Performance-Based Framework for Assessing Thermal Comfort Conditions at the HUB on the University of Washington Campus

Amanda Worthy

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2021

Committee:

Dorothy Reed

Jessica Kaminsky

Program Authorized to Offer Degree:

Civil Engineering

University of Washington

Abstract

Performance-Based Framework for Assessing Thermal Comfort Conditions at the HUB on the University of Washington Campus

Amanda Worthy

Chair of the Supervisory Committee:

Dorothy Reed

Department of Civil Engineering

Mechanical practices for preserving commercial building indoor environmental quality, specifically within the thermal comfort domain, require extensive resource inputs. On average, building heating, ventilation, air conditioning, and cooling (HVAC) systems account for roughly 39% of the energy consumption in office buildings [1]. Additionally, studies suggest that the average American spends 90% of their time indoors [2], making the protection and governance of indoor environmental quality critical for protecting human health. Building heating and cooling (ASHRAE) standards exist to regulate commercial building indoor temperature and ventilation requirements; however, it is unclear if current standards are reliable, or if the standards should be revised to better optimize occupant comfort and building energy consumption. This paper examines the ASHRAE 55-2017 Section 5.4 thermal comfort limit state equation through applying a performance-based framework to data collected at the Husky Union Building (HUB), on the University of Washington, Seattle campus. Preliminary results suggest that the existing ASHRAE limit state guideline is often exceeded during the summer season. Additionally, there is a strong correlation between summer maximum daily outdoor temperatures

and summer maximum daily indoor temperatures in the naturally ventilated building. This relationship suggests future challenges for maintaining occupant comfort throughout extreme heating events and changing climate conditions.

Table of Contents

This research investigates thermal comfort in a low-rise building on a university campus in Seattle, Washington using subjective and objective time series data. The data provides required inputs for a performance-based approach to occupant comfort criteria. “Performance-based” in this context is derived from civil engineering approaches to structural design e.g. [3]. Because thermal comfort is related to indoor air temperature, its control within buildings is directly related to natural and mechanical ventilation, as well as occupant-based energy demand. Thermal comfort actions at the building level are related to sustainability goals and objectives. In this thesis, background material on the formulation of occupant comfort criteria is derived using a performance-based approach, provided in Chapter 1. In Chapter 2, indoor environmental quality, of which thermal comfort is a subset, is discussed. Chapter 3 provides the details of the case study location for time series data analysis. Chapter 4 presents the occupant comfort criteria using the methodology outlined in Chapter 1, including extensive statistical examination. Chapter 5 summarizes the results of the investigation, examines them in the context of sustainability goals, and suggests future directions for the investigation of IEQ.

Chapter 1: Introduction and Background

Chapter 1 introduces the thermal comfort field and outlines motivations for this thesis. It further expands on the performance-based design framework and introduces the reliability methodology conducted on thermal comfort data collected at the University of Washington, Seattle campus.

History of Thermal Comfort Guidelines

Indoor Environmental Quality (IEQ) refers to the quality of a building's environment in relation to the health and wellbeing of those who occupy it [4]. The field primarily encompasses indoor air quality, thermal comfort, acoustics, and lighting. IEQ principles are considered in a building's lifecycle use phase, focusing on direct occupant needs during operation. Because occupant needs vary throughout workplaces and climates, the field is often difficult to holistically capture in conventional owner-driven building design and construction approaches.

Research in thermal comfort and its relation to energy resiliency has recently expanded, due to concerns of climate change and increased outdoor air pollution events (including wildfire smoke, smog, etc..) [5]. The field originally based its standards on a physiological heat balance model coined the "Predicted Mean Vote (PMV)" in the 1970s until an adaptive system was developed by de Dear and Braager (1998) [6] Nicol and Humphrey (2002) [7].

The adaptive approach to thermal comfort hypothesizes that contextual factors and past thermal history modify building occupants' thermal expectations and preferences, De Dear and Braager analyzed the previously used "static model to thermal comfort, viewing occupants as passive recipients to thermal stimuli driven by the physics of the body's thermal balance with its immediate environment." They initially advocated for the use of the static model although it ignored important cultural, climatic, social, and contextual dimensions of comfort. Current ASHRAE 55 standards now reflect adaptive considerations. Research and literature in the thermal comfort domain focus on refining the adaptive occupant driven approaches to thermal comfort, hoping to promote sustainability, and building resiliency.

In particular, de Dear and Braager's research has compared occupant behavior between naturally ventilated buildings and buildings with functional mechanical heating and cooling (HVAC) systems [6]. They found that occupants in naturally ventilated buildings had a much wider range of temporal tolerance than those in centralized mechanically ventilated buildings. It was noted that the occupant comfort variation between building ventilation types was not limited to physical explanations, such as the correlation between indoor and outdoor temperature, garments, and indoor ventilation; thus concluding that psychological adaption of thermal comfort occurred from exceeding expectations. These results illustrate the complexities of properly implementing building design standards that holistically capture comfort for the majority of building occupants and evolving occupant expectations of conditions.

From a review of the literature eg.. [8] [9] [10], it has been noted that there are thermal preference discrepancies among occupants due to age, gender, income, thermal history, education, and socio-cultural preferences in addition to the environmental and personal variables. Malik et al. expanded on "rebound" and "pre-rebound" effects concerning thermal comfort [8]. These phenomena suggest that when occupants are aware that they have energy-efficient buildings and technologies, they tend to not primarily care about monetary savings. This attitude often leads to higher energy consumption and a desire for higher thermal comfort. Mailik's research indicates the limitations of addressing subjective occupant desires too explicitly. Building design safety codes and standards must balance occupant demand while adhering to available energy resources.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) outlines guidelines for maintaining occupant thermal comfort in the United States (ASHRAE 55-2017). These standards include consideration of indoor and outdoor temperature, thermal radiation, humidity, and airspeed. ASHRAE specifies guidelines that "a significant proportion of the occupants will find acceptable at a certain metabolic rate and clothing level."[11]. ASHRAE and the thermal comfort community outline 6 metrics that they believe commercial building thermal factors depend on, including, personal metabolic rate, individual clothing preferences surrounding airspeed, relative humidity, thermal radiation (both long and short wave), and temperature. It is important to maintain standards that address both occupant needs for a functional building environment as well as energy resource limitations of the community.

Thermal comfort strategies have been proposed using passive or active temperature mitigation. Passive strategies do not rely on mechanical systems and can be used in situations when energy resources are limited. Examples of passive mitigation strategies in the thermal comfort domain include a change of clothing; increased personal ventilation (e.g., open a window); a change in personal direct sunlight exposure (e.g. close blinds, move to a shaded region; and a change in activity (e.g. to more of a resting heart rate state). Active strategies rely on mechanical systems to change indoor environmental quality conditions. Examples of active mitigation for thermal comfort include changing the temperature through a ventilation system or an air conditioning system.

Conventional mechanical commercial building thermal requirements are maintained by Heating, Ventilating, and Air Conditioning (HVAC) Systems. HVAC systems offer systems for thermal and humidity comfort, including heating, cooling, dehumidification, and humidification, ventilation, including filtration of recirculated air, the exhaust of undesirable air, and air movement, in addition to space pressurization, including control infiltration and makeup of exhausted air. Components in a commercial HVAC system include a boiler, cooling tower, chiller, pumps, pipes, control valves, air handler, and VAV terminal units [12]. On average, HVAC systems account for roughly 39% of the energy consumption in office buildings [1], making the thermal comfort field pivotal for building sustainability and resiliency.

Sustainable engineering design attempts to maximize cost and overall safety - both social and environmental. In this context, if occupant comfort is explicitly considered to meet every individual's exact needs, the broad range of preferences will compromise environmental and economic goals. If occupant considerations are neglected, the functionality and productive use of the building is compromised. Reliability analysis, used in performance-based framework, aims to optimize design, given safety and resource constraints.

The proposed framework addresses indoor thermal comfort conditions and compares them to existing ASHRAE standards. Specifically, in this thesis, full-scale in situ time-series data collected at the HUB on the University of Washington campus is analyzed. Probability analysis is used to identify time intervals where ASHRAE limits are exceeded and situations where occupant comfort and productivity [9] are compromised. Overall, a mathematical approach to assessing the HUB building functionality is presented.

Performance-Based Analysis Framework

Reliability analysis is often used in structural engineering applications to understand the amount of stress or demand a system component will be able to withstand. This analysis is important for risk calculations and to identify where errors may propagate in a system.

Haldar and Mahadevan [11] define "the probabilistic assurance of *performance* to be referred to as *reliability*. In this context, *performance* is defined as a structural system (or component) in which the capacity of the system (or component) exceeds the demand placed on it. Capacity can be represented by a strength value and demand by a load-induced stress value. That is, reliability analysis in engineering systems ensures that the capacity, resistance, or supply, will satisfy the demand. Throughout structural, mechanical, and geotechnical engineering, supply can be expressed in terms of resistances, e.g. capacity, or strength of individual members, whereas demand can be expressed in terms of applied loads, and load combinations [13].

Reliability is often used to express project successes, thus the probability of failure, or reliability index (β), is used to quantify the percentage of capacity exceedances. To find the probability of failure, specific performance criteria must be explicitly defined and outlined. Capacity must be identified and examined against the demand failure surface, or limit state equations. The system is reliable if the capacity, or resistance of the structure, R, exceeds the demand, or load on the structure, S, shown in Figure 1.

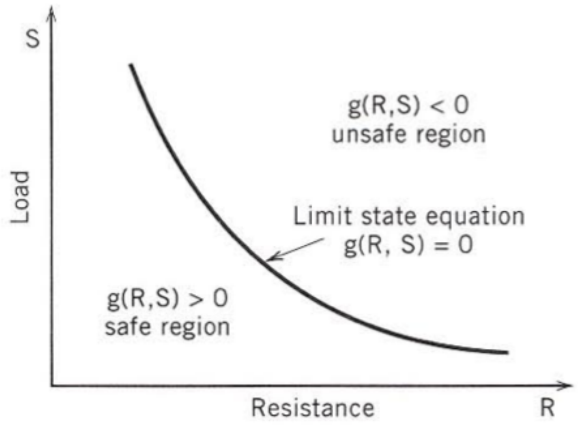

Figure 1. Reliability Limit State Concept [13]

In this application, reliability is defined in thermal comfort terminology. That is, the system is not reliable if the indoor air temperature exceeds the comfortable building temperature capacity, calculated through ASHRAE 55-2017 Section 5.4 standards. ASHRAE 55-2017 standards are explicitly outlined in the section ASHRAE Limit State Examined.

