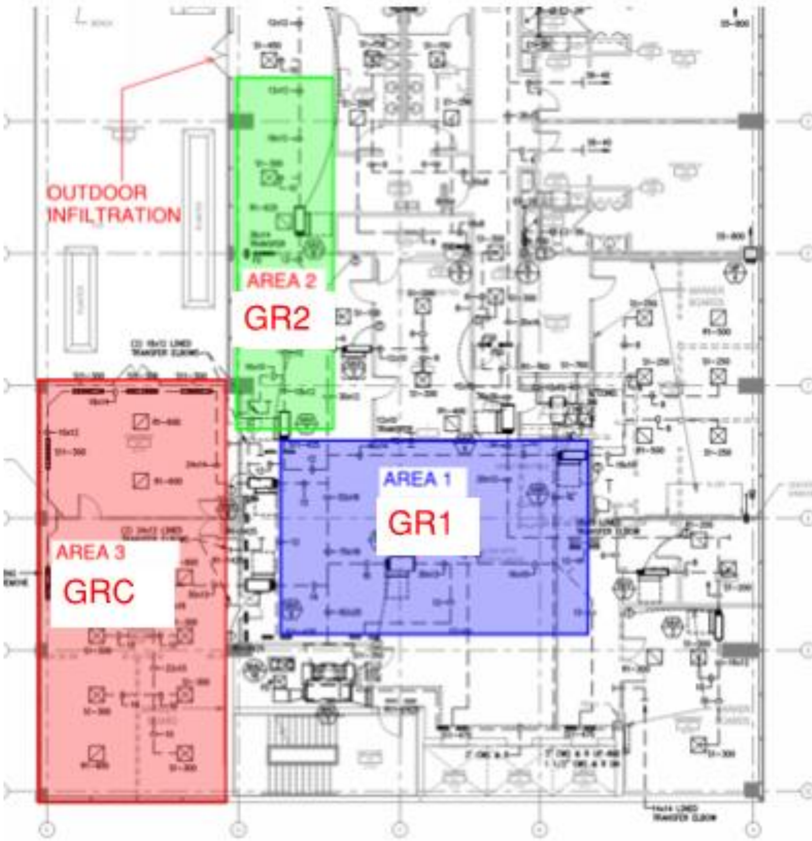
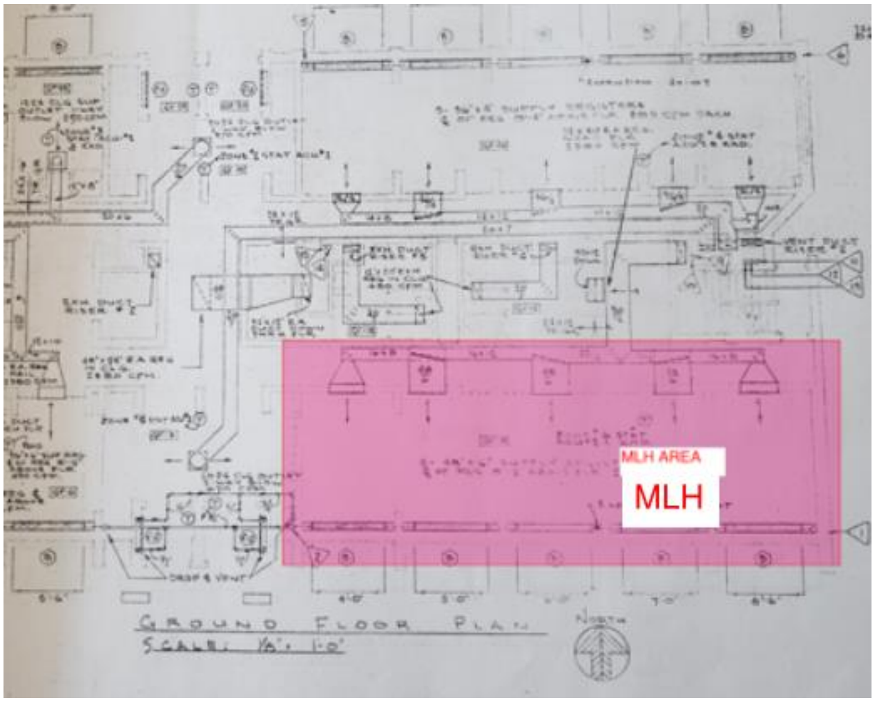


Figure A2

Margaret Loock Hall Floor Plan



Appendix B – Initial Email to Participants

Ureche, Nora

From: Ureche, Nora
Sent: Wednesday, December 9, 2020 6:55 PM
Subject: Voluntary Survey for MSOE Residents

MSOE Residents,
I am a graduate student studying the effects of indoor air quality in residential halls, and I am surveying anybody interested who lives in Margaret Loock Hall or the Grohmann Tower. You do need to be 18 years of age or above to participate.
The survey takes around 15 minutes maximum and is **completely voluntary.**
It asks questions about how often you are in the residential halls, how satisfactory the residential halls are, and your overall comfort level residing in the residential halls. The areas I am focusing on with your responses would be the public areas in both buildings, which is the first floor of MLH, and the fourth floor of the Tower.
Should you choose to participate in this survey, **all of your answers will be anonymous and confidential.**
If you are interested, please respond back to me and I will distribute the survey out at a later date! If you have any questions or concerns, please do not hesitate to contact me at urechenm@msoe.edu.

Appendix C – Second Email to Participants

Ureche, Nora

From:	Ureche, Nora
Sent:	Monday, December 14, 2020 9:41 AM
Subject:	Voluntary Survey

Survey Participant,
Thank you for taking the time to complete this survey for my study. Once again I will reiterate that **the survey is completely voluntary, and your responses will be anonymous and confidential**. Your responses should relate to your experiences with the public area in your respective residential hall. Should you choose not to complete this survey, there is no need to contact me and let me know, you simply can just not fill the survey out.
If you have any questions please contact me at urechenm@msoe.edu.

The anonymous link to the survey is provided below:
https://msoe.qualtrics.com/jfe/form/SV_5ywwxc6f8vnjtcx

If you feel a question does not apply to you, feel free to put "N/A" or if it is a scaled question, place the scale at a neutral 3 or 4! Not every comment box needs to be filled out, most of them are provided in case you would like to elaborate on your answer. Also, this is a licensed survey from the UK, so some spellings may look different—if you need elaboration on any question, once again you can always ask for clarification at urechenm@msoe.edu.

Appendix D – Tabulated Raw Data

Table D1

Grohmann Tower Area 1 IAQ Data

GROHMANN TOWER AREA 1					
Date	Time	Temperature [F]	RH [%]	CO2 [ppm]	PM2.5 [ug/m^3]
1/11/2021	3:30	68.36	18.2	514	2.9
1/12/2021	12:30	66.56	19.9	536	5.3
1/13/2021	12:00	70.16	21.1	561	3.7
1/14/2021	1:10	66.02	28.2	544	4.4
1/15/2021	12:30	67.64	24.4	578	2.8
1/18/2021	4:00	67.28	18	551	3
1/19/2021	12:45	65.3	20.5	563	3.4
1/20/2021	12:00	68.18	11.4	497	2.8
1/21/2021	1:00	72.14	15.2	460	1.6
1/22/2021	11:45	67.46	8.7	507	1.9
1/25/2021	1:10	68.18	16.6	492	3.1
1/26/2021	11:40	68.36	20.2	435	1.5
1/27/2021	12:25	68.72	12.3	499	3.9
1/28/2021	12:40	68.36	8.3	511	2.6
1/29/2021	12:00	68.36	11	534	3.7
2/1/2021	1:45	70.34	16.5	465	1.8
2/2/2021	11:50	69.26	17.7	485	2.8
2/3/2021	12:50	71.96	14.6	483	2.9
2/15/2021	1:25	71.96	4.9	551	3.2
2/15/2021	1:45	72.5	3.7	540	1.9
2/15/2021	2:10	73.58	3.8	590	2.2
2/15/2021	2:20	74.12	3.7	610	2
2/15/2021	2:35	73.58	4	639	2
2/15/2021	2:55	72.5	4.7	674	2
2/16/2021	2:15	75.02	7.2	521	1.9
2/16/2021	2:30	75.02	7.3	520	2.1
2/16/2021	2:40	74.84	7.3	521	1.7
2/16/2021	2:50	75.02	7.4	520	1.7
2/16/2021	3:00	74.84	7.4	519	2.1
2/16/2021	3:10	74.66	7.6	508	1.9
2/16/2021	3:20	74.48	8.5	512	1.9
2/16/2021	3:30	74.48	8.3	515	1.7
2/17/2021	1:35	72.5	8.2	492	2.7
2/17/2021	1:45	73.58	7.4	504	3.2
2/17/2021	1:55	73.94	7.7	501	2.8
2/17/2021	2:05	73.94	7.5	507	2.5
2/17/2021	2:15	74.12	7.5	509	2.4
2/17/2021	2:25	74.12	7.4	506	3.1
2/17/2021	2:35	73.76	7.6	512	2.8
2/18/2021	11:50	72.86	8.7	457	3.5
2/18/2021	12:05	73.94	7.6	460	3
2/18/2021	12:20	73.58	7.7	478	2.7
2/18/2021	12:35	74.12	7.4	486	2.6
2/18/2021	12:45	74.48	7.6	479	2.7
2/18/2021	12:55	74.84	7.3	493	2.5
2/18/2021	1:05	76.28	6.6	489	2.5
2/18/2021	1:15	76.46	6.5	507	2.4
2/18/2021	1:25	77.36	6.9	503	2.2
2/18/2021	1:35	77.36	6.7	504	2.3
2/18/2021	1:45	78.44	5.7	508	2.3

Table D2

Grohmann Tower Area 2 IAQ Data

GROHMANN TOWER AREA 2					
Date	Time	Temperature [F]	RH [%]	CO2 [ppm]	PM2.5 [ug/m^3]
1/11/2021	3:40	70.52	21.5	480	3
1/12/2021	12:35	70.16	20	463	5.1
1/13/2021	12:00	73.94	16.9	497	4.4
1/14/2021	1:15	70.34	25.2	536	5.1
1/15/2021	12:30	72.68	23.2	521	2.5
1/18/2021	4:10	69.98	18	489	3
1/19/2021	12:45	68.36	15.2	508	3.3
1/20/2021	12:05	71.06	10.7	497	3
1/21/2021	12:00	73.58	13.8	459	1.2
1/22/2021	11:45	73.94	9.1	516	1.7
1/25/2021	1:15	69.98	16	491	2.7
1/26/2021	11:45	70.16	19.2	435	1.3
1/27/2021	12:30	74.66	9.8	511	4.2
1/28/2021	12:45	75.56	6.8	513	3
1/29/2021	12:00	82.94	9.2	531	3.8
2/1/2021	1:50	72.68	16.7	486	1.7
2/2/2021	11:55	70.88	16.9	509	3.4
2/3/2021	12:55	78.62	10.6	487	3.1
2/15/2021	1:30	71.06	4.1	527	2.6
2/15/2021	1:50	73.04	4.4	542	2.6
2/15/2021	2:05	73.76	4.3	592	2.1
2/15/2021	2:20	74.48	3.7	631	2.1
2/15/2021	2:35	72.86	4	630	2.1
2/15/2021	2:55	73.58	4.9	682	2.2
2/16/2021	2:15	75.56	7.1	518	2
2/16/2021	2:30	74.66	7.4	515	2.1
2/16/2021	2:40	74.66	7.1	517	1.8
2/16/2021	2:50	75.02	8	519	1.8
2/16/2021	3:00	74.84	7.7	533	1.9
2/16/2021	3:10	74.3	7.5	505	2
2/16/2021	3:20	74.12	7.8	511	2
2/16/2021	3:30	74.12	10.5	514	1.6
2/17/2021	1:35	73.04	7.9	482	2.6
2/17/2021	1:45	73.58	7.8	513	2.3
2/17/2021	1:55	74.12	7.7	506	2.8
2/17/2021	2:05	74.12	8.1	508	2.5
2/17/2021	2:15	74.66	8	515	2.1
2/17/2021	2:25	74.12	7.8	513	2.3
2/17/2021	2:35	74.12	7.8	516	2.5
2/18/2021	11:50	72.14	8.6	456	3.2
2/18/2021	12:05	73.94	7.5	456	3.2
2/18/2021	12:20	73.76	8	481	2.8
2/18/2021	12:35	75.02	7.6	481	2.5
2/18/2021	12:45	74.84	8	478	2.4
2/18/2021	12:55	76.64	7.2	493	2.6
2/18/2021	1:05	78.08	6.8	485	2.6
2/18/2021	1:15	78.07	6.6	507	2.4
2/18/2021	1:25	78.98	6.2	501	2.2
2/18/2021	1:35	78.98	6.4	503	2.3
2/18/2021	1:45	79.88	5.6	506	2.3