The limit state function (g (R, S)) defines the boundary between the safe and unsafe regions. For thermal comfort, this function is as follows:

$$g(R,S) = g(T_{indoor,\ limit} - T_{indoor,actual}) \tag{1}$$

Where $T_{indoor,\ actual}$ is the indoor global temperature measured in one minute intervals during working hours indoors at the HUB at height 0.6 meters over a period of nine months and $T_{indoor,limit}$ is the ASHRAE 55-2017 Section 5.4 -derived value determined using the adaptive comfort relationship from outdoor temperatures and reference [8].

Specifically for the summer quarter, the performance-based design will examine the probability of $[g(\ R,\ S\ )] < 0$, or when the indoor temperature exceeds the ASHRAE limit.

$$P\left(T_{indoor,\ limit} - T_{indoor,actual}\right) > P(*)\ ,0 \tag{2}$$

The amount of the exceedance, as well as the frequency of exceedance, will be examined in more detail in Chapter 4.

Because the data sets for analysis are limited, Monte Carlo simulation is employed to "run" experimental tests for different sets of temperature conditions. It is noted that the indoor temperature is related to the outdoor temperature, and extensive meteorological datasets for the region exist.

Chapter 2: Air Quality and Indoor Environmental Quality

Chapter 2 outlines the indoor environmental quality (IEQ) domain, in which thermal comfort is a subset. IEQ metrics include indoor air quality, thermal comfort, lighting, and acoustics. Although it would be optimal to cater towards each individual occupant preference, large ranges of preferences make it environmentally unsustainable and uneconomical. Sustainable building frameworks aim to provide guidance for building development and suggest a balance between meeting resource sustainability goals and considering individual occupant preferences. Chapter 2 expands on the history of sustainable building frameworks and elaborates on the most common framework, Leadership in Energy and Environmental Design, or LEED.

Air Pollution Constituents and Regulations

An estimated 7 million people worldwide are killed by air pollution [14]. With 4.2 million deaths attributed to outdoor, or ambient, air pollution and around 3.8 million from household air pollution [14]. Human exposure to deadly air concentrations can lead to stroke, heart disease, lung cancer, as well as acute and chronic respiratory illnesses. Air pollution-related deaths disproportionately affect lower-income countries and communities, although 91% of the world's population lives in locations where air concentrations exceed World Health Organization, or WHO, limit standards [14]. Air pollution is commonly caused by energy generation, combustion cycles, industry processes, heating, transportation, and incineration; relative contributions of each process differ locationally and are context specific. Air pollution can additionally be attributed to natural events such as a wildfires or volcanic eruptions.

In the United States, air pollution regulations are outlined within the Clean Air Act. The United States Protection Agency has identified National Ambient Air Quality Standards (NAAQS) for six criteria air pollutants, including: Carbon Monoxide, Lead, Nitrogen Dioxide, Ozone, Particulate Matter (PM2.5 and PM10), and Sulfur Dioxide [15]. These primary regulations limit constituent air concentrations based on the human health effects associated with exposure and toxicity. Secondary standards also exist to limit welfare effects on the population, these include impairment of visual range, acid deposition to lakes and streams, and damage to crops. If an area is reporting concentration levels higher than the guideline standards, then that region is classified as a "non-attainment area," for any singular pollutant. In contrast, regions meeting the guidelines are identified as "attainment areas". Different regional classifications and jurisdictions aim to decrease harmful emissions through differing stringencies throughout air pollution permitting procedures.

Hazardous Air Pollutants (HAPs) are a set of air pollutants that are not included in the EPA criteria pollutant list. HAPs are known to be associated with the degradation of human and environmental health and tend to have high carcinogenic properties. HAPs have different regulatory and legislative guidelines than criteria pollutants. Industrial facilities are considered "major" HAP emitters if their operations have the potential to emit more than 10 tons/year for an individual HAP, and more than 25 tons/year of all identified HAPs combined [16]. Deadly concentrations of HAPs and carcinogenic Volatile Organic Compounds (VOCs) can exist in household and indoor building settings.

Greenhouse gases are identified as gases that have the property to absorb infrared radiation, or heat energy [17]. They contribute to air pollution by interfering with the earth's energy balance and warming the earth's climate. Respective gas constituents have different global warming potential factors that correspond to their molecular formulas. Typically, greenhouse gas emissions are reported in Carbon Dioxide equivalence and quantified through comparisons between their molecular weights. Current atmospheric carbon dioxide concentrations equate to roughly 386 parts per million. It is estimated that the release of roughly 1 trillion tons of Carbon Dioxide between the years 2000 and 2050 will limit the warming of the earth below 2 degrees Celsius [18]. In the context of thermal comfort heating and cooling strategies, greenhouse gasses are emitted throughout all building lifecycle stages, including resource extraction, manufacturing, transportation, use, and end of life. The operational carbon dioxide equivalence, reported during the building use stage, and embodied carbon dioxide equivalence, reported through building materials, must be explicitly examined when considering and developing appropriate building heating and cooling infrastructure.

This section has outlined a general overview of practices and motivation strategies for controlling ambient air concentrations in the United States. Research in Indoor Environmental Quality (IEQ) advocates for the protection of indoor spaces- including but not limited to -indoor air pollution concentration levels.

Indoor Environmental Quality

Advocation for Indoor Air Quality in the United States developed alongside germ and filth theory in the late 19th century. It was brought to attention that germs could be present invisibly in the air and could exist in more greatly concentrated in certain growing environments. Max Joseph von Pettenkofer (1818-1902) observed how indoor air ventilation influenced carbon dioxide concentrations and further set a precedent for present-day air monitoring strategies [3]. The field has since then developed more holistically to include additional Indoor Environmental Quality metrics such as thermal comfort, acoustics, and lighting.

As defined by the Center for Disease Control, Indoor Environmental Quality refers to the quality of a building's environment in relation to the health and well-being of those who occupy the space within it [19]. Motivations behind preserving building indoor environmental quality include protection of human health, increased quality of life, and reduction of both stress and occupant injuries. That is, better IEQ can enhance the lives of building occupants, increase the resale value of a building, and reduce liabilities for building owners [20]. Current research in indoor environmental quality investigates the interaction of the four domains, with occupants, energy use, and building sustainability.

Compromised indoor air quality can deteriorate building occupant's health, both in the short term and the long term [21]. Air pollutants are sourced from compromised outdoor air entering the building, or indoor production processes including but not limited to: fuel burning combustion processes, tobacco products, building materials, central heating and cooling systems, cookstoves, and household cleaning solutions [22]. Humans uptake oxygen and exhale carbon dioxide, therefore, occupant loadings rates additionally influence indoor air pollution levels.

Indoor air quality mitigation strategies are separated into two categories, those being to reduce/irradicate the pollution source, or to provide adequate ventilation to disperse the pollutant. Both mechanical strategies, such as a fan or HVAC system, and natural strategies, such as window or door openings, can provide adequate building ventilation. Natural ventilation can reduce building energy consumption from cooling demands [23] and decreases the likelihood of building occupants being symptomatic with sick building syndrome [24]. However, natural ventilation is harmful in regions with adverse outdoor air quality and extreme outdoor temperatures. Mechanically ventilated buildings have intake air filters to collect pollutants such as Ozone and Particulate Matter ($PM_{2.5}$), which are documented to negatively affect occupant health [25], although these practices are largely energy and resource-intensive. Current research in indoor air quality aims to quantify the interactions between pollutant levels and occupant psychological/physiological states through surveying and satisfaction questionnaires [25].

Acoustic comfort is another Indoor Environmental Quality domain- defined as a building's capacity to protect occupants from noise and offer an acoustic environment suitable for the building's respective productive use [25]. Investment in the domain is necessary because there is a widely observed direct relationship between acoustic comfort and occupant productivity in commercial buildings [26]; however, research indicates that acoustic comfort is not considered a high priority in building design [27]. Building spaces are identified to be acoustically sound if they demonstrate minimal amounts of echoing and excess noise controls from indoor and outdoor adjacent spaces [28]. That is, workplace sound disturbances originate from two categories: annoyance from various noises and lack of communication privacy. It is established in [29] that irregular noises from telephones, talking, alarms, and abrupt machinery noises create more workplace disturbances than regular sounds. Implementation of noise masking devices and reverberation absorbing building materials can help decrease these irregular noise disturbances.

Additional noise reduction strategies include blocking sounds through space layout designs and workspace barriers.

Another human sense, vision, is considered in building design through the IEQ visual comfort domain. It is well established that occupant work performance, productivity, comfort, and satisfaction depend on adequate workplace lighting [25]. Visual comfort encompasses building lighting demands and occupant views from workplaces. If addressed ineffectively, lighting can exacerbate screen glare or decrease the ability for occupants to view details in their workspaces. Lighting needs can be met through natural windows or artificial lighting sources. However, natural lighting is preferred by occupants due to the therapeutic impact of natural views and its interaction with the circadian rhythm [30]. Natural practices also decrease building energy consumption from lighting demands but may increase building heating and cooling electrical needs. Best practices in visual comfort advocate for access to daylighting and quality views, while maintaining building energy sustainability and cost objectives.

Sick building syndrome (SBS) can occur when indoor environmental quality considerations are neglected throughout building design and building use lifecycle phases. The phenomenon encompasses a group of health problems that are caused by the indoor environment. Symptoms of SBS are associated with acute health discomfort and include headache, eye, nose, or throat irritation, dry cough, dry or itchy skin, dizziness and nausea, difficulty in concentrating, fatigue, and sensitivity to odors [24]. Sources that exacerbate the building condition include inadequate ventilation, chemical contaminants from indoor sources- such as adhesives, carpeting, upholstery, manufactured wood products, and VOC emitting compounds, chemical contaminants from outdoor pollutants, and biological contaminants- such as bacteria, mold, pollen, and viruses [24]. Research indicates that SBS symptoms are 30 to 200 times more prevalent in mechanically ventilated buildings than in naturally ventilated buildings [31] and that SBS leads to a rise in hospital visits, disproportionately in mechanically ventilated buildings [32]. Selection of quality lighting, ventilation, heating, and acoustic comfort strategies can decrease the likelihood of building SBS symptoms. Sustainable building frameworks aim to provide holistic criteria for, and motivation behind designing for occupant and environmental needs – in turn decreasing the likelihood of developing SBS.

Indoor environmental quality focuses on protecting the well-being of building occupants through four unique domains centered around human senses- smell, touch, sound, and internal health. Although each domain is elaborated on separately in this paper section, intersections are identified between them. Performance-based analysis conducted in this thesis only considers the IEQ thermal comfort domain; however, this framework can be expanded to analyze indoor air quality, acoustics, and lighting.

Sustainable Building Design Frameworks

Designing specifically for occupant needs, resiliency, and sustainability is becoming popular with an increasing prevalence of natural disasters and concern for climate change. The building construction sector is highly resource extensive, consuming a third of global resources, one-sixth of global freshwater withdrawals, 25% of wood harvested, and 40% of all raw materials [33]. Additional water and energy inputs are necessary to maintain a building's functionality during use. In 2019, residential and commercial buildings encompassed 28% of end-use energy in the United

States [34], sourcing the majority of the energy from fossil fuels. Humans have a large interaction with the built environment, making the functionality of buildings and the protection of indoor environmental quality critical for preserving human health.

Many building wellbeing frameworks have been developed to incentivize and categorize systems that are essential to human and environmental health. These frameworks are necessary for developing new sustainable building regulations and for general oversight in the construction market.

The LEED (Leadership in Energy and Environmental Design) Framework is the most popular of the sustainable building rating systems in the United States. It was developed by the US Building Council in 1993. The LEED Building Design and Construction (BD+C) framework, which also includes major building renovations, encompasses the following categories: (1) Location and Transportation, (2) Sustainable Sites, (3) Water Efficiency, (4) Energy and Atmosphere, (5) Materials and Resources, (6) Indoor Environmental Quality, (7) Innovation, and (8) Regional Priority.

In the most recent framework version, Indoor Environmental Quality accounts for 18 of the possible 100 LEED framework point opportunities and is broken up into four domains: Indoor Air Quality, Thermal Comfort, Acoustics, and Lighting. A total of 9 different credit opportunities exist ranging from 1 to 3 points each, and three prerequisite categories must be met to qualify for LEED framework evaluation. Table 1 outlines the most up-to-date LEED framework credit opportunities in IEQ and is sorted by Domain, Category, Corresponding Building Applications, Intent defined in the LEED handbook v4.1.

Additional well-building rating systems in the United States include BREEAM (Building Research Establishment Assessment Method), WELL, Fitwell, Green Globes, and the Living Building Challenge [35].

Table 1. Indoor Environmental Quality Parameters Defined in LEED v4.1 Guidelines

Domain	Category	Title	Intent (LEED v4.1)
Indoor Air Quality	Prerequisite 1	Minimum Indoor Air Quality Performance Required	To contribute to the comfort and well-being of building occupants by establishing minimum standards for indoor air quality (IAQ).
	Prerequisite 2	Environmental Tobacco Smoke Control Required	To prevent or minimize exposure of building occupants, indoor surfaces, and ventilation air distribution systems to environmental tobacco smoke.
	Credit (1-2)	Enhanced Indoor Air Quality Strategies	To promote occupants' comfort, well-being, and productivity by improving indoor air quality.

	Credit (1-3)	Low- Emitting Materials	To reduce concentrations of chemical contaminants that can damage air quality, human health, productivity, and the environment.
	Credit (1)	Construction Indoor Air Quality Management Plan	To promote the well-being of construction workers and building occupants by minimizing indoor air quality problems associated with construction and renovation.
	Credit (1-2)	Indoor Air Quality Assessment	To establish better quality indoor air in the building after construction and during occupancy.
Thermal Comfort	Credit (1)	Thermal Comfort	To promote occupants' productivity, comfort, and well-being by providing quality thermal comfort.
Acoustics	Prerequisite 1	Minimum Acoustic Performance Required	To provide classrooms that facilitate teacher-to-student and student-to-student communication through effective acoustic design.
	Credit (1-2)	Acoustic Performance	To provide workspaces and classrooms that promote occupants' well-being, productivity, and communications through effective acoustic design.
Lighting	Credit (1-2)	Interior Lighting	To promote occupants' productivity, comfort, and well-being by providing high-quality lighting.
	Credit (1-3)	Daylight	To connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.
	Credit (1-2)	Quality View	To give building occupants a connection to the natural outdoor environment by providing quality views.

Chapter 3: Data Collection Methods and Sampling Site Location

Chapter 3 elaborates on the case study sampling location, addressing specific local sustainability goals, and the case study building layout. Chapter 3 then expands on sampling techniques and measures taken to mitigate data biases and interferences.

The University of Washington Sustainability Goals

The University of Washington is a public research and academic institution located in Seattle, Washington. In the 2019-2020 academic year, the total student enrollment was 59,381, with undergraduate, graduate, and professional enrollment totaling 42,522, 14,628, and 2,209 students respectively. The campus employed 31,093 faculty and staff with a consolidated endowment at a market value of roughly $3,560,000,000 [36].

The University published a Climate Action Plan in 2009 aiming to promote sustainability in campus operations. This plan was redeveloped into the UW Sustainability Action Plan, including 10 measurable targets, on July 1st, 2020. The 10 targets are highlighted in Figure 2. Targets 8 and 10 direct relate to sustainability research conducted in this project. Target 8 aims to lower energy usage intensity by 25%, attempting to reduce electrical emissions through conservation efforts and increased investment in clean energy technologies. Target 10 aims to decrease greenhouse gas emissions from electricity consumption and transportation services. Additional efforts are in place to decrease environmental emissions across campus food, buildings, transportation, construction, and waste.

10 TARGETS AND THE ACTIONS WE'RE TAKING 2021–2025

	TARGET	ACTIONS		GUIDING PRINCIPLES*
I.	Double Student, Staff, and Faculty Sustainability Engagement by 2024	• Whole U and UW Sustainability Collaborate To Expand University-wide Communication	• Expand Professional Development Opportunities For Faculty and Staff • Inventory and Expand Community Engagement	● ● ● ○ ○
II.	One UW-Wide Sustainability Framework by 2022	• Adopt a University-wide Definition of Sustainability • Develop Standardized Reporting of Academic Content	• Identify Minimum Learning Outcomes • Determine Feasibility of a Student Sustainability Hub	● ○ ● ○ ○
III.	Double Sustainability-Oriented Research Projects by 2025	• Develop Sustainability Research Catalog	• Expand Campuses as a Living Laboratory	○ ● ○ ○ ○
IV.	Comprehensive Equitable Purchasing Targets by 2022	• Increase Student Engagement with Procurement Services	• Align Purchasing with Business Diversity and Equity Targets	○ ○ ● ○ ○
V.	5% Lower Emissions from Professional Travel by 2025	• Expand Online Conferencing	• Establish a Bank of High-Quality Greenhouse Gas Offsets	○ ○ ○ ● ○
VI.	35% of Food is From Local Sources by 2025	• Partner with Suppliers, Vendors and Campus Growers to Procure Food Locally		○ ○ ● ● ○
VII.	12% or Less of Commutes Are Single-Occupancy by 2028	• Promote Commute Options Toward SOV Reduction	• Promote Car Shares and UW Shuttle Service	○ ○ ● ● ●
VIII.	15% Lower Energy Usage Intensity by 2025	• Implement Cost Effective Conservation Investments	• Expand Campus Meter Monitor O&M Program • Purchase Only Energy Star Appliances	○ ○ ○ ● ○
IX.	10% Less Solid Waste by 2025	• Divert Compostable Waste from Recycling and Landfilling	• Implement Low-Waste Campus Kitchens	○ ○ ○ ● ●
X.	45% Reduction of Greenhouse Gas Emissions by 2030	• Electrify UW Transportation Services	• Plan to Repower the Seattle Campus • Implement Campus Solar Plan	○ ○ ○ ○ ●

*A PLAN GROUNDED BY THESE PRINCIPLES

- Ensure Students Achieve Sustainability Literacy
- Choose our Research Conscientiously
- Keep Equity and Inclusion at the Center
- Use Resources Responsibly
- Decarbonize

Figure 2. UW 10 Sustainability Targets and Actions Taking in 2021-2025 [37]

The University of Washington purchases the bulk of its electricity from Seattle City Light (SCL). The campus also maintains a small amount of onsite electricity generation sourced from solar panels and a steam power plant. Total electricity use on the Seattle campus in 2016 equated to

307,987,203 kWh or 5365 kWh/person. Electricity consumption per square foot was 20 kWh. Overall, electricity consumption has risen from 2000 to 2016, although electricity per capita and square foot has slightly decreased. On average, since 2000, electricity consumption per academic quarter is highest in the summer, as reported in Figure 3 [38]. The increase in consumption across the summer quarter is caused by increased cooling system and ventilation requirements throughout the cities hotter months. This offers worrisome insight for maintaining thermal comfort and building resiliency under increasing global temperatures and a changing global climate. Onsite renewable energy systems can provide energy security in times when grid infrastructure is compromised.

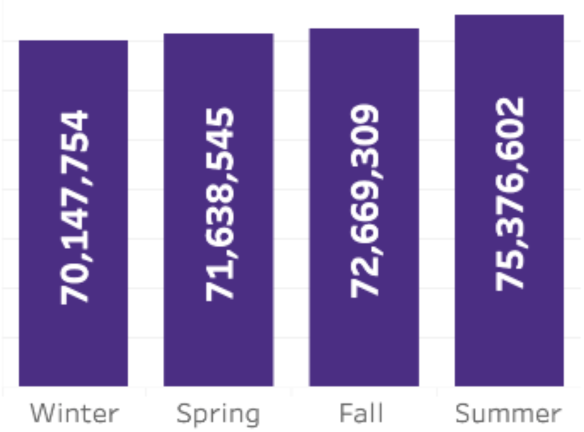

Figure 3. UW Seattle Campus Average Electricity Consumption by Quarter (2000-2016 data) [38]

The Husky Union Building on the UW, Seattle Campus

The Husky Union Building, or HUB, on the University of Washington campus provides a dynamic event center for current students, visiting students, and university faculty. The multiuse, low-rise, 273,442 square foot building was built in 1949 and went through a two-year renovation in 2013.