Table D3

Grohmann Tower Conference Room IAQ Data

GROHMANN TOWER CONFERENCE ROOM					
Date	Time	Temperature [F]	RH [%]	CO2 [ppm]	PM2.5 [ug/m^3]
1/11/2021	3:40	66.92	19	464	3
1/12/2021	12:30	67.46	19.6	479	3.1
1/13/2021	12:00	71.24	21.8	441	4.6
1/14/2021	1:15	69.08	24.4	452	5.4
1/15/2021	12:35	71.24	22	468	3
1/18/2021	4:05	67.46	18.4	470	3.3
1/19/2021	12:50	68.72	14.1	489	2.9
1/20/2021	12:10	69.62	9.2	493	2.9
1/21/2021	1:05	74.48	13.3	454	1.3
1/22/2021	11:50	71.42	6.7	518	1.6
1/25/2021	1:15	68.18	15.7	485	3
1/26/2021	11:50	71.24	19.2	443	1.3
1/27/2021	12:25	71.96	11.2	508	4.4
1/28/2021	12:45	75.38	5.7	516	2.9
1/29/2021	12:10	79.34	6.2	539	4.6
2/1/2021	1:50	71.42	15.4	469	1.7
2/2/2021	12:00	71.78	16.4	523	3.1
2/3/2021	1:00	76.82	10.7	482	3.3
2/15/2021	1:30	69.98	3.7	564	2.7
2/15/2021	1:50	72.86	3.4	538	2.2
2/15/2021	2:00	73.4	4.4	559	2.2
2/15/2021	2:15	73.76	4.1	639	1.8
2/15/2021	2:35	73.58	4.1	644	1.8
2/15/2021	2:50	73.22	5.2	679	2.1
2/16/2021	2:15	76.28	7.2	520	1.9
2/16/2021	2:30	74.66	7.5	518	1.9
2/16/2021	2:40	74.66	7.2	520	1.8
2/16/2021	2:50	74.84	7.6	520	1.8
2/16/2021	3:00	74.66	7.5	524	2.2
2/16/2021	3:10	74.48	7.5	508	2
2/16/2021	3:20	74.3	7.9	512	1
2/16/2021	3:30	74.48	8.6	514	1.7
2/17/2021	1:35	72.86	8	482	3
2/17/2021	1:45	73.76	8.5	536	2.6
2/17/2021	1:55	74.66	7.5	504	2.4
2/17/2021	2:05	74.66	7.6	512	2.5
2/17/2021	2:15	75.02	7.7	510	2.4
2/17/2021	2:25	74.66	7.7	513	2.6
2/17/2021	2:35	74.66	7.6	515	2.7
2/18/2021	11:50	71.78	9.1	458	3.3
2/18/2021	12:05	74.66	7.5	452	3.2
2/18/2021	12:20	74.12	7.8	480	2.7
2/18/2021	12:35	75.02	7.5	464	2.6
2/18/2021	12:45	75.02	7.3	469	2.3
2/18/2021	12:55	76.82	7.1	487	2.6
2/18/2021	1:05	79.52	6.4	480	2.8
2/18/2021	1:15	80.24	6.3	494	2.8
2/18/2021	1:25	82.04	6	492	2.1
2/18/2021	1:35	82.04	6.1	490	2.2
2/18/2021	1:45	87.26	5.2	504	2.3

Table D4

Margaret Loock Hall Area IAQ Data

		MLH			
Date	Time	Temperature [F]	RH [%]	CO2 [ppm]	PM2.5 [ug/m^3]
1/11/2021	3:10	70.2	20.4	444	5.2
1/12/2021	12:20	71.34	19.6	457	5.4
1/13/2021	12:15	71.6	23.3	465	5.7
1/14/2021	12:25	64.4	28.7	460	7.7
1/15/2021	12:45	69.26	25.2	457	4.3
1/18/2021	4:15	63.86	18	452	4.5
1/19/2021	12:35	67.28	15.4	466	4.5
1/20/2021	12:20	66.56	9.9	447	3.9
1/21/2021	1:10	77.72	16.1	422	1.3
1/22/2021	12:00	73.94	6.7	449	1.6
1/25/2021	1:00	69.98	17.6	460	2.7
1/26/2021	11:30	74.66	20.3	430	1.7
1/27/2021	12:40	77	12.6	434	2.4
1/28/2021	12:30	72.68	7.7	420	3.1
1/29/2021	11:50	73.76	11.6	423	3.7
2/1/2021	1:35	70.7	16.4	435	2.1
2/2/2021	11:40	71.24	16.2	406	2.9
2/3/2021	12:40	72.14	14	441	4.5
2/15/2021	1:15	67.46	10.5	436	2.1
2/15/2021	3:05	70.16	10.1	432	2.7
2/15/2021	3:15	71.96	8.5	410	2.2
2/15/2021	3:25	73.22	8.2	397	2.2
2/15/2021	3:35	73.58	8.1	400	2.1
2/15/2021	3:45	73.58	8	415	1.9
2/16/2021	10:45	73.4	13.7	437	2
2/16/2021	11:00	73.94	12.3	410	1.9
2/16/2021	11:15	74.66	12	402	2
2/16/2021	11:25	75.2	12	408	1.9
2/16/2021	11:35	75.02	11.5	411	1.8
2/16/2021	11:45	75.02	12	401	1.9
2/16/2021	11:55	75.56	10.7	403	1.9
2/16/2021	12:05	75.74	11.1	433	2
2/16/2021	12:20	75.92	11.9	419	2.1
2/16/2021	12:30	75.38	11.5	421	2
2/16/2021	12:40	75.92	11.4	426	2
2/16/2021	12:50	75.92	11.4	420	2.1
2/17/2021	12:00	72.32	12.1	443	2.7
2/17/2021	12:10	74.48	11.9	426	2.5
2/17/2021	12:20	74.66	11.9	422	2.5
2/17/2021	12:30	74.66	11.2	417	2.6
2/17/2021	12:40	74.48	10.9	422	2.5
2/17/2021	12:50	74.48	11.5	438	2.5
2/17/2021	1:00	74.66	12.1	427	2.3
2/17/2021	1:10	74.48	11.6	443	2.6
2/17/2021	1:20	74.66	11.9	456	2.4
2/17/2021	1:30	74.66	12.5	436	2.4
2/18/2021	11:15	71.24	12.8	432	2.9
2/18/2021	11:25	73.76	11.1	412	2.4
2/18/2021	11:35	74.78	10.2	409	2
2/18/2021	11:45	74.84	10.9	411	2.5

Appendix E – Basic Statistical Information of Area Measurements

Statistics

Variable	N	Mean	StDev	Variance	Median
GR1 Temperature	22	69.528	2.827	7.994	68.360
GR1 Humidity	22	14.97	6.26	39.15	15.85
GR1 Co2	22	514.76	40.57	1646.17	509.00
GR1 Particulates	22	2.890	0.930	0.866	2.800

Statistics

Variable	N	Mean	StDev	Variance	Median
GR2 Temperature	22	73.100	3.341	11.162	72.905
GR2 Humidity	22	13.91	5.90	34.82	14.50
GR2 Co2	22	501.81	32.54	1058.78	502.29
GR2 Particulates	22	2.942	1.093	1.195	3.000

Statistics

Variable	N	Mean	StDev	Variance	Median
GRC Temperature	22	71.988	3.479	12.102	71.420
GRC Humidity	22	13.43	6.14	37.65	13.70
GRC Co2	22	491.05	37.19	1382.73	483.50
GRC Particulates	22	2.934	1.090	1.187	2.950

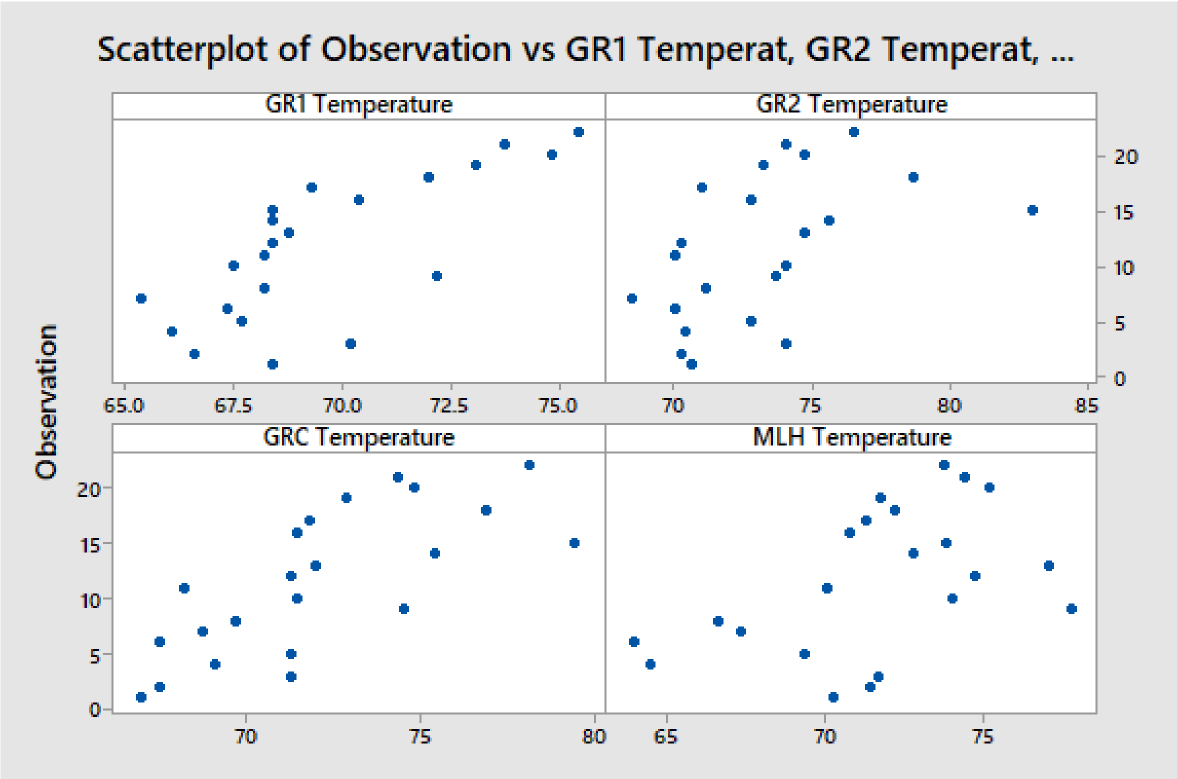
Statistics

Variable	N	Mean	StDev	Variance	Median
MLH Temperature	22	71.506	3.642	13.267	71.630
MLH Humidity	22	15.61	5.73	32.86	15.75
MLH Co2	22	438.54	18.37	337.30	438.00
MLH Particulates	22	3.469	1.618	2.617	3.000

Appendix F – Normality Testing Temperature Across all Areas

Figure F1

Scatterplot Tests for Randomness of Temperature



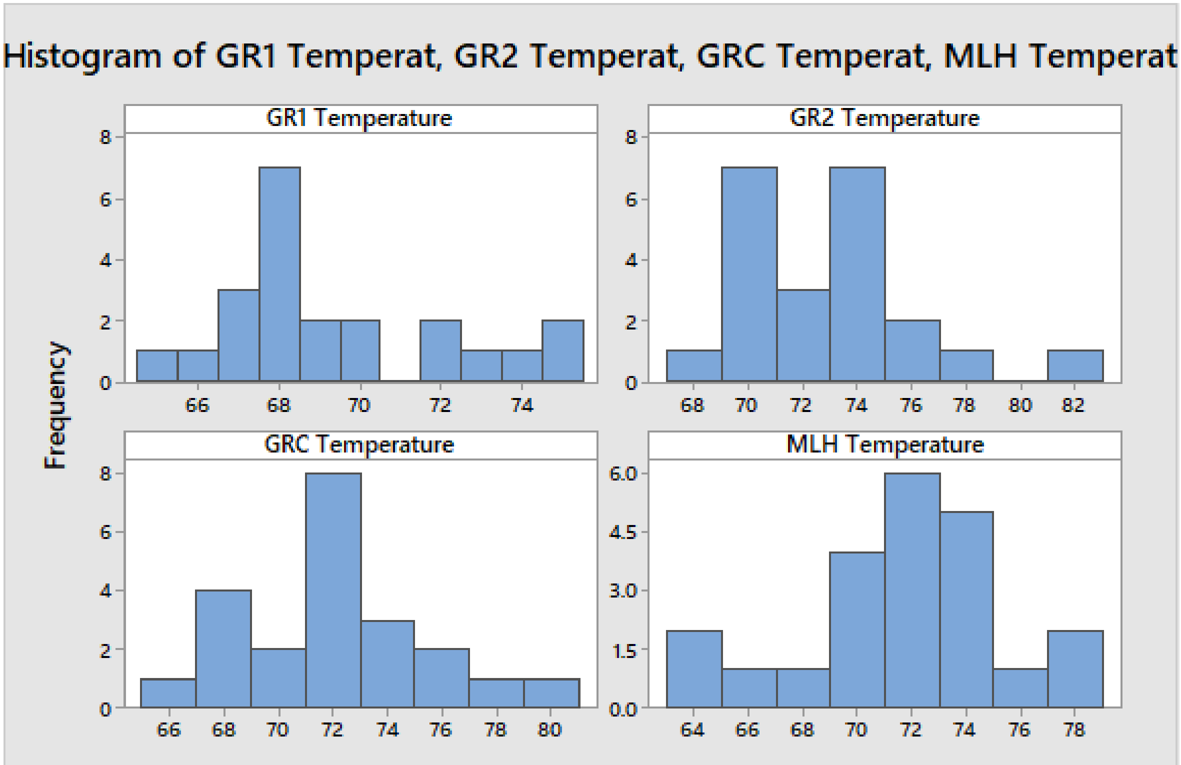
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observation number.