Figure 4. The HUB on the UW Campus [39]

The building is Leadership in Energy and Environmental Design Gold certified, achieving 64 credits from the LEED 2009 New Construction certification. Explicit credits that were met for the HUB are outlined in Figure 5. The scorecard suggests a strong building performance in innovation, water efficiency, and sustainable sites, but calls for improvements in Indoor Environmental Quality, Energy and Atmosphere, and Materials and Resources.

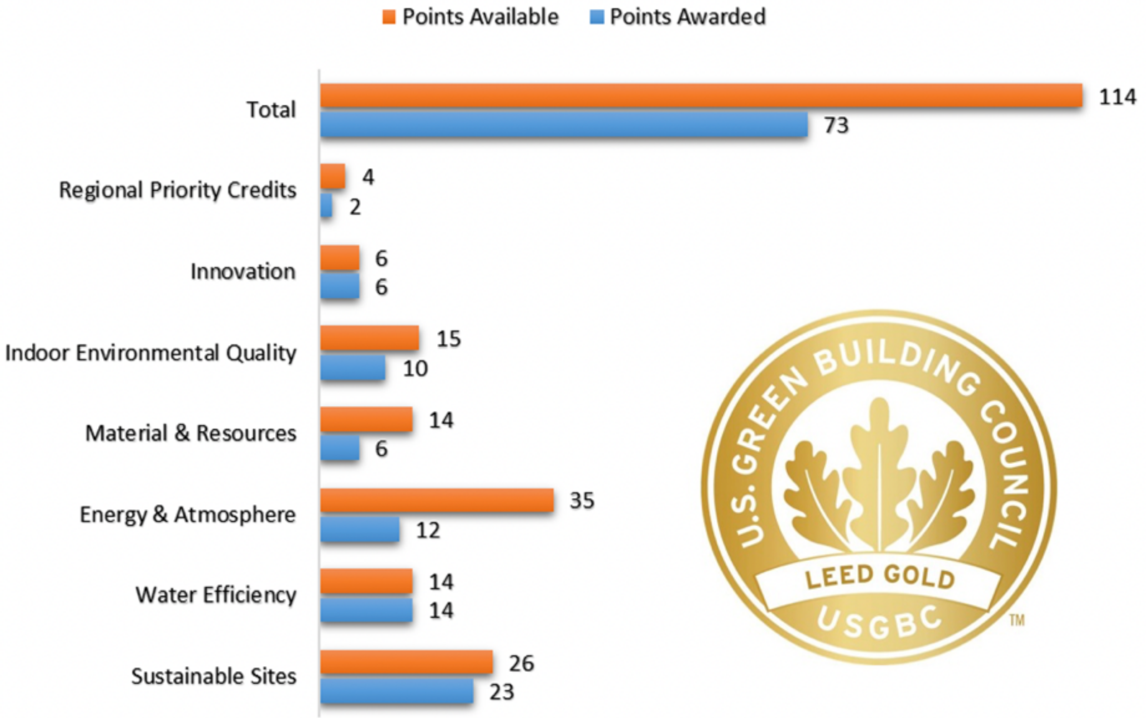

Figure 5. UW HUB LEED Scorecard

The building did not meet LEED BD+ C: New Construction v.3 guidelines for Controllability of Thermal Comfort Systems (EQc6.2) or Thermal Comfort Design (EQc7.1) within the IEQ domain [40]. The LEED credit opportunities associated with thermal comfort and their intent are outlined in Table 2. It is important to note that the HUB LEED scorecard is different than the one outlined in Chapter 2 - the field is continuously evolving with more stakeholder interest and research, thus updated versions of more stringent and resilient frameworks are frequently released. The most up-to-date framework during the HUBs remodel was LEED v.3.

Table 2. LEED BD+ C: New Construction v.3 Credits Pertaining to Thermal Comfort

Credit Category	Intent
Controllability of Systems- Thermal Comfort (EQc 6.2)	To provide a high level of thermal comfort system control by individual occupants or groups in multi-occupant spaces (e.g., classrooms or conference areas) and promote their productivity, comfort, and well-being [41].
Thermal Comfort- Design (EQc7.1)	To provide a comfortable thermal environment that promotes occupant productivity and well-being [42].

Data Collection Methods

Time series of global indoor and outdoor temperatures were collected during three academic quarters, Summer 2014, Fall 2014, and Winter 2015, at the HUB building on the University of Washington Campus.

Indoor global temperature measurements were sampled at the Student Legal Services office, located in the northern part of the third floor. The office space has west-facing windows and was chosen as a represented space for average indoor environmental quality building conditions. The average baseline occupant load included a staff supervisor and two to three student employees. Additional variable occupants include those seeking legal service guidance and enter on an appointment-only basis.

Figure 6. SLS Office and Sampling Station

SLS office samples were taken in the middle of the office space in the occupant seating area. The space received adequate natural ventilation from motorized operable windows. Measures were taken to mitigate indoor air quality and temperature bias by sampling at a location with limited direct sunlight availability and through proper distancing between instruments and occupants. Indoor global temperature measurements were sampled using the Extech HT30 instrument. The sampling station setup is shown in Figure 6, along with the SLS office location. Accuracy and range parameters for the device are presented in Table 3.

Table 3. Indoor global temperature instrument specifications

Instrumentation	Sensor Type	Accuracy	Range
Extech HT30	Blackball: 1.57 Diameter, 1.37 Height	Indoor Global Temperature +/- 4 ° F	Wet Bulb Global Temperature 32 ° F to 122° F
		Outdoor Global Temperature +/- 5.5 ° F	Wet Bulb Global Temperature 32 ° F to 176° F
		Dry Bulb Temperature +/- 1.8 ° F	Dry Bulb Temperature 32 ° F to 122° F
		Relative Humidity +/- 3%	Relative Humidity 0% to 100%

It is important to note that different seasonal data collected throughout the respective quarters are assessed separately and independently in this analysis. The Fall quarter is split into two sections that correspond with the presence of building heating mechanisms. The first section encompasses dates from October 2nd to November 10th. The second includes November 10th through December 12th. The Section 5.4 ASHRAE 55-2017 standards mandate that no heating systems are in operation; however, the Winter quarter data and the second half of the Fall quarter data do not follow this prerequisite. Additional ASHRAE 55-2017 Section 5.4 prerequisites, listed below, are met.

Temperature observations were taken every minute inside the HUB between 8:00 and 20:00 Pacific Time for each date examined, totaling 720 observations per day. Dates with missing or incomplete data were removed from statistical analysis to eliminate potential biases from the variation of temperatures throughout the day. Global Indoor Temperature Measurements throughout each academic quarter are shown in a histogram in Figure 7. For a reality check, indoor temperature observations during the summer season are warmer than those observed throughout the fall and winter months. Figure 8 displays the collected global indoor temperature time series data for all of the dates measured.

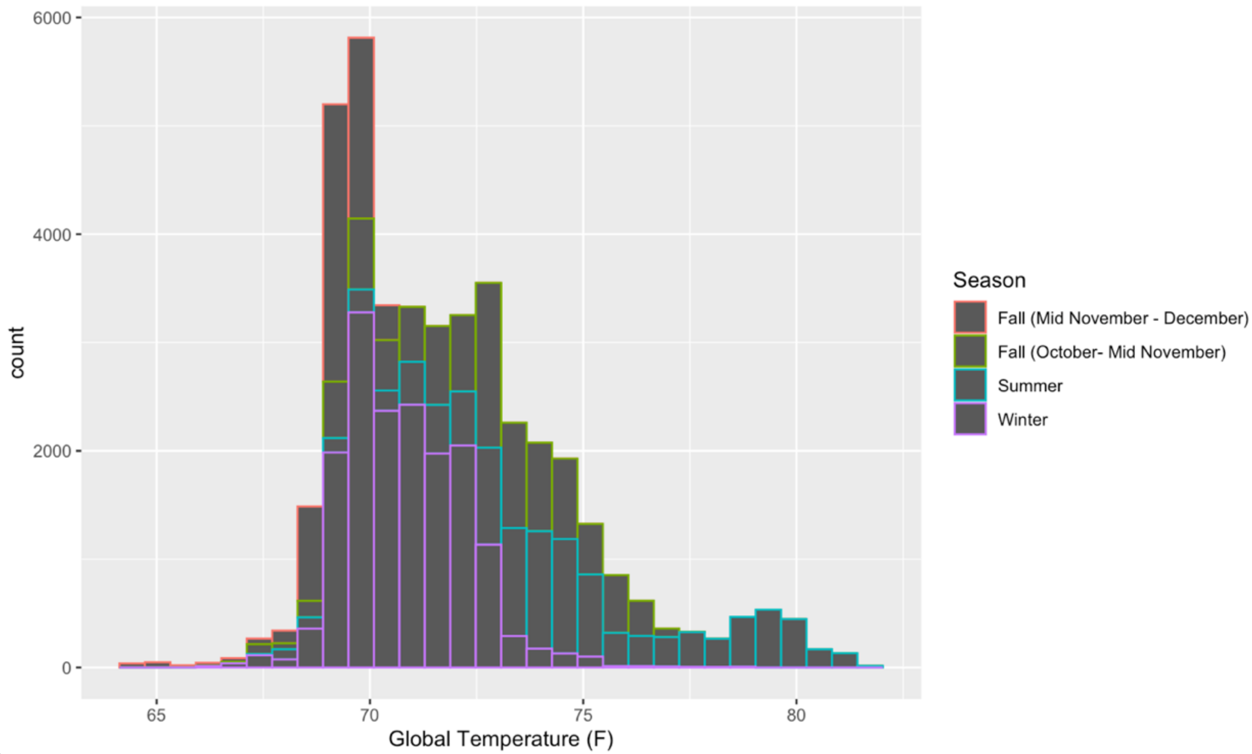

Figure 7. Histogram of Indoor Global Temperature Measurements taken in Spring, Fall, and Winter at The UW HUB

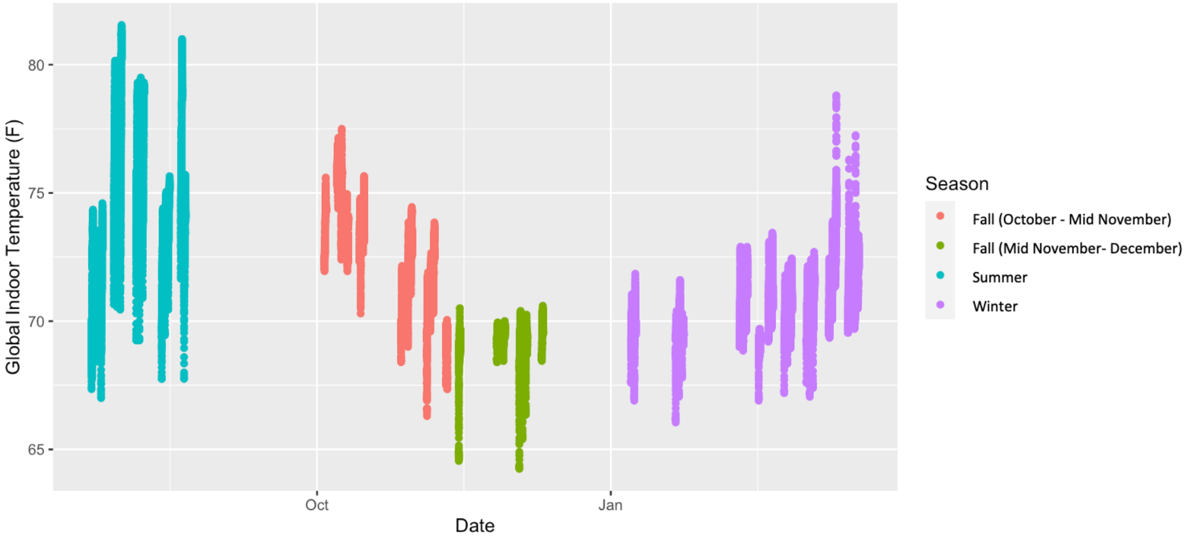

Figure 8. Global Indoor Temperature Time Series Data

Chapter 4: Performance-Based Design Analysis

Chapter 4 elaborates on the performance-based analysis taken to examine thermal comfort limit state equations in this thesis. It first introduces Monte Carlo methods, then expands on probability density functions and model characteristics. Finally, it outlines criteria for best fit model selection, with a specific focus on extreme value distributions.

Methodology and the Monte Carlo Simulation Technique

Computer simulation techniques and models are commonly used to study uncertainty and reliability. These methods use observed data and their probability distributions to identify and extrapolate data trends. Comparative to laboratory testing, these techniques are more inexpensive and less resource extensive.

The Monte Carlo Simulation technique is used in this paper because the data sets for analysis are limited. That is, indoor temperatures were collected over a defined time interval, probability density functions are used to find trends in the collected data and model or simulate data for similar days.

To use Monte Carlo Simulations, 6 essential conditions must be satisfied: 1) Define the problem in terms of random variables; 2) Quantify the probability characteristics for all random variables through Probability Density Functions or Probability Mass Functions and identify corresponding parameters; 3) Generate random variable values; 4) Evaluate the defined problem, or limit state, for each trial simulation; 5) Extract probability results for each N simulation; 6) Determine the accuracy of the trials [10].

In this case study, density histograms of indoor temperatures were plotted and examined. Then probability density functions, including Normal, Lognormal, Weibull, and Extreme Value, were parameterized to model the indoor temperature data. Then, the distribution model of best fit was chosen through K-S testing, The Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and Quantile- Quantile (Q-Q) plots. From here, best-fit model parameters were identified and noted. Finally, the Monte Carlo method was used to gather trial values through a uniform distribution random number generator. The values are fit to the selected probability distribution, chosen to explicitly represent each limit state parameter. Many independent trials, in this case, 10,000,000, were counted, documented, and tested against the limit state equation.

ASHRAE Limit State Examined

The HUB building meets ASHRAE 55-2017 Section 5.4 standards for Determining Acceptable Thermal Conditions in Occupant-Controlled Naturally Conditioned Spaces during the summer and the start of the fall quarter. Mechanical heating processes are activated in colder months to maintain safe building temperatures, which violates Section 5.4 prerequisites. ASHRAE 55-2017 Section 5.3 outlines thermal comfort procedures for mechanically ventilated buildings using a psychrometric chart. This process is considerably more complicated than the process examined for in this report. Although, this report focuses more on the cooling thermal comfort applications rather than heating.

The ASHRAE guidelines are expanded on bellow with the following criteria requirements [11]:

a) There is no mechanical cooling system (e.g., refrigerated air conditioning, radiant cooling, or desiccant cooling) installed. No heating system is in operation.
b) Representative occupants have metabolic rates ranging from 1.0 to 1.3 met.
c) Representative occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5 to 1.0 clo.
d) The prevailing mean outdoor temperature is greater than 10°C (50°F) and less than 33.5°C (92.3°F).

If prerequisites are met, the allowable indoor operative temperature is determined using the mean daily outdoor temperature, defined as the simple arithmetic mean of all the outdoor dry-bulb temperature observations for the 24-hour day. The allowable indoor operative temperatures are defined in Equations 3-6 and are shown graphically in Figure *9* (Figure 5.4.4 in ASHRAE in 55-2017).

$$T_{in(°\mathrm{C})\mathrm{Upper}} = 0.31T_{out} + 21.3 \tag{3}$$

$$T_{in(°\mathrm{C})\mathrm{Lower}} = 0.31T_{out} + 14.3 \tag{4}$$

$$T_{in(°\mathrm{F})\mathrm{Upper}} = 0.31T_{out} + 60.5 \tag{5}$$

$$T_{in(°\mathrm{F})\mathrm{Lower}} = 0.31T_{out} + 47.9 \tag{6}$$

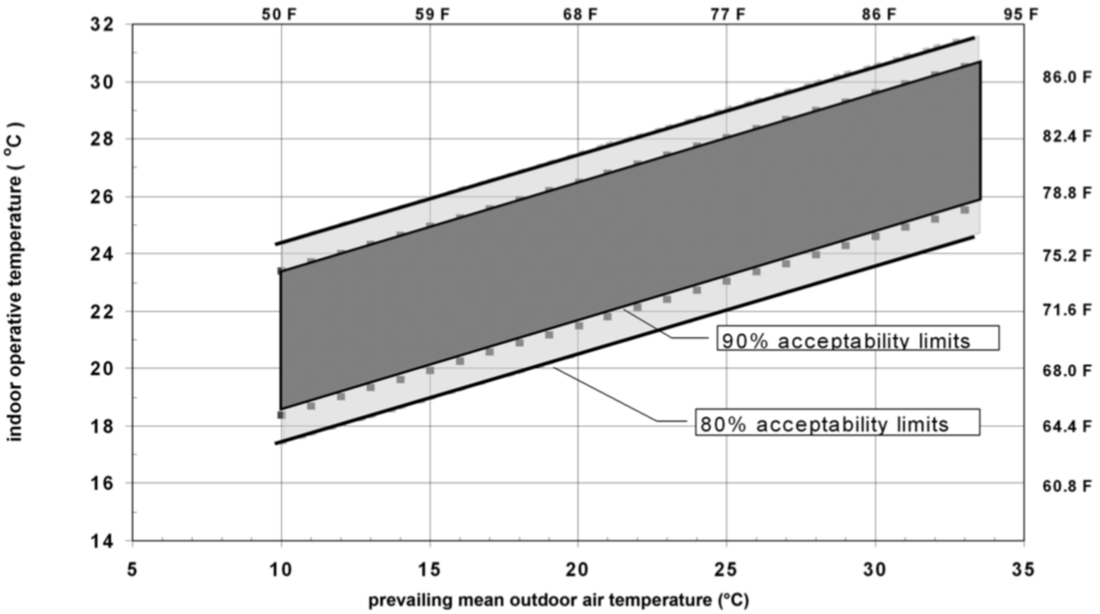

Figure 9. Acceptable operative temperature t_O ranges for naturally conditioned spaces [7]

Preliminary Analysis of Summer, Fall, and Winter Timeseries Data

The upper and lower temperature threshold limits were calculated using the mean daily outdoor temperature through ASHRAE 55-2017 Standards, equations (5) and (6). Assuming normally distributed upper and lower limits for outdoor temperature, the average indoor limit value is calculated for each respective season; summer, both fall sections, and winter and is shown in Table 4. These values are used as constants in the limit state equation.

Table 4. Calculated Average ASHRAE 80% Temperature Threshold Limit Ranges for Summer, Fall, and Winter respectively

	Average ASHRAE 80% Temperature Threshold Limit Ranges (C)	Average ASHRAE 80% Temperature Threshold Limit Ranges (F)
Summer 2014	20.51 to 27.51	68.92 to 81.52
Fall 2014 (10/2 - 11/10)	18.68 to 25.68	65.62 to 78.22
Fall 2014 (11/11 - 12/12)	16.56 to 23.56	61.81 to 74.41
Winter 2015	17.04 to 24.04	62.67 to 75.27

Lognormal, Normal, and Weibull distributions were considered and fit to the indoor global temperature data for each quarter.

The Kolmogorov-Smirnov (K-S) test was used to assess each model with its corresponding goodness of fit. The values are summarized in Table 5 and plotted for Summer, Fall Subsections, and Winter in Figure 14. The K-S test is used to determine if a sample comes from a population with a specific distribution. The K-S test D statistics value is computed for a significance of alpha equal to 0.05 using $1.36/\sqrt{n}$ for 10080, 9360, 5760, and 16560 observations in Summer, Start of Fall, End of Fall, and Winter. It is important to note that the K-S test alpha significance values favor smaller data sets, thus the proposed distribution fits were not under the alpha threshold values [13].