[b] Horizontal axis depicts the temperature at that observation number.

Figure F2

Histogram Plot Tests for Normality of Temperature



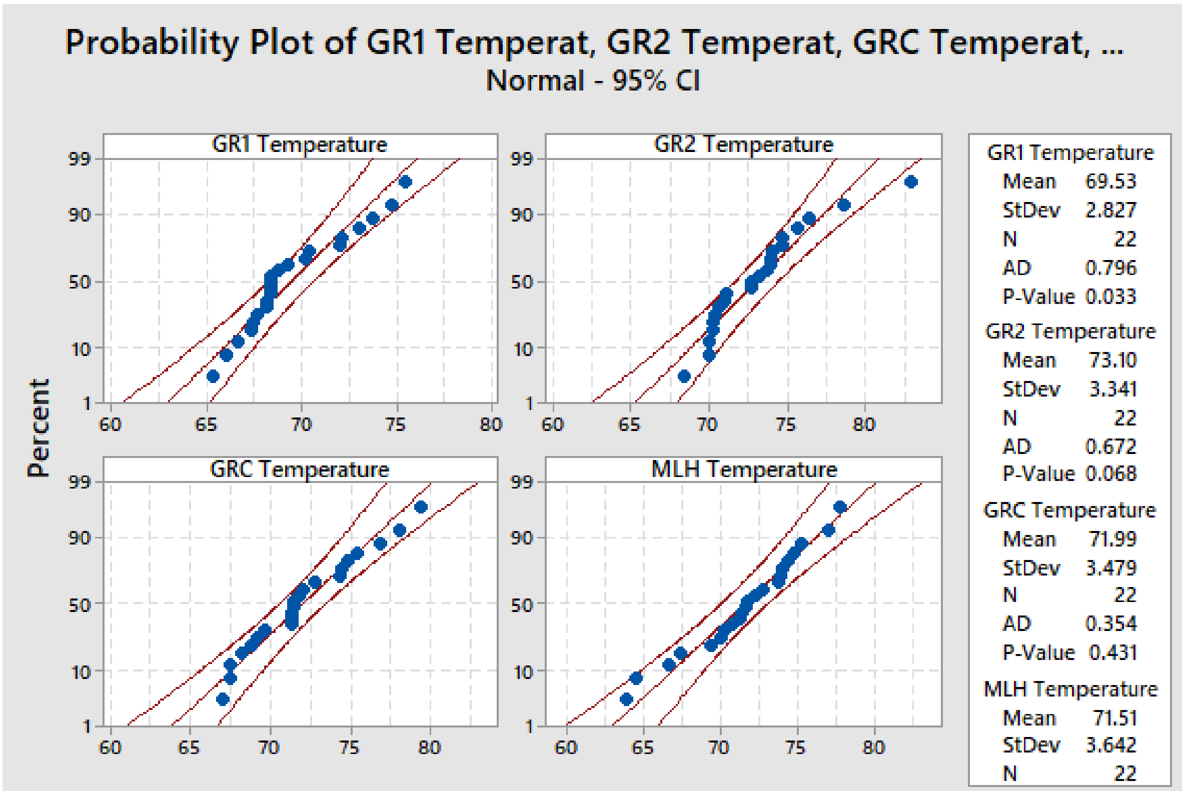
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the frequency observed with the associated temperature.

[b] Horizontal axis depicts the observed temperature.

Figure F3

Probability Plot Tests for Normality of Temperature



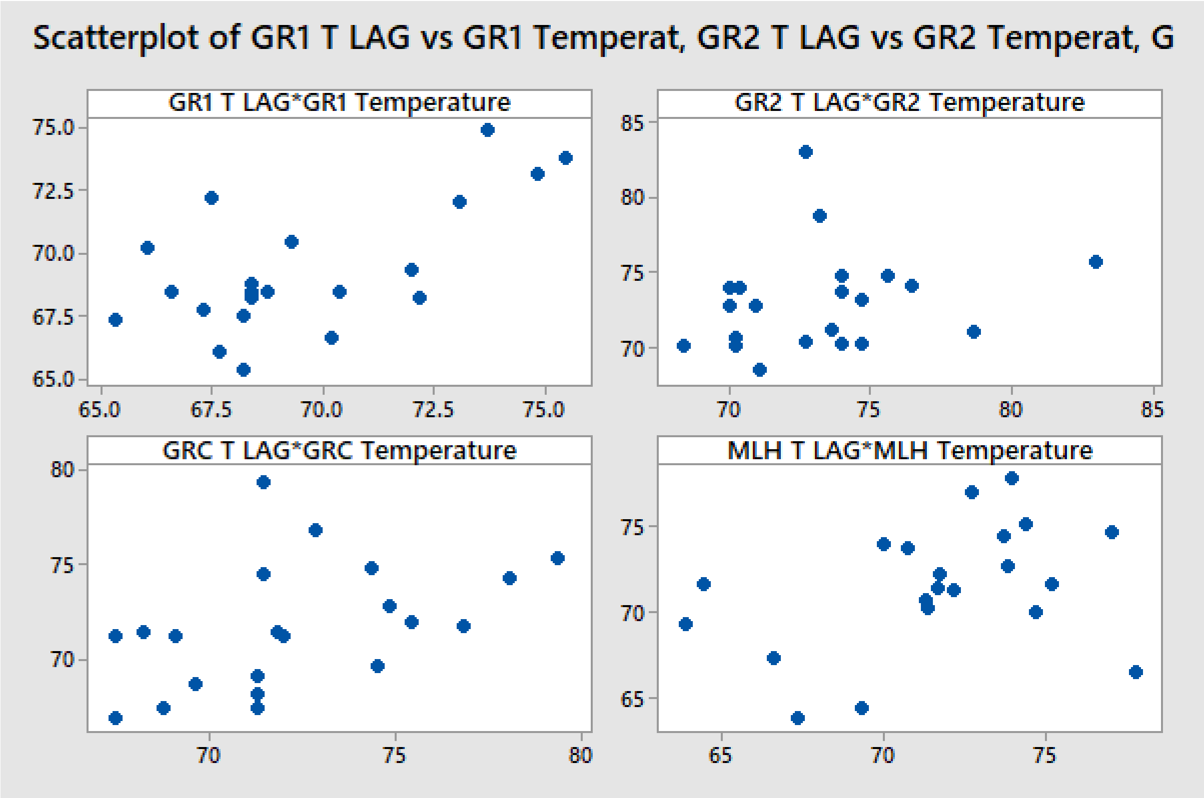
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the ordered response values of the z-scores of the observed temperature.

[b] Horizontal axis depicts the observed temperature.

Figure F4

Scatterplot Tests for Correlation of Temperature



Note. Created by the author of this report using Minitab software.

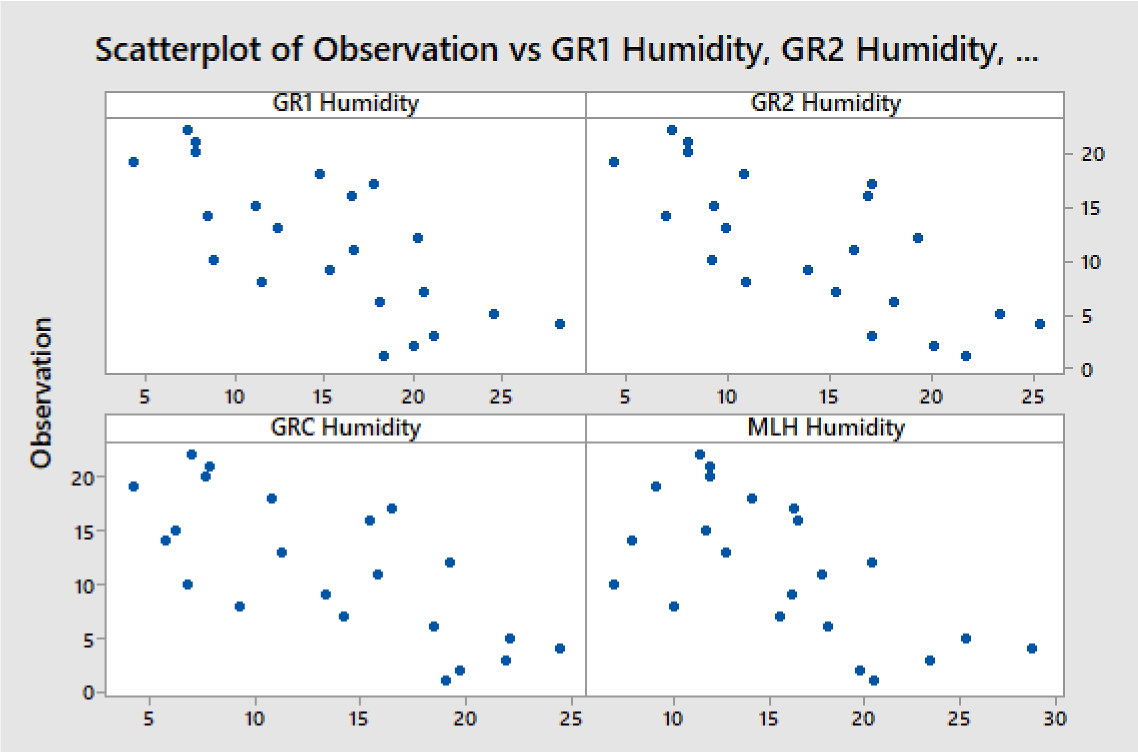
[a] Vertical axis depicts the observed temperature data set with a lag of one.

[b] Horizontal axis depicts the observed temperature.

Appendix G – Normality Testing Humidity Across all Areas

Figure G1

Scatterplot Tests for Randomness for Humidity



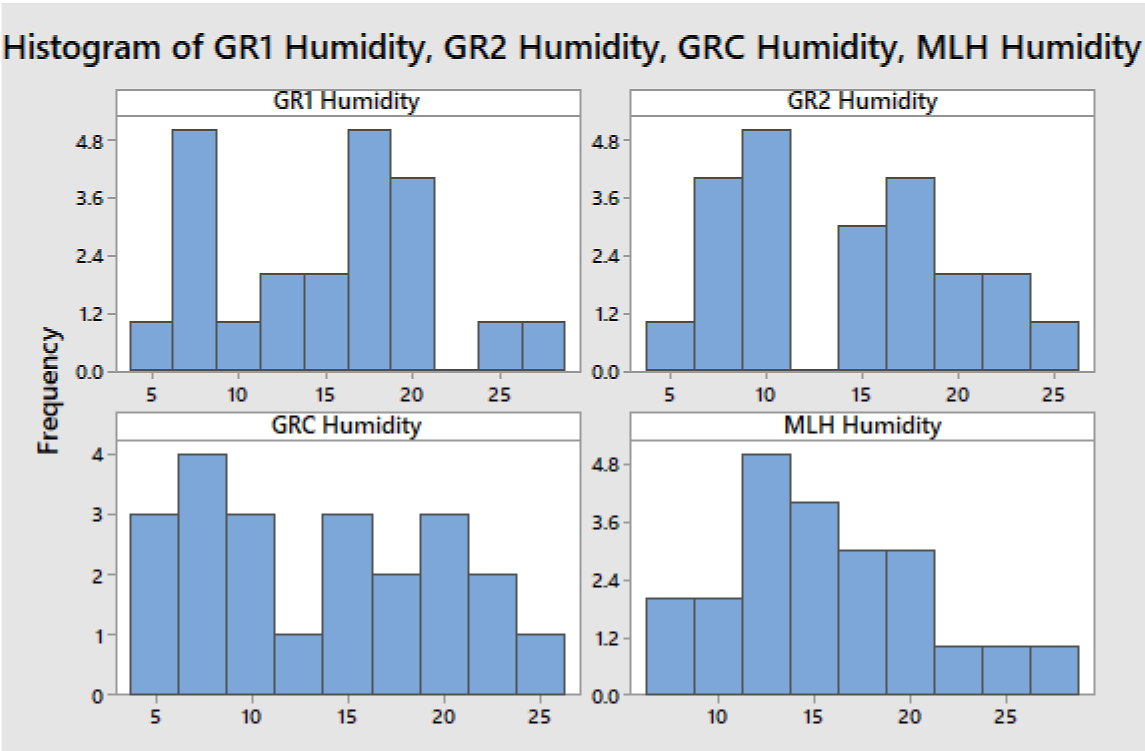
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observation number.