Although the fitted distributions did not meet this significance value, distributions were chosen to best represent the indoor air temperatures due to the best graphical fitting and lowest comparable K-S test value for each of the three seasons. Distribution expectation, and variance are documented in Table 6 and will be used in Monte Carlo simulations to assess the thermal comfort limit state equation (7).

$$g(R,S) = g(T_{indoor,\ limit} - T_{indoor,actual}) \tag{7}$$

Table 5. Calculated K-S Test Distribution Fits for Indoor Air Temperatures in Summer, Fall, and Winter respectively

	K-S Test Weibull	K-S Test Normal	K-S Test Lognormal	D Value at 95% Significance
Summer 2014	0.148	.0945	0.086	0.013
Fall 2014 (10/2 - 11/10)	0.062	0.062	0.067	0.014
Fall 2014 (11/11 - 12/12)	0.094	0.181	0.186	0.018
Winter 2015	0.151	0.069	0.067	0.011

Table 6. Distribution Fits and Model Parameters for Indoor Air Temperatures in Summer, Fall, and Winter respectively

	Distribution Fit	Expectation	Variance
Summer 2014	Lognormal	78.4	9.0
Fall 2014 (10/2 -11/10)	Normal	72.6	4.1
Fall 2014 (11/11-12/12)	Weibull	69.2	0.8
Winter 2015	Lognormal	70.8	1.9

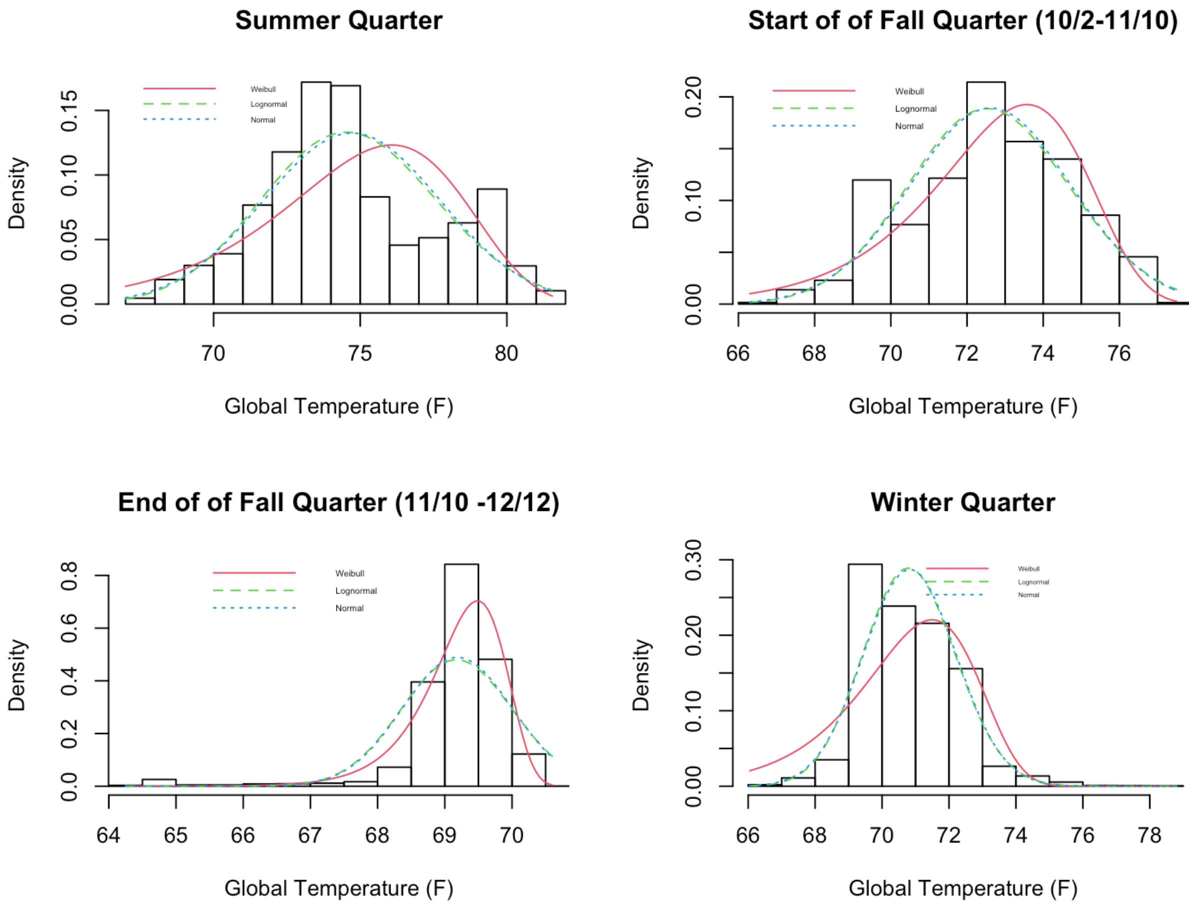

Figure 10. Histograms of HUB Indoor Global Temperatures with Fitted Distributions for Summer 2014, both Fall 2014 subsections, and Winter 2015 Quarters

The Monte Carlo Results are outlined in Table 7, along with the ASHRAE temperature range, calculated from the given datasets mean and standard deviation and the outdoor temperatures. The temperature range is reiterated from earlier in the report to facilitate comparison. The lower bound percentage of exceedance refers to the instances where the temperature threshold exceeds the lower threshold bound, and the upper percentage of exceedance denotes the exceedances of the upper bound, higher temperature, range. Zero probability of failure suggest zero failure trails during 10,000,000 Monte Carlo simulations and can be interpreted as very high beta values with little probability of failure associated with their temperature limit.

Table 7. Monte Carlo Simulation Percentage of Exceedance for Summer, Fall, and Winter respectively

	ASHRAE Temperature Range Threshold (F)	Lower Bound Percentage of Exceedance	Upper Bound Percentage of Exceedance
Summer	68.92 to 81.52	2.5%	1.3%

Start of Fall	65.62 to 78.22	0.04 %	0.4%
End of Fall	61.81 to 74.41	$1.5*10^{-5}$ %	0%
Winter	62.67 to 75.27	0%	0.08%

Monte Carlo method results illustrate a higher probability of failure of the ASHRAE temperature range limits in the Summer Quarter and the Start of the Fall Quarter compared to the End of Fall, and Winter Quarter. This finding is attributed to the fact that no mechanical ventilation or heating mechanisms were functional during the warmer quarters, suggesting more indoor temperature variability in these seasons.

Extreme Value Analysis on the Summer Quarter Time Series Data

The highest university energy demands and the highest probability of ASHRAE thermal comfort limit state exceedance exist during the Summer Quarter. Therefore, additional analysis is performed to better understand building resilience, energy reliance, and the relationships between indoor and outdoor temperatures [43].

It is important to acknowledge that seasonal temperatures vary across years and that due to this variability, data collected from one year may not holistically capture the next. That is, 2014 temperatures in August were reported higher on average from those collected between 1998 and 2020, shown in Figure 11; suggesting that all Seattle summers may not layout in parallel with the observations in this report.

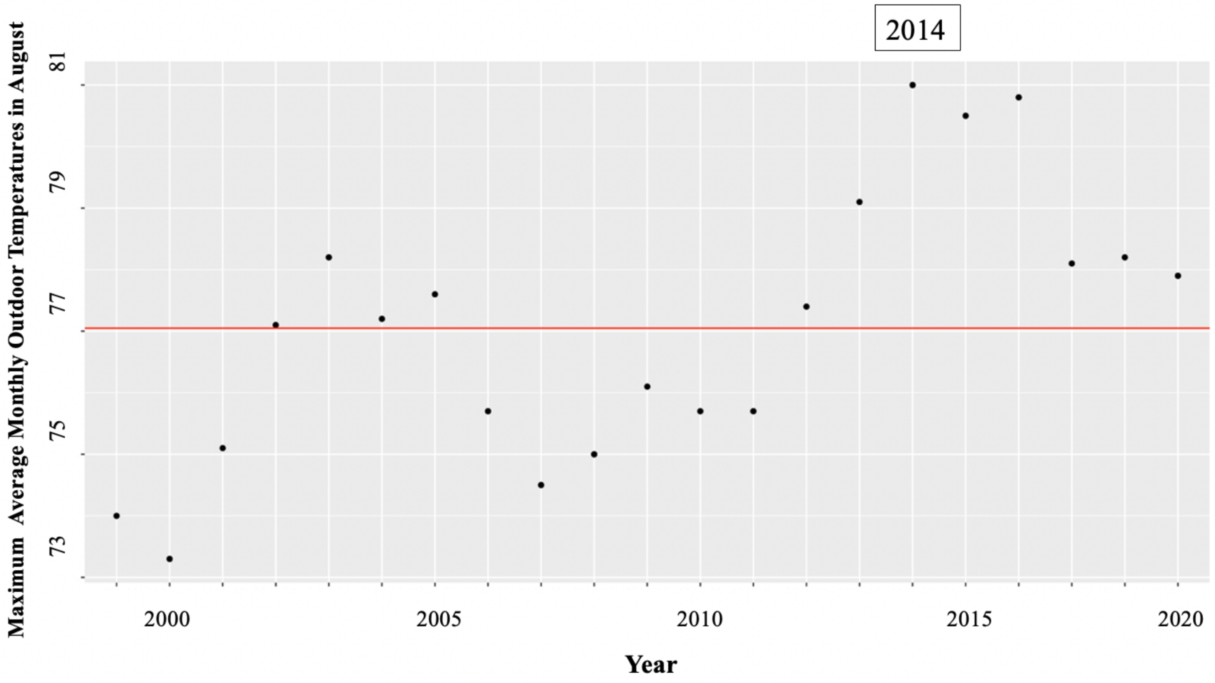

Figure 11. Annual average temperatures for August in Seattle, WA from 1998 to 2020

As previously mentioned, 720 indoor temperature observations were recorded for each day examined in this data analysis. Time series data for the summer quarter is shown in Figure 12. Larger temperature spreads are present on July 29th, July 30th, July 31st, August 5th, August 6th, August 7th, and August 19th.