[b] Horizontal axis depicts the humidity level at that observation number.

Figure G2

Histogram Plot Tests for Normality of Humidity



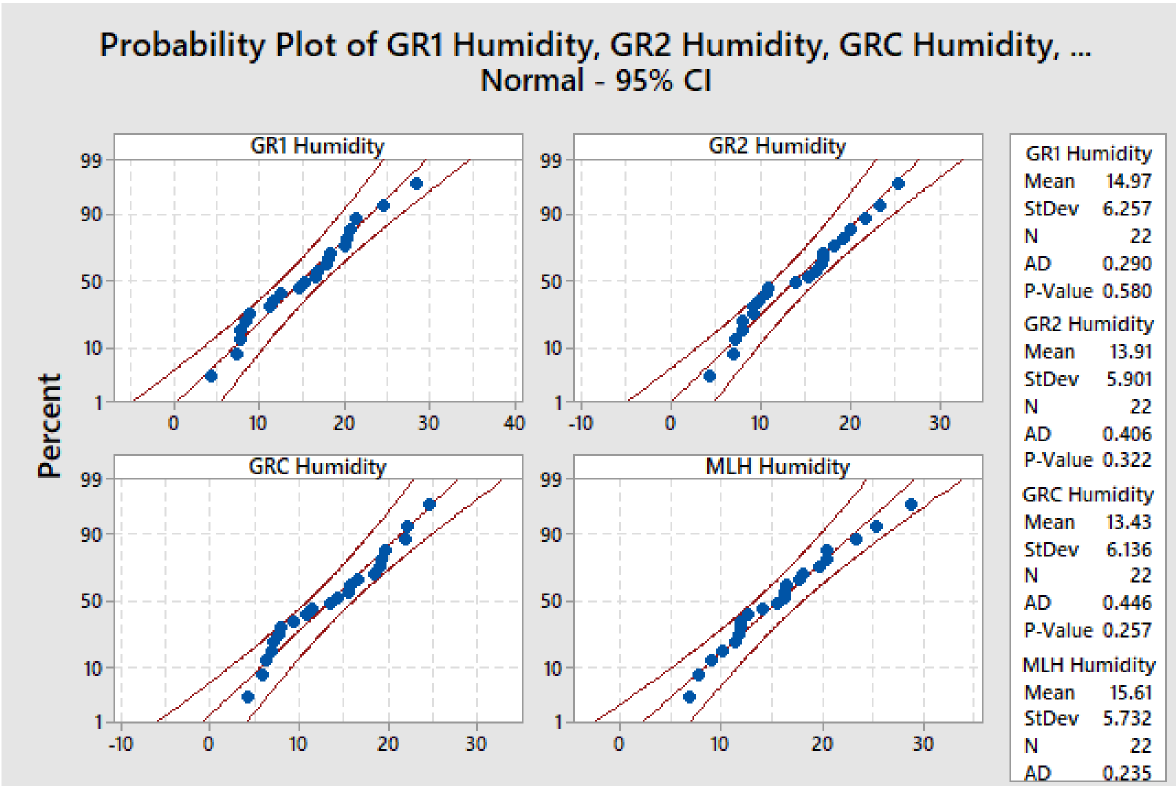
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the frequency observed with the associated humidity level.

[b] Horizontal axis depicts the observed humidity levels.

Figure G3

Probability Plot Tests for Normality of Humidity



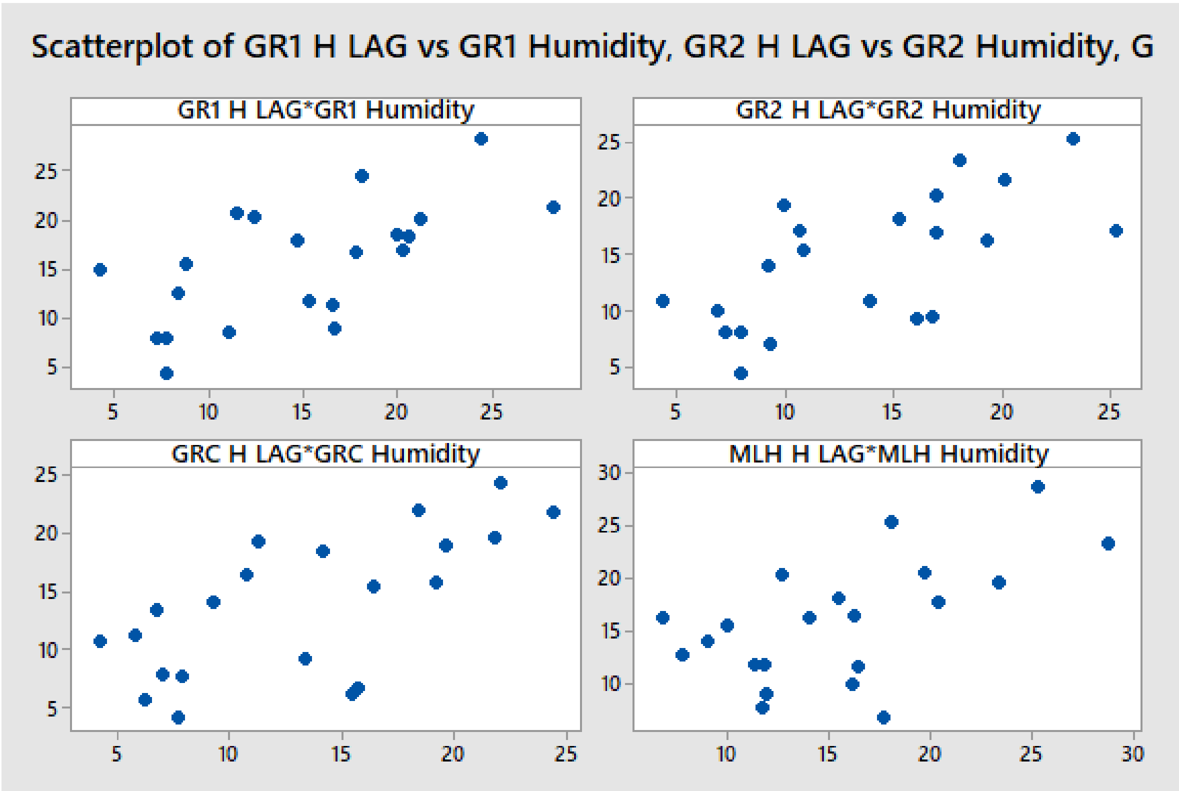
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the ordered response values of the z-scores of the observed humidity levels.

[b] Horizontal axis depicts the observed humidity levels.

Figure G4

Scatterplot Tests for Correlation of Humidity



Note. Created by the author of this report using Minitab software.

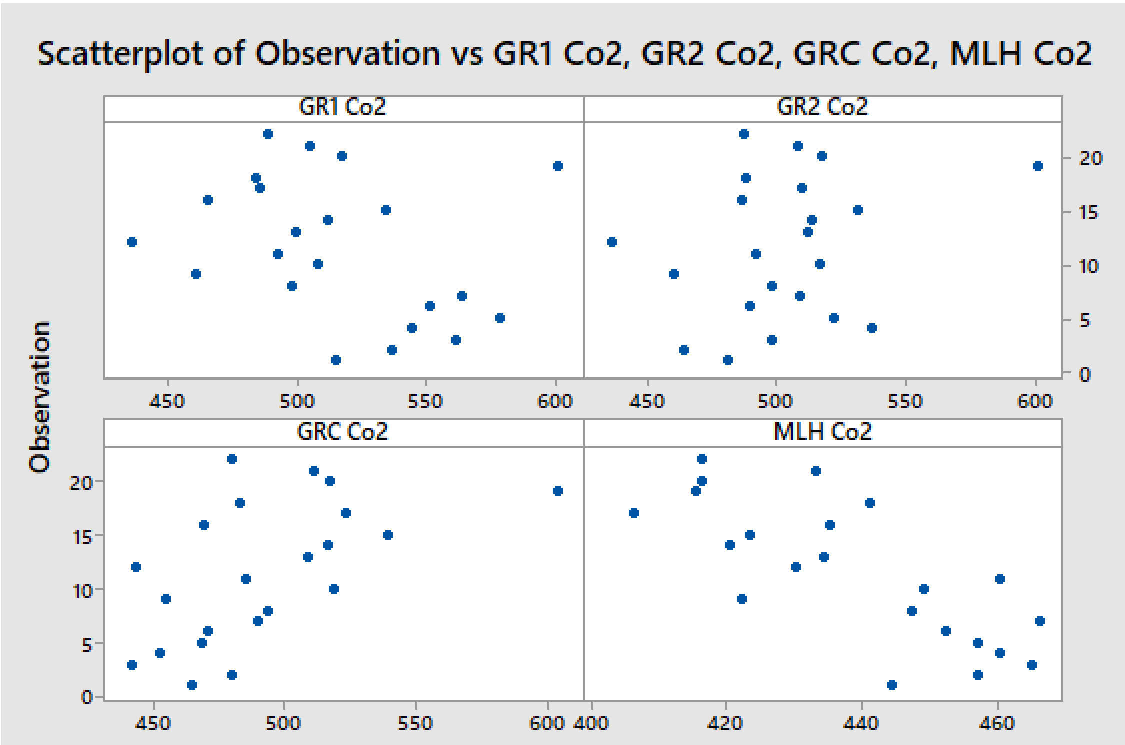
[a] Vertical axis depicts the observed humidity levels data set with a lag of one.

[b] Horizontal axis depicts the observed humidity levels.

Appendix H – Normality Testing Carbon Dioxide Across all Areas

Figure H1

Scatterplot Tests for Randomness for Carbon Dioxide



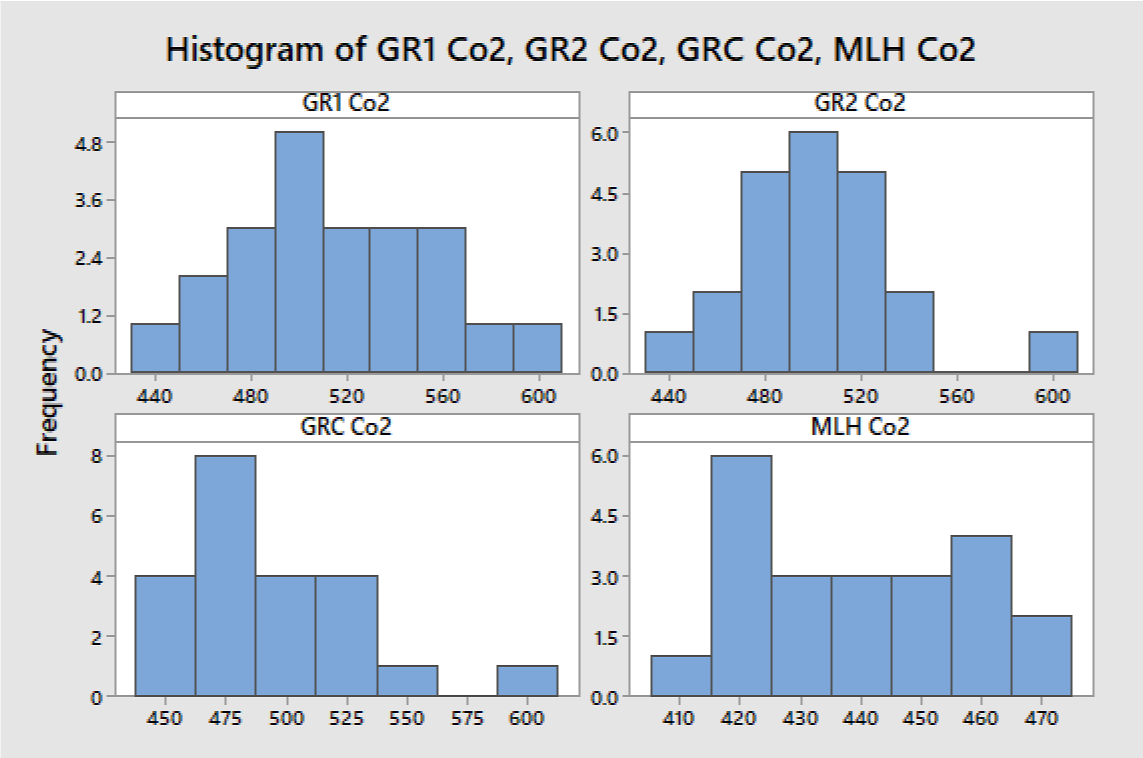
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observation number.

[b] Horizontal axis depicts the carbon dioxide level at that observation number.

Figure H2

Histogram Plot Tests for Normality for Carbon Dioxide



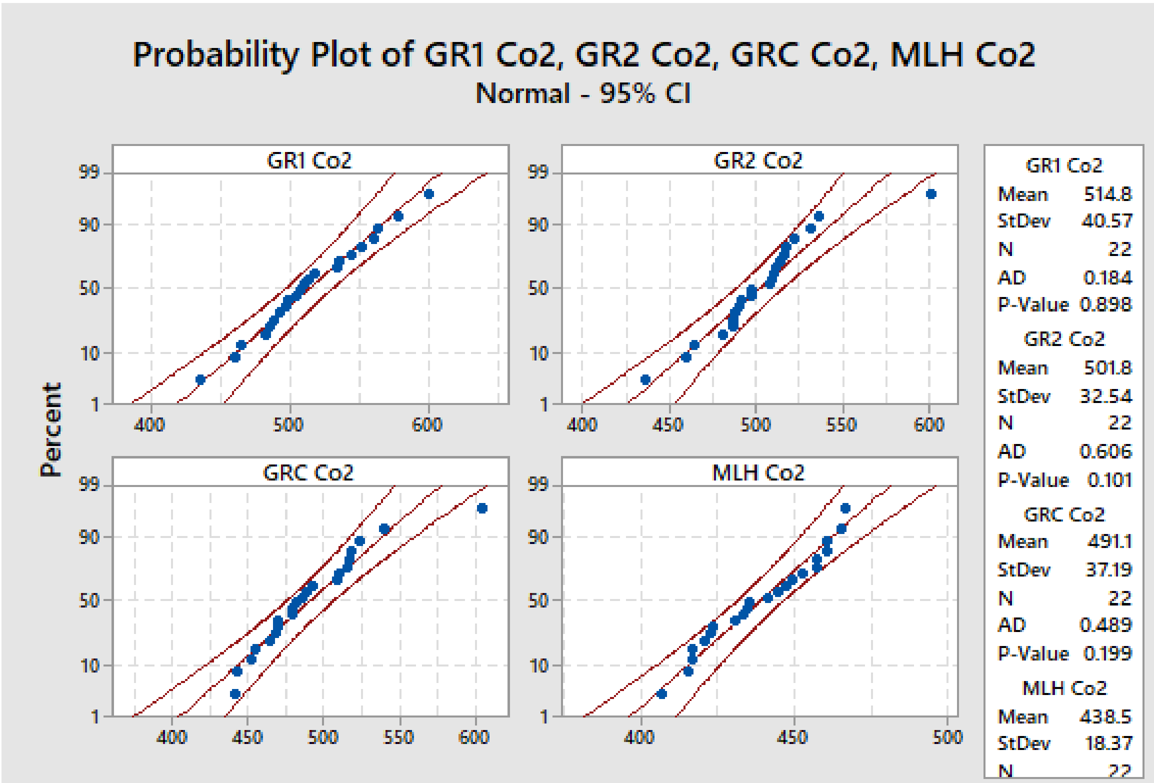
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the frequency observed with the associated carbon dioxide level.

[b] Horizontal axis depicts the observed carbon dioxide levels.

Figure H3

Probability Plot Tests for Normality for Carbon Dioxide



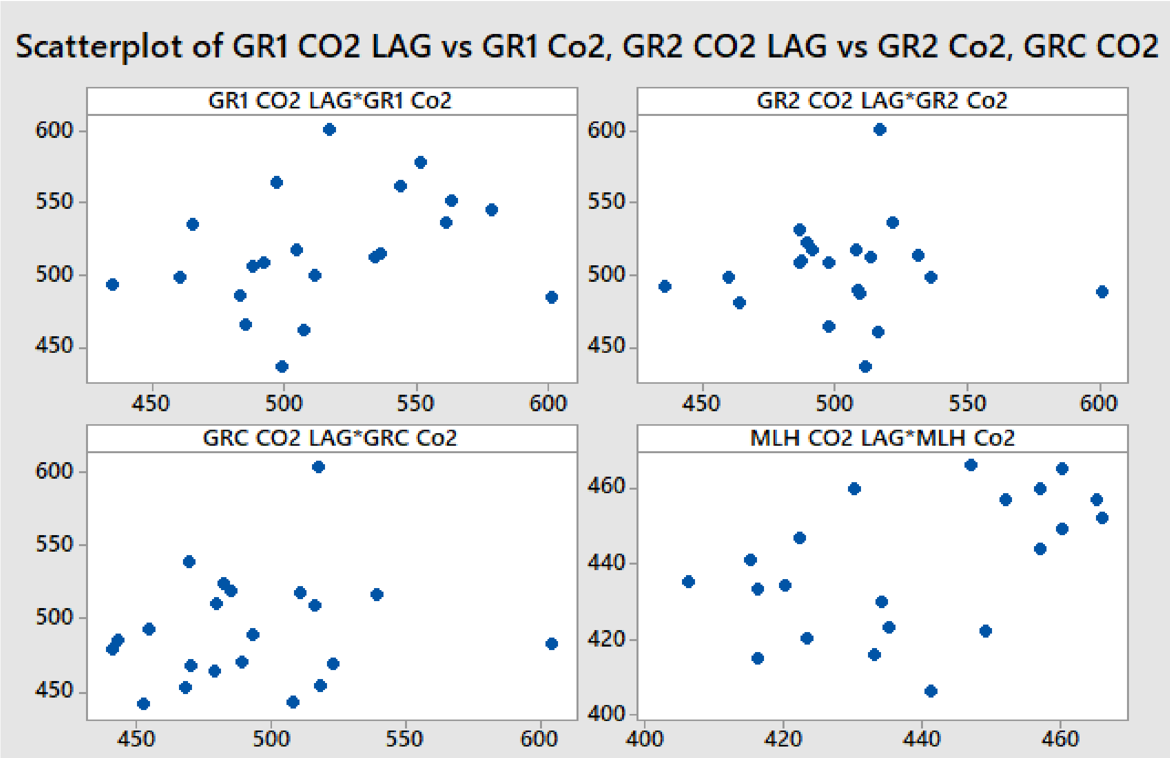
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the ordered response values of the z-scores of the observed carbon dioxide levels.

[b] Horizontal axis depicts the observed carbon dioxide levels.

Figure H4

Scatterplot Tests for Correlation for Carbon Dioxide



Note. Created by the author of this report using Minitab software.

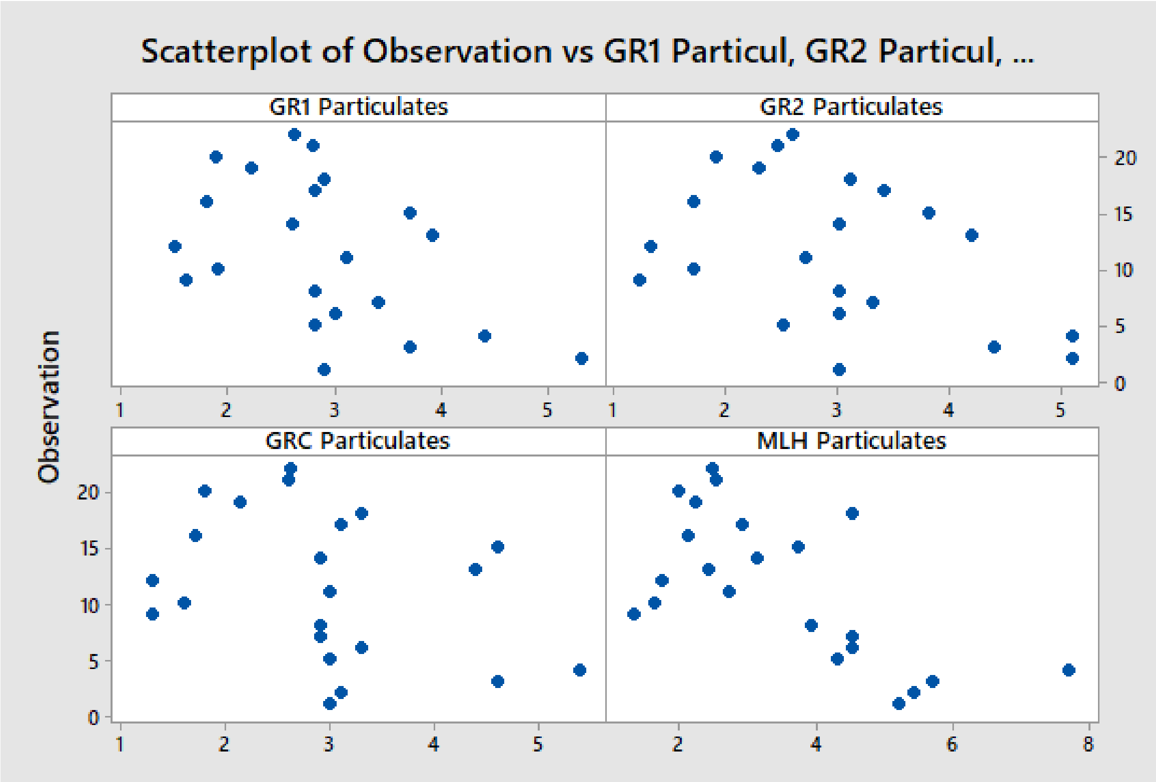
[a] Vertical axis depicts the observed carbon dioxide levels data set with a lag of one.

[b] Horizontal axis depicts the observed carbon dioxide levels.

Appendix I – Normality Testing Particulates Across all Areas

Figure I1

Scatterplot Tests for Randomness for Air Particulates



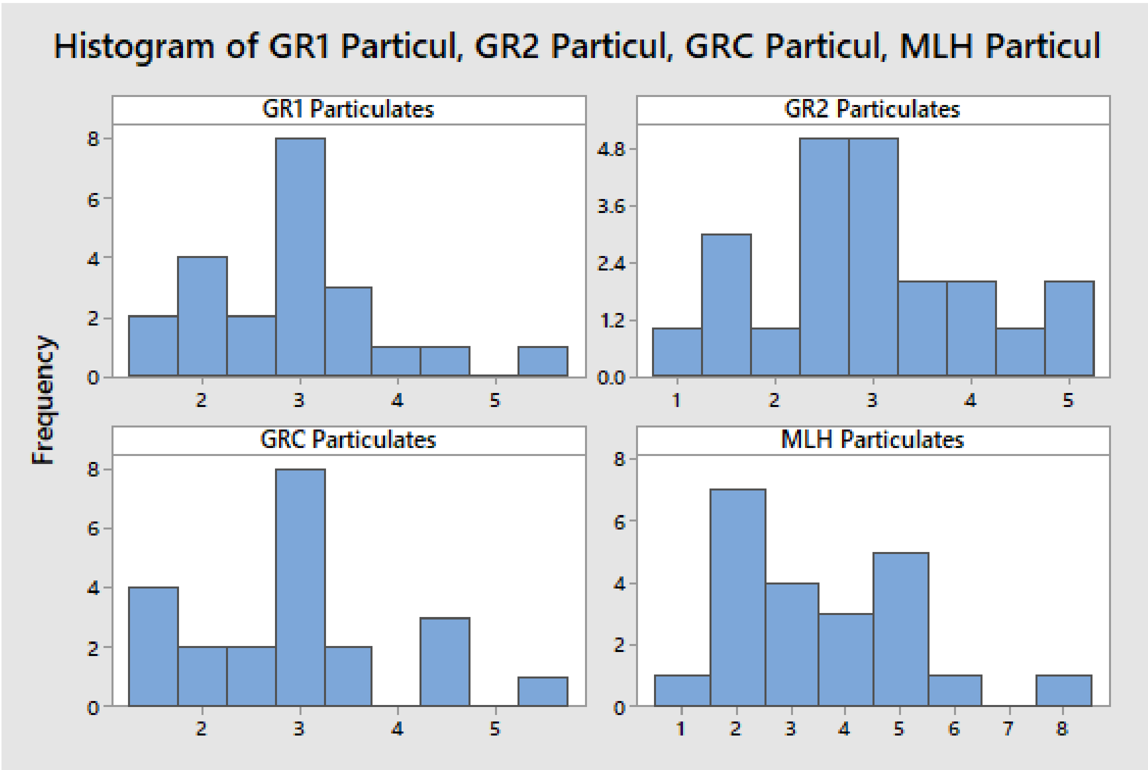
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observation number.