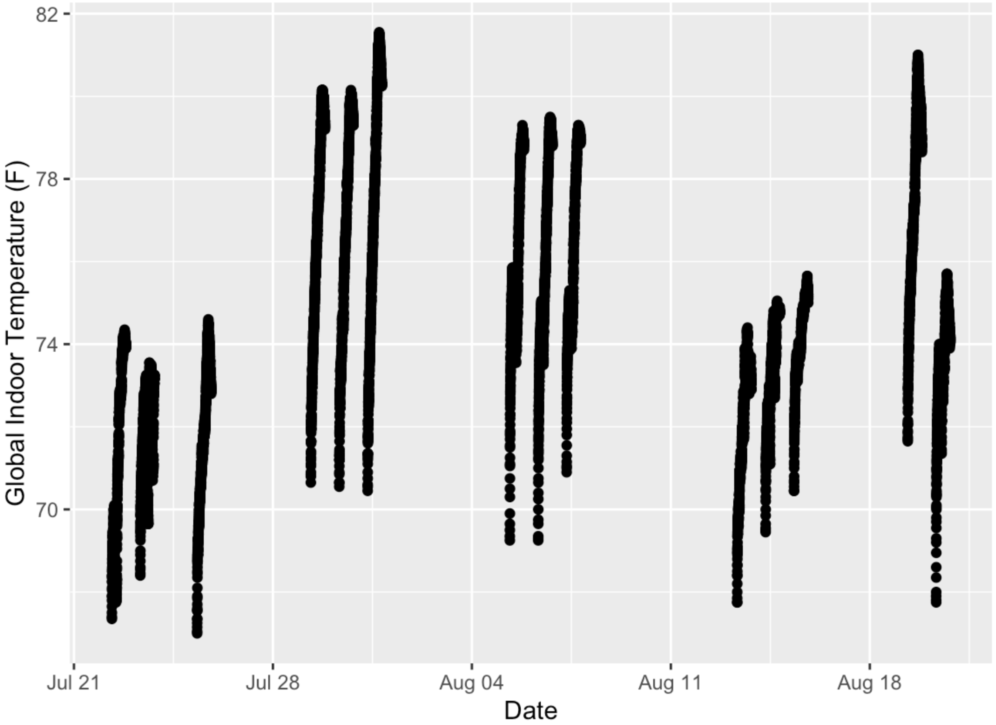

Figure 12. Indoor Global Temperature Measurements at the HUB during the Summer Quarter

The larger temperature spreads are consistent with higher outdoor temperature values, which are plotted in Figure 13, Outdoor temperature values and the daily maximum indoor temperature, in Fahrenheit, maintain a linear relationship, Equation (8), with an Adjusted R-Squared value of 0.82.

$$Tobs\ (°\mathrm{F})_{,indoor} = 0.408 * Tobs(°F)_{,\ Outdoor} + 46.45 \qquad (8)$$

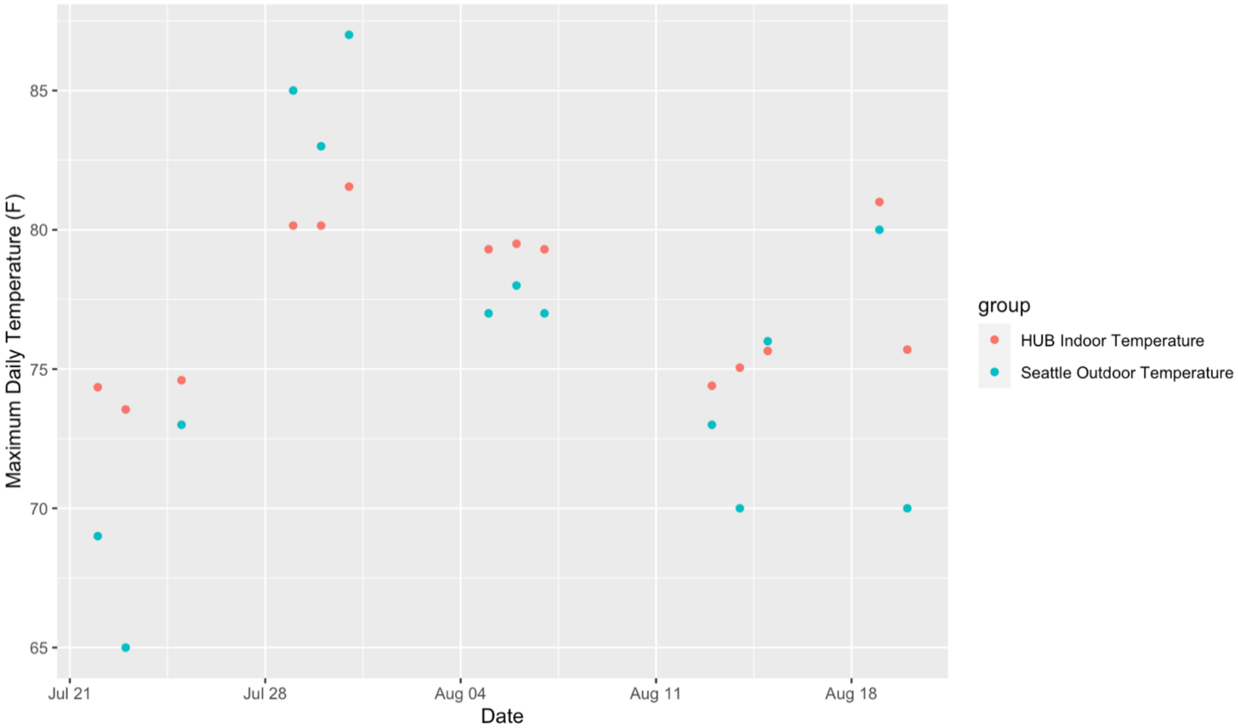

Figure 13. Indoor and Outdoor Maximum Daily Temperature Measurements during the Summer Quarter

Maximum indoor daily temperature measurements are fit to extreme value distributions using the extRemes package in R. The extRemes was created by the Weather and Climate Impacts Assessment Science (WCIAS) Program at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and is configured to work with extreme temperature data [44]. Distributions examined for fit include the Generalized Extreme Value (GEV), generalized Pareto (GP), Gumbel, and Exponential. Using the Maximum Likelihood Estimation method, the GEV and Gumbel distributions obtained the lowest AIC and BIC values. The Gumbel and General Extreme Value (GEV) distributions were fit to the summer extreme indoor value temperature dataset and density curves are displayed in Figure 14.

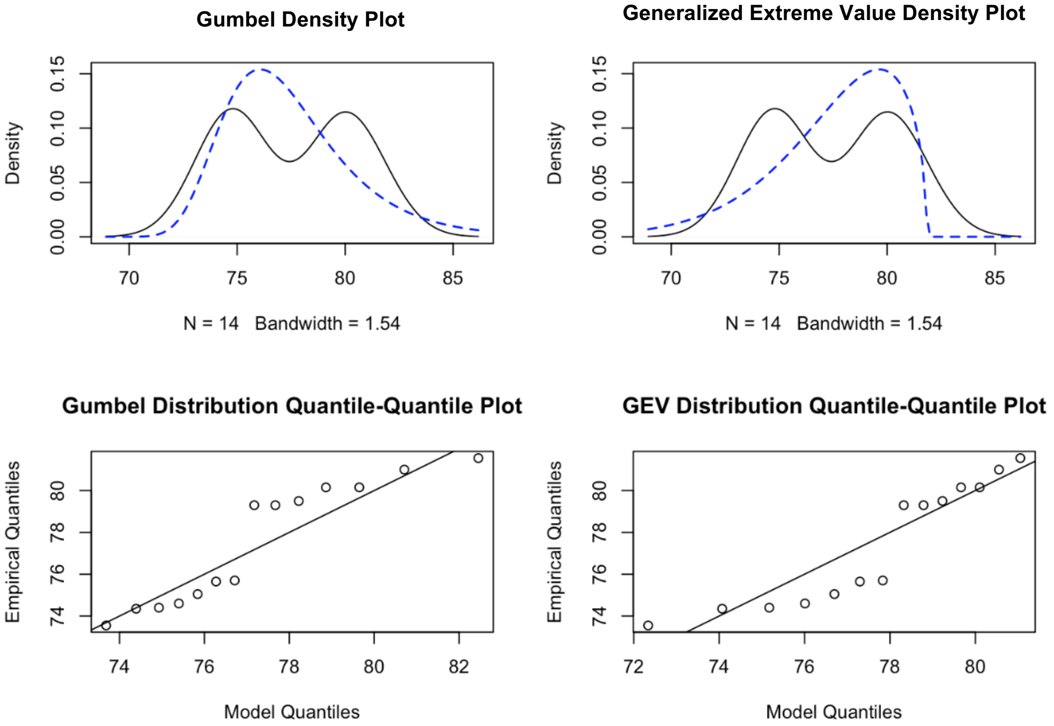

Figure 14. Density distribution and Q-Q plots examining summer extreme value indoor temperature data

The summer extreme value density is partially bimodal, potentially caused by lower or cloudy outdoor temperature days, as shown when comparing Figure 12. Indoor Global Temperature Measurements at the HUB during the Summer Quarter and Figure 13. Indoor and Outdoor Maximum Daily Temperature Measurements during the Summer Quarter. The Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Quantile- Quantile (Q-Q) Plot [45], and upper tail values were most precisely predicted by the Gumbel distribution, thus the Gumbel distribution was chosen to best represent the maximum indoor temperature values during the summer quarter at the HUB. The Gumbel distribution parameter values and their corresponding model fit are outlined in Table 8.

Table 8. Gumbel Extreme Value Distribution MLE Fit

Parameter	Location	Scale
	76.07	2.39
	Mean	Standard Deviation
	77.45	3.06
Model Fit	AIC	BIC
	72.57	73.85

The same procedure is taken for Summer, Fall, and Winter. Limit State Analysis was used to assess the Summer Quarter Maximum Daily Indoor temperature values against the upper ASHRAE 55-

2017 80% Comfort Standard Threshold. A Gumbel distribution with its corresponding MLE fit was simulated through 10,000,000 Monte Carlo Simulations. The percentage of a single indoor temperature exceedance per day of the ASHRAE temperature threshold and different temperature barriers during the summer quarter are outlined in Table 9.

Table 9. Monte Carlo Simulation Probability of Exceedance Values for Summer Maximum Daily Indoor Temperatures

Temperature Threshold (F)	Percentage of Exceedance
81.52 (ASHRAE 55-2017 Standard)	2.3%
80	10%
78	30.2%
76	53.6%
74	72.3%
72	84.4%

Chapter 5: Conclusions

Chapter 5 summarizes the results of the investigation, examines them in the context of sustainability goals, and suggests future directions for this research.