[b] Horizontal axis depicts the air particulate level at that observation number.

Figure I2

Histogram Plot Tests for Normality for Air Particulates



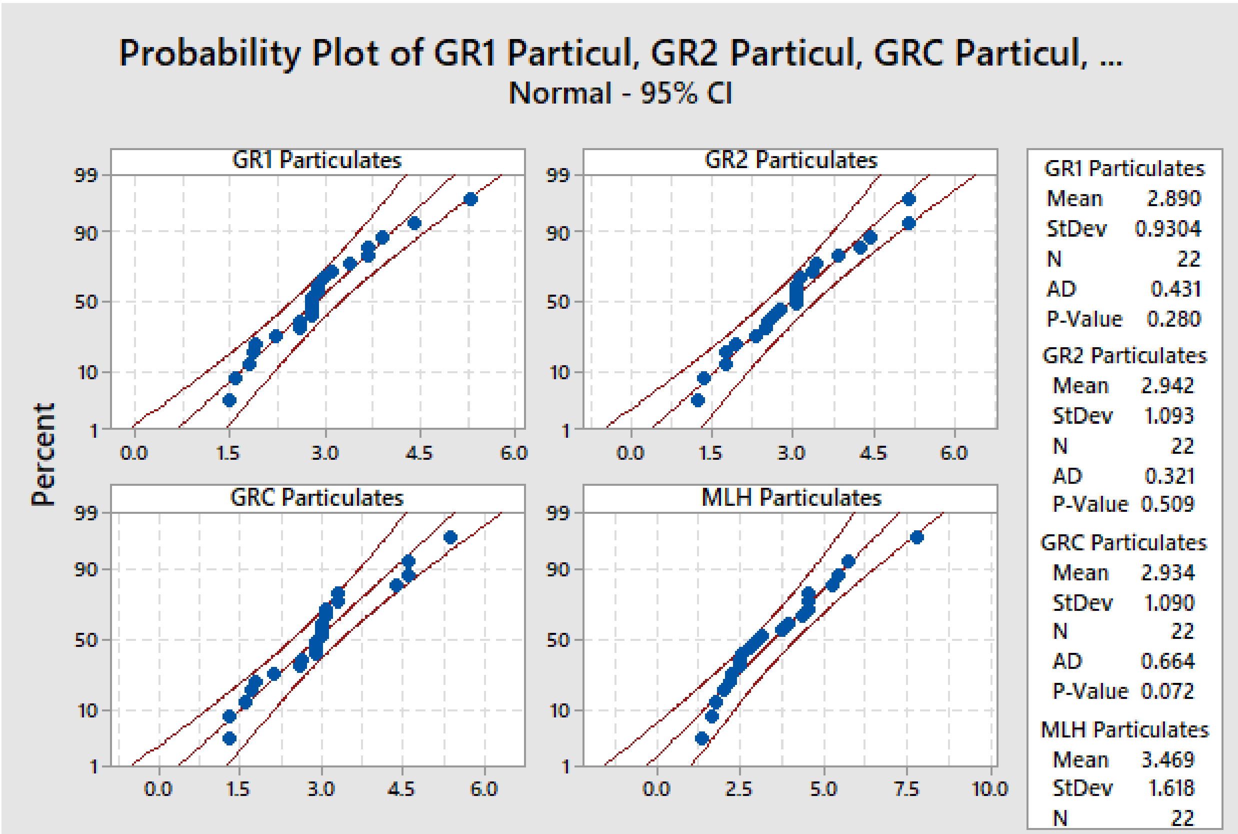
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the frequency observed with the associated air particulate level.

[b] Horizontal axis depicts the observed air particulate levels.

Figure I3

Probability Plot Tests for Normality for Air Particulates



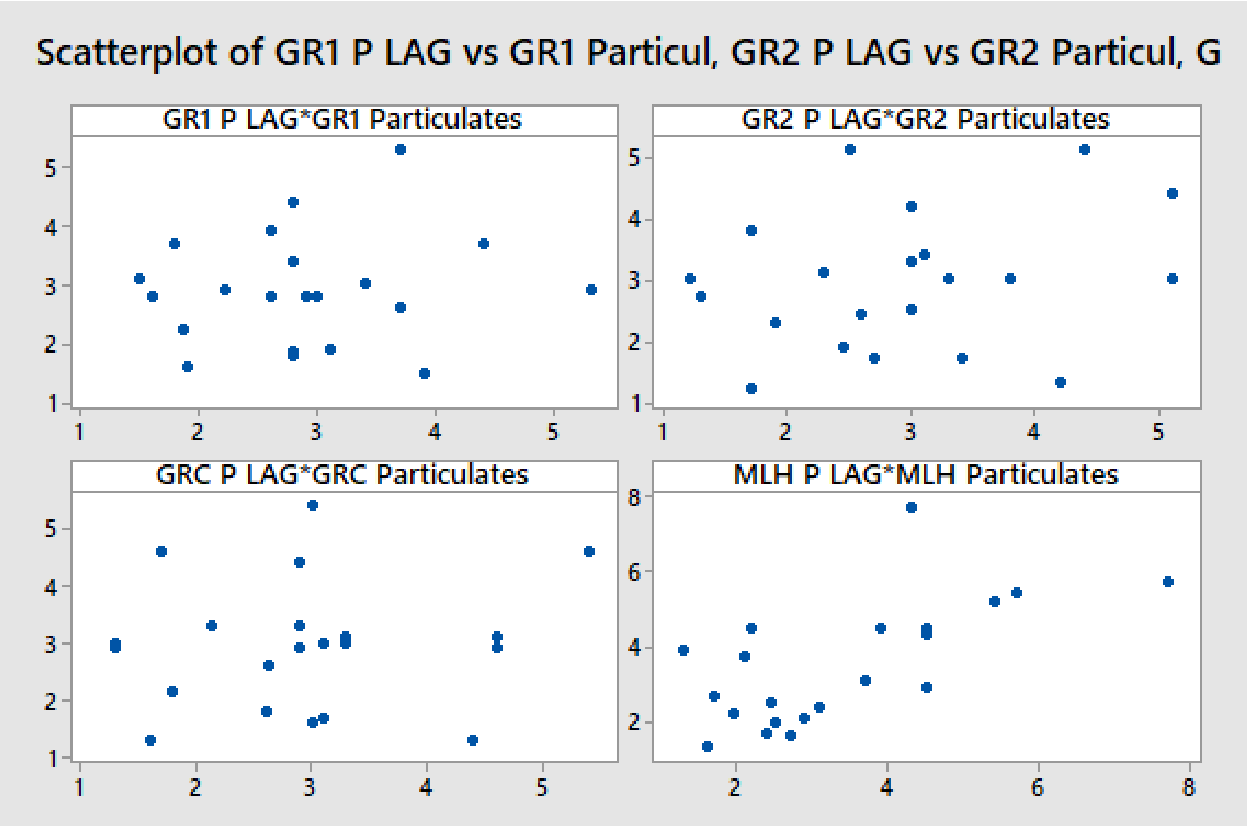
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the ordered response values of the z-scores of the observed air particulate levels.

[b] Horizontal axis depicts the observed air particulate levels.

Figure I4

Scatterplot Tests for Correlation for Air Particulates



Note. Created by the author of this report using Minitab software.

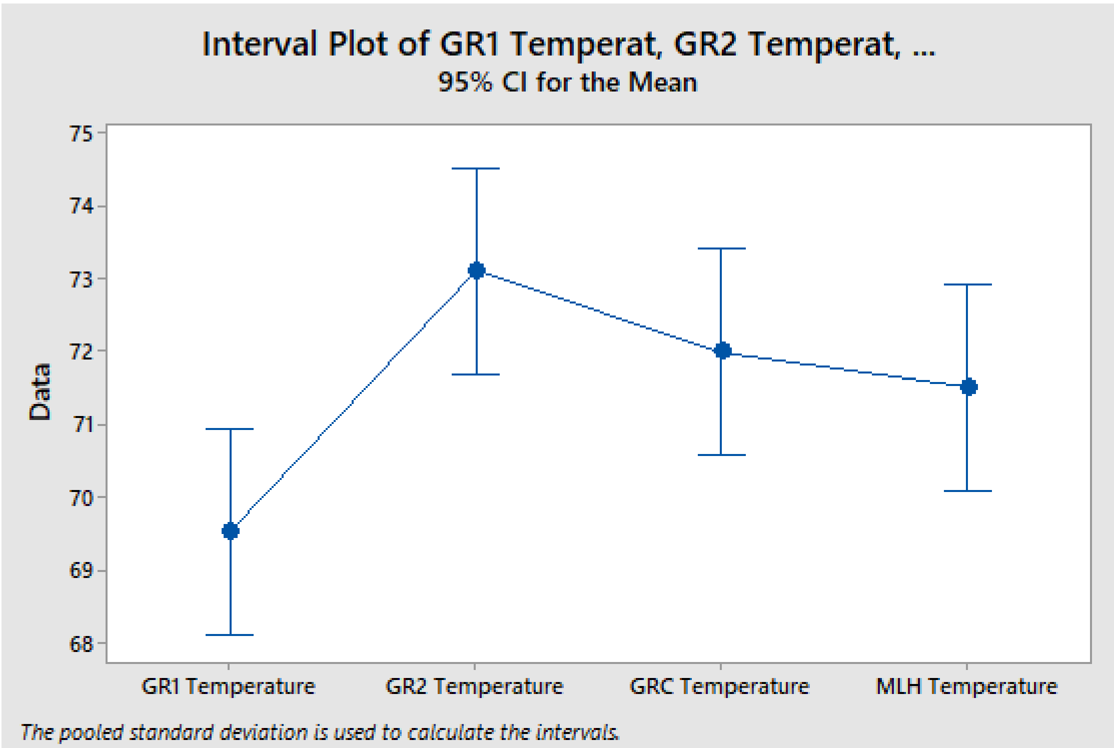
[a] Vertical axis depicts the observed air particulate levels data set with a lag of one.

[b] Horizontal axis depicts the observed air particulate levels.

Appendix J – Results of Temperature Tukey Test

Figure J1

95% Confidence Interval Plots of Temperature of Each Area



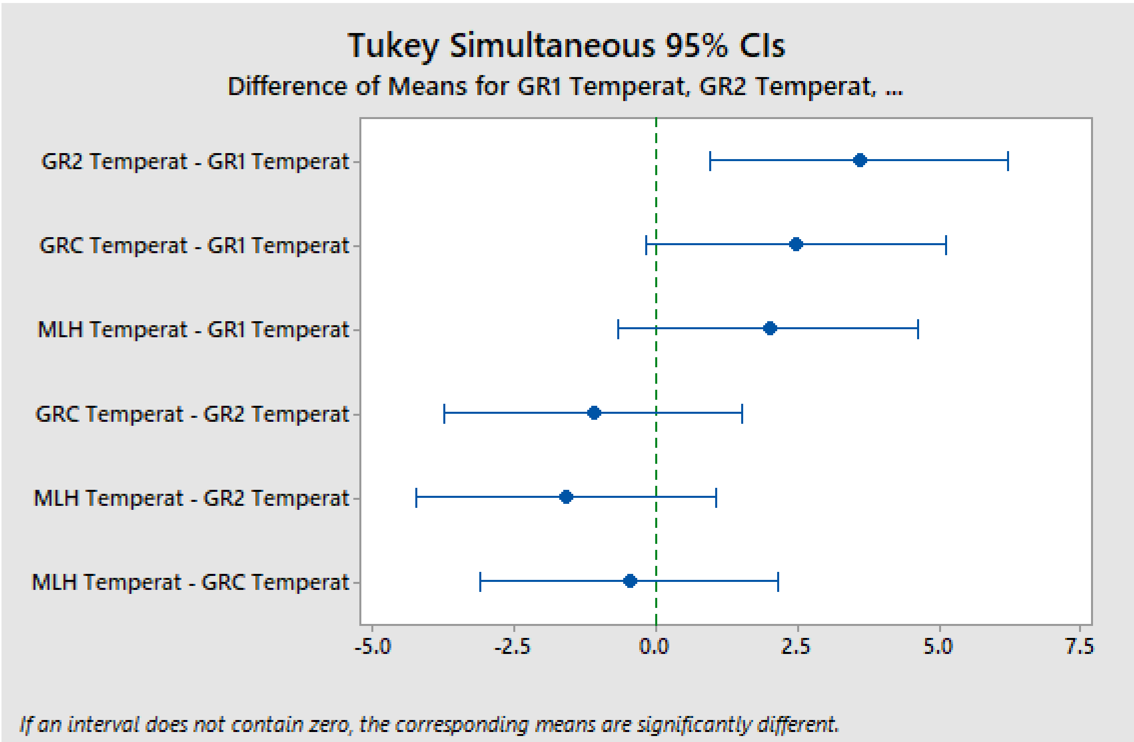
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observed temperature.

[b] Horizontal axis depicts the measured areas.

Figure J2

95% Confidence Interval Plots of Temperature Differences Between Areas



Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the two areas that are compared against each other.

[b] Horizontal axis depicts the difference of the two areas in degrees Fahrenheit.

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	GR1 Temperature, GR2 Temperature, GRC Temperature, MLH Temperature

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	147.0	49.00	4.40	0.006
Error	84	935.0	11.13		
Total	87	1082.0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.33632	13.59%	10.50%	5.16%

Means

Factor	N	Mean	StDev	95% CI
GR1 Temperature	22	69.528	2.827	(68.113, 70.942)
GR2 Temperature	22	73.100	3.341	(71.685, 74.514)
GRC Temperature	22	71.988	3.479	(70.573, 73.402)
MLH Temperature	22	71.506	3.642	(70.091, 72.920)

Pooled StDev = 3.33632

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

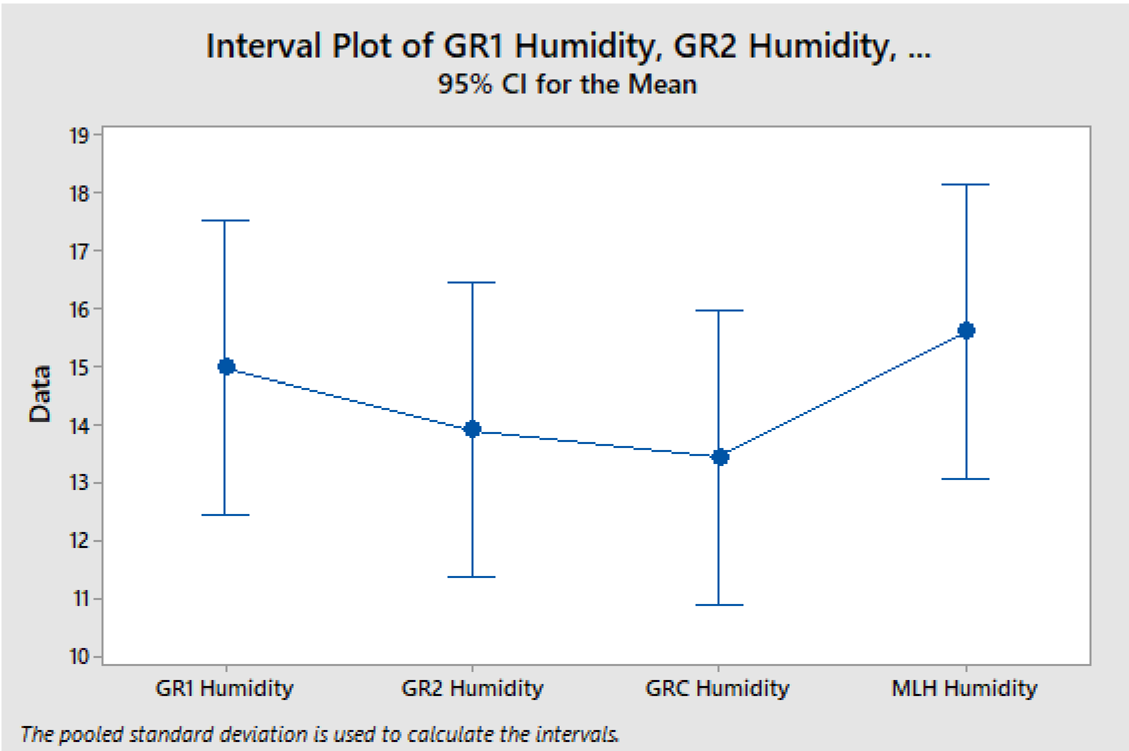
Factor	N	Mean	Grouping	
GR2 Temperature	22	73.100	A	
GRC Temperature	22	71.988	A	B
MLH Temperature	22	71.506	A	B
GR1 Temperature	22	69.528		B

Means that do not share a letter are significantly different.

Appendix K – Results of Humidity Tukey Test

Figure K1

95% Confidence Interval Plots of Relative Humidity of Each Area



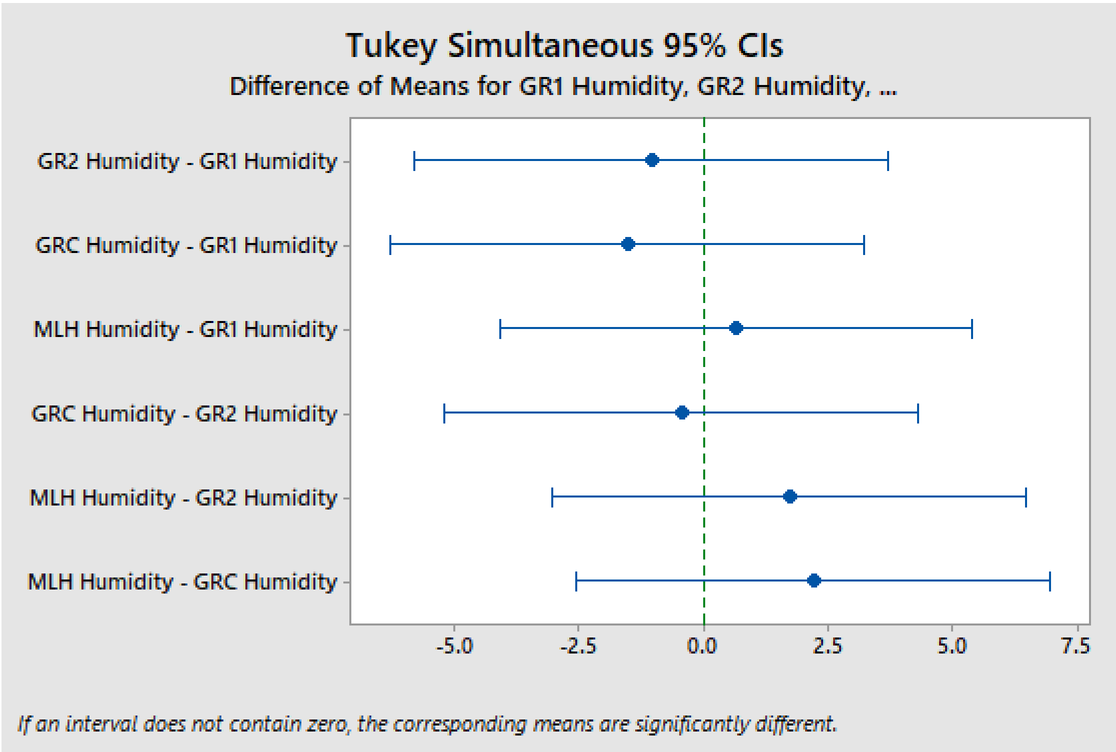
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observed humidity level.

[b] Horizontal axis depicts the measured areas.

Figure K2

95% Confidence Interval Plots of Relative Humidity Differences Between Areas



Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the two areas that are compared against each other.

[b] Horizontal axis depicts the difference of the two areas in relative humidity percentage.

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	GR1 Humidity, GR2 Humidity, GRC Humidity, MLH Humidity

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	64.72	21.57	0.60	0.619
Error	84	3033.87	36.12		
Total	87	3098.59			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
6.00979	2.09%	0.00%	0.00%

Means

Factor	N	Mean	StDev	95% CI
GR1 Humidity	22	14.97	6.26	(12.42, 17.52)
GR2 Humidity	22	13.91	5.90	(11.36, 16.45)
GRC Humidity	22	13.43	6.14	(10.88, 15.98)
MLH Humidity	22	15.61	5.73	(13.06, 18.16)

Pooled StDev = 6.00979

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

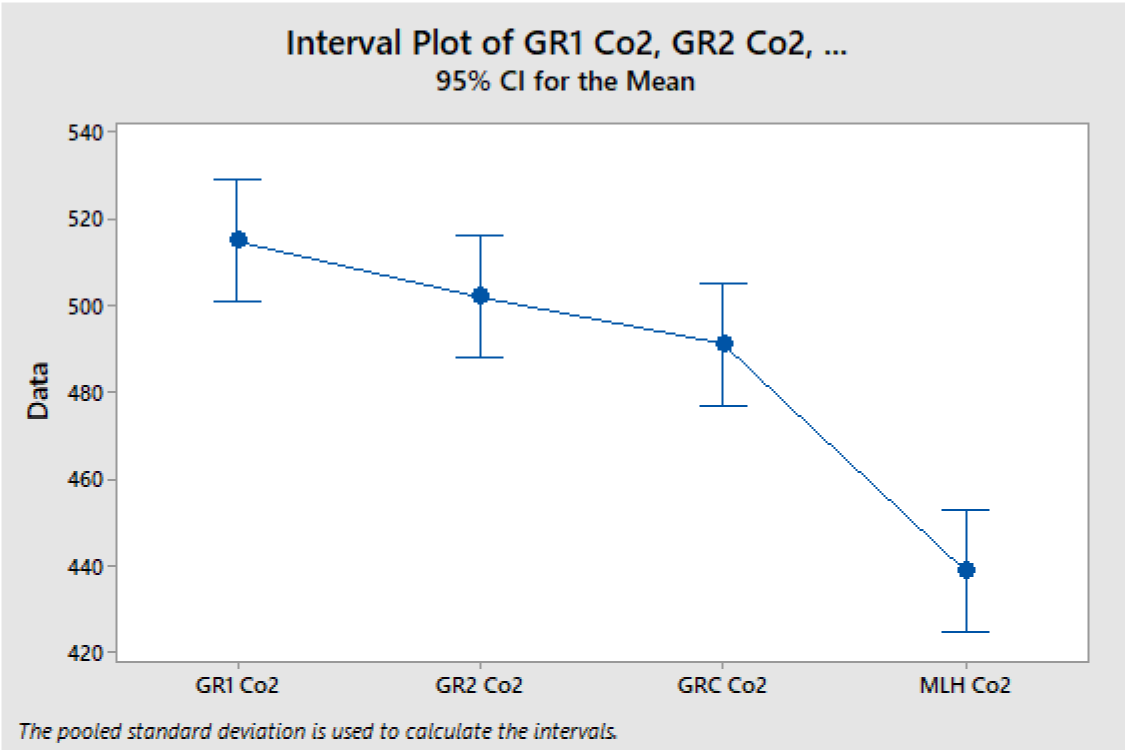
Factor	N	Mean	Grouping
MLH Humidity	22	15.61	A
GR1 Humidity	22	14.97	A
GR2 Humidity	22	13.91	A
GRC Humidity	22	13.43	A

Means that do not share a letter are significantly different.

Appendix L – Results of Carbon Dioxide Tukey Test

Figure L1

95% Confidence Interval Plots of Carbon Dioxide Level of Each Area



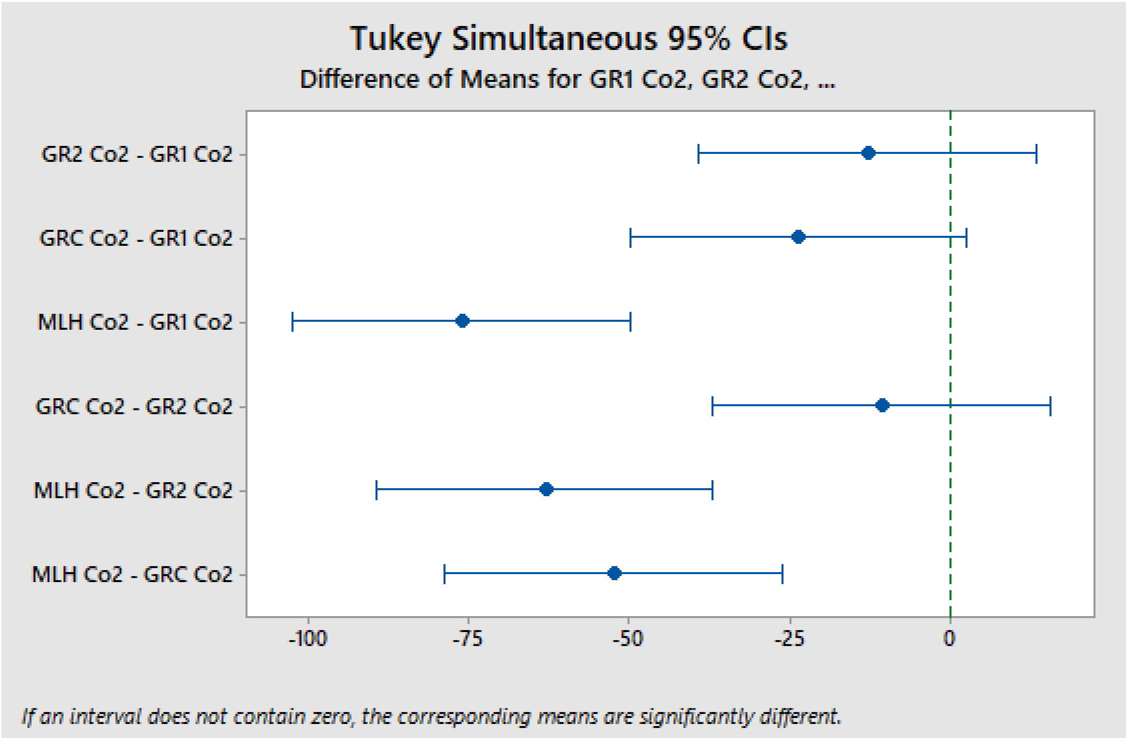
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observed carbon dioxide level.

[b] Horizontal axis depicts the measured areas.

Figure L2

95% Confidence Interval Plots of Carbon Dioxide Level Differences Between Areas



Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the two areas that are compared against each other.

[b] Horizontal axis depicts the difference of the two areas in parts per million (ppm).

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	GR1 Co2, GR2 Co2, GRC Co2, MLH Co2

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	73784	24595	22.23	0.000
Error	84	92925	1106		
Total	87	166709			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
33.2602	44.26%	42.27%	38.82%

Means

Factor	N	Mean	StDev	95% CI
GR1 Co2	22	514.76	40.57	(500.66, 528.86)
GR2 Co2	22	501.81	32.54	(487.71, 515.91)
GRC Co2	22	491.05	37.19	(476.95, 505.16)
MLH Co2	22	438.54	18.37	(424.44, 452.64)

Pooled StDev = 33.2602

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

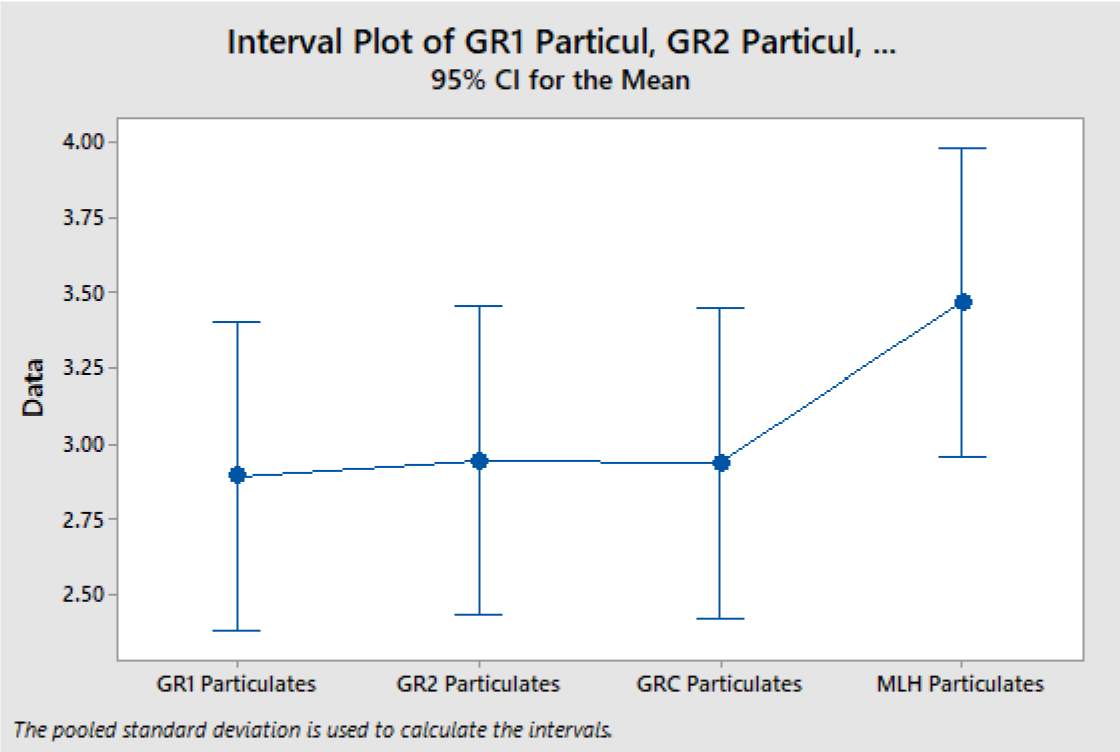
Factor	N	Mean	Grouping	
GR1 Co2	22	514.76	A	
GR2 Co2	22	501.81	A	
GRC Co2	22	491.05	A	
MLH Co2	22	438.54		B

Means that do not share a letter are significantly different.

Appendix M – Results of Particulates Tukey Test

Figure M1

95% Confidence Interval Plots of Air Particulate Level of Each Area



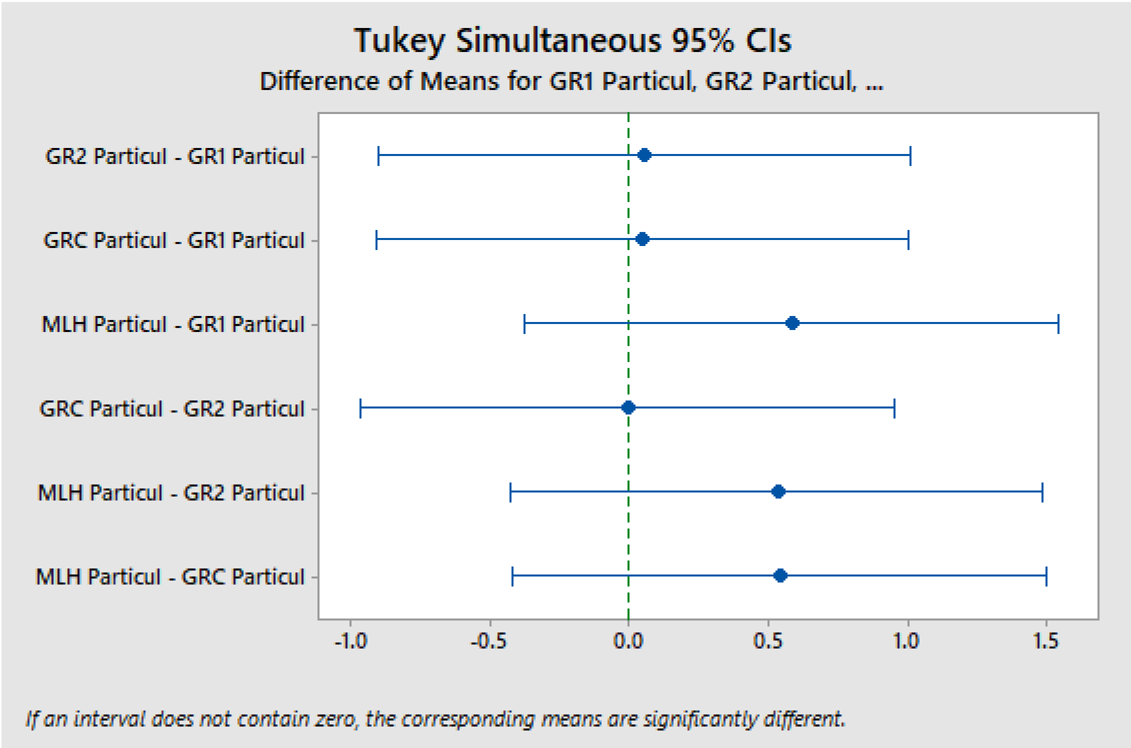
Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the observed level of air particulates ($PM_{2.5}$).

[b] Horizontal axis depicts the measured areas.

Figure M2

95% Confidence Interval Plots of Air Particulate Level Differences Between Areas



Note. Created by the author of this report using Minitab software.

[a] Vertical axis depicts the two areas that are compared against each other.

[b] Horizontal axis depicts the difference of the two areas in [µg/m^3].

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	4	GR1 Particulates, GR2 Particulates, GRC Particulates, MLH Particulates

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	3	4.970	1.657	1.13	0.342
Error	84	123.172	1.466		
Total	87	128.142			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.21092	3.88%	0.45%	0.00%

Means

Factor	N	Mean	StDev	95% CI
GR1 Particulates	22	2.890	0.930	(2.377, 3.404)
GR2 Particulates	22	2.942	1.093	(2.428, 3.455)
GRC Particulates	22	2.934	1.090	(2.420, 3.447)
MLH Particulates	22	3.469	1.618	(2.956, 3.982)

Pooled StDev = 1.21092

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping
MLH Particulates	22	3.469	A
GR2 Particulates	22	2.942	A
GRC Particulates	22	2.934	A
GR1 Particulates	22	2.890	A

Means that do not share a letter are significantly different.

Appendix N – Hypothesis Tests Results

Two-Sample T-Test and CI: MLH Co2, GR1 Co2

Method

μ_1: mean of MLH Co2
μ_2: mean of GR1 Co2
Difference: $\mu_1 - \mu_2$

Equal variances are assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
MLH Co2	22	438.5	18.4	3.9
GR1 Co2	22	514.8	40.6	8.7

Estimation for Difference

Difference	Pooled StDev	95% CI for Difference
-76.22	31.49	(-95.38, -57.06)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-8.03	42	0.000

Two-Sample T-Test and CI: MLH Co2, GR2 Co2

Method

μ_1: mean of MLH Co2
μ_2: mean of GR2 Co2
Difference: $\mu_1 - \mu_2$

Equal variances are assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
MLH Co2	22	438.5	18.4	3.9
GR2 Co2	22	501.8	32.5	6.9

Estimation for Difference

Difference	Pooled StDev	95% CI for Difference
-63.27	26.42	(-79.35, -47.19)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-7.94	42	0.000

Two-Sample T-Test and CI: MLH Co2, GRC Co2

Method

μ_1: mean of MLH Co2
μ_2: mean of GRC Co2
Difference: $\mu_1 - \mu_2$

Equal variances are assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
MLH Co2	22	438.5	18.4	3.9
GRC Co2	22	491.1	37.2	7.9

Estimation for Difference

Difference	Pooled StDev	95% CI for Difference
-52.51	29.33	(-70.36, -34.67)

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

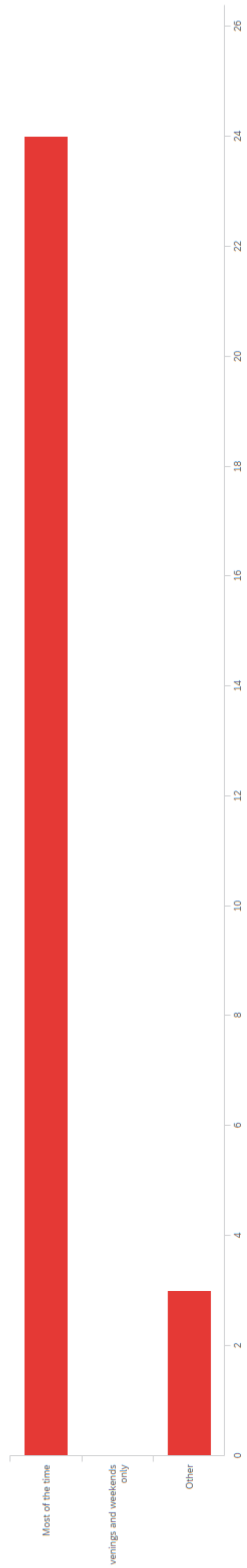
T-Value	DF	P-Value
-5.94	42	0.000

Appendix O – Summarized Qualitative Survey Results

How Long Has Resident Lived in Residence Hall:

Do Residents Spend Most of Their Time in the Residence Hall:

Do Residents Study in the Residence Halls:



Winter Temperature Conditions Responses

Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
Uncomfortable or comfortable?	2.00	7.00	5.23	1.44	2.08	22
Too hot or too cold?	2.00	6.00	4.45	0.99	0.98	22
Stable or it varies during the day?	1.00	7.00	4.32	1.69	2.85	22

Winter Air Conditions Responses

Field	Minimum	Maximum	Mean	Std Deviation	Variance	Count
Still or draughty?	1.00	7.00	3.14	1.83	3.36	21
Dry or humid?	1.00	5.00	1.90	1.30	1.69	20
Fresh or stuffy?	1.00	7.00	4.27	1.63	2.65	22
Odorless or smelly?	1.00	6.00	2.85	1.49	2.23	20