Discussion and Conclusion

The built environment was created to decrease the burden of disease and illness on humans. It has cultivated shelters, energy infrastructure, water management strategies, transportation access, and community gathering locations. While having different productive use cases, infrastructure is owned by individuals, communities, industries, governments, and cooperation's. By the same token, for a commercial building to be deemed functional, it should cultivate a strong working environment while protecting occupants from the burden of illness and diseases - specifically from indoor environmental quality factors.

The Indoor Environmental Quality thermal comfort domain directly relates to building sustainability, corporate energy goals, and occupant productivity. A performance-based analysis is conducted on the thermal comfort stimuli at a university building to determine if ASHRAE standards are safe and reliably maintained at a naturally ventilated building in the Pacific Northwest climate. Seattle, Washington is an important location to perform the outlined performance-based analysis because the majority of the current building infrastructure lacks adaptability for shifting weather patterns and wildfire smoke throughout the summer [46]. According to the American Housing Survey, in 2013 only 31% of households in the Seattle metro area had some sort of air conditioning. This number has risen to 44%, 6 years later [46].

Additionally, there is a discrepancy among income groups with infrastructure adaption, with 53% of homeowners having implemented AC and only 28% of renters [47]. In 2019, Seattle's metro had the lowest ranking for residential implementation of Air Conditioning among metro areas tracked, behind San Francisco, with a 47% adoption [47].

Results outlined in Chapter 4 indicate that thermal comfort ASHRAE guidelines are most often exceeded throughout the summer quarter. Additionally, that there is a large (53.6%) percentage of maximum indoor daily temperature exceedance during the summer beyond 76° Fahrenheit, and a smaller (2.3%) exceedance beyond the ASHRAE seasonal temperature threshold of 81.52° Fahrenheit. It should be noted that building temperatures above 76° Fahrenheit in the Pacific Northwest climate can be quite hot, the medical definition of room temperature from the Merriam-Webster Dictionary [48] is 59° to 77° F.

Traditionally, performance-based analysis is conducted to determine the reliability of civil infrastructure - specifically in structural applications - yet the framework in this report is adapted for building conditions. Eurocode 1 suggests recommended Reliability Index Values, β, for variable limit state loads and different structure classes [49], [50]. Reliability Class 1 (RC1) is the least stringent and has low consequences for loss of human life and economic, social, or environmental consequences small or negligible. Class (RC2) has medium and considerable consequences, including bridge infrastructure. Class 3 (RC3) has the highest consequences and the most stringent accepted failure. Eurocode annual probability of failures for RC3, RC2, and RC1 are 10^{-7}, 10^{-6}, and 10^{-5} respectively. To put in the context of this thesis, an extreme indoor building temperature has a different acceptable level of risk than a structural failure. Consistent daily indoor temperature exceedances call for a reevaluation of the current heating and cooling strategies in Seattle. It is suggested that commercial building owners implement additional building cooling infrastructure during the summer months to mitigate the loss of work productivity from compromised indoor conditions. It is also suggested that this infrastructure development supplies energy from resilient and robust systems - so that in case of an extreme weather event- building functionality is not compromised. There are considerable documented building reliability evaluations for extreme wind and water-related events, however, limited building reliability analysis for extreme heat-related events exist [46].

Current ASHRAE standards for naturally conditioned spaces compute indoor temperature recommendations from one variable predicator: outdoor temperature. Data collected in this case study during the summer suggest that the outdoor daily maximum temperature is a good direct indicator of indoor daily maximum temperature- resulting in an R Squared Value of 0.82. This correlation value is highly accepted in real-world data applications and validates current ASHRAE guideline standards. However, further research could be taken to study how additional parameters affect indoor temperature conditions. Some parameters include, but are not limited to, occupancy loadings, technological systems in use, indoor ventilation wind speeds, humidity, local air dispersion rates, and direct sunlight radiation into the respective location analyzed. Of course, because the thermal comfort field is adaptive and regional specific this correlation is only confirmed for Seattle Pacific-Northwest outdoor summer temperatures.

In this specific case study circumstance, both passive and active strategies exist for maintaining comfortable building temperatures in the summer while adhering to university sustainability goals.

Increasing natural air ventilation during the nighttime, through opening windows, will help to buffer the building temperature rise during daytime hours. This strategy is cost effective but could lead to compromised building indoor air quality conditions if the outdoor air is contaminated. Development of AC infrastructure in the HUB will help maintain indoor building thermal conditions but will increase building energy consumption. The addition of an onsite renewable energy production system can offset the environmental degradation associated with additional energy consumption and can provide more building resiliency.

It is important to consider the types of uncertainty and implicit biases present throughout the proposed probability-based framework to better understand model assumptions and results. In structural engineering, aleatoric uncertainty relates to the inherited variability of basic information, or how unknows differ each time an experiment is run. Overall, these uncertainties are difficult to mitigate due to their presence in nature. Epistemic uncertainty is described as the imperfect knowledge of the real world and how systems operate in theory versus in practice. In civil engineering, epistemic uncertainty can be reduced through the application of enhanced models and improved experiments. The effect of aleatoric randomness can lead to a calculated probability or risk, whereas epistemic uncertainty can express the uncertainty of estimated risk. [51]. In this report, examples of aleatoric uncertainties include uncertainties in occupant window opening behavior, temperature mixing conditions, and variability in the overall collected data from sensor drift. In this project context, examples of epistemic uncertainties include Monte Carlo Model assumptions, as well as discrepancies in sample frequencies and the data collection process.

There are intersections between indoor environmental quality domains and differing performance optimization strategies for each domain – making it difficult to determine the best practices in thermal comfort and for overall building functionality. A call for further research and data collection is advised to more accurately represent the intersections between the four domains themselves and their associated energy consumptions. That is, a satisfactory performance in thermal comfort may increase building energy demands while decreasing building acoustic comfort from HVAC noise. There is a current research agenda to investigate the best multi-domain IEQ building practices [52] in order to revise sustainable building guidelines and to provide general guidance in the building market. Further research could provide an optimal strategy that would cater to all IEQ needs yet address building sustainability goals, and economic project constraints; Performance based analysis framework can help adhere in cultivating these strategies.

In conclusion, regulating building indoor conditions is difficult due to the complexity of individual preferences and the intersection between project economics and environmental sustainability. There is no silver bullet for maintaining thermal comfort in every building thus different scenarios must be examined explicitly for individual user groups and climate conditions. However, because people spend 90% of their time indoors, any enhancement of indoor environment quality will lead to higher occupant comfort, productivity, and ultimately benefit society.

References

[1] "hvac-factsheet-energy-breakdown.pdf." Accessed: Nov. 19, 2020. [Online]. Available: https://www.environment.gov.au/system/files/energy/files/hvac-factsheet-energy-breakdown.pdf

[2] N. E. Klepeis *et al.*, “The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants,” *J Expo Sci Environ Epidemiol*, vol. 11, no. 3, pp. 231–252, Jul. 2001, doi: 10.1038/sj.jea.7500165.

[3] “SEAOC, Vision 2000, conceptual framework for performance-based seismic design. Recommended Lateral Force Requirements and Commentary, 1996, 1996: p. 391-416.”.

[4] “CDC - Indoor Environmental Quality - NIOSH Workplace Safety and Health Topic,” Jul. 02, 2019. https://www.cdc.gov/niosh/topics/indoorenv/default.html (accessed Nov. 17, 2020).

[5] R. F. Rupp, N. G. Vásquez, and R. Lamberts, “A review of human thermal comfort in the built environment,” *Energy and Buildings*, vol. 105, pp. 178–205, Oct. 2015, doi: 10.1016/j.enbuild.2015.07.047.

[6] R. J. de Dear and G. S. Brager, “Developing an Adaptive Model of Thermal Comfort and Preference,” p. 19.

[7] F. Nicol and M. Humphreys, “Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings,” *Energy and Buildings*, vol. 34, pp. 563–572, Jul. 2002, doi: 10.1016/S0378-7788(02)00006-3.

[8] J. Malik, R. Bardhan, and P. Banerji, “Rethinking indoor thermal comfort in the era of rebound and pre-bound effect for the developing world: A systematic review,” *Indoor Air*, vol. 30, no. 3, pp. 377–395, 2020, doi: 10.1111/ina.12664.

[9] “Thermal comfort and productivity - Evaluation of workplace environment in a task conditioned office | Elsevier Enhanced Reader.” https://reader.elsevier.com/reader/sd/pii/S036013230900167X?token=9ACCB0FC65F7A26E6558A93CD7B49B65CF53854BF7AEC1118DCAB603EF90276CA11622788064710EB1A9E5B09A592593 (accessed Nov. 19, 2020).

[10] M. Indraganti, R. Ooka, and H. B. Rijal, “Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender,” *Energy and Buildings*, vol. 103, pp. 284–295, Sep. 2015, doi: 10.1016/j.enbuild.2015.05.042.

[11] “ASHRAE 55-2017npdf - Google Search.” https://www.google.com/search?q=ASHRAE+55-2017npdf&oq=ASHRAE+55-2017npdf&aqs=chrome..69i57j0l2.8902j0j7&sourceid=chrome&ie=UTF-8 (accessed Nov. 23, 2020).

[12] R. Hart, “Introduction to Commercial Building HVAC Systems and Energy Code Requirements,” p. 63.

[13] *Haldar, Achintya, and Sankaran Mahadevan. Probability, Reliability, and Statistical Methods in Engineering Design. New York: John Wiley, 2000. Print.*

[14] “Air pollution.” https://www.who.int/westernpacific/health-topics/air-pollution (accessed Jul. 06, 2021).

[15] “US EPA, OAR. 2014a. ‘NAAQS Table.’ Other Policies and Guidance. US EPA. April 10, 2014. https://www.epa.gov/criteria-air-pollutants/naaqs-table.”

[16] O. US EPA, “Hazardous Air Pollutants,” *US EPA*, Dec. 02, 2015. https://www.epa.gov/haps (accessed Jul. 06, 2021).

[17] “‘Greenhouse Gas | Definition, Emissions, & Greenhouse Effect.’ n.d. Encyclopedia Britannica. Accessed January 28, 2021. https://www.britannica.com/science/greenhouse-gas.”

[18] "Biello, David. n.d. 'How Much Is Too Much?: Estimating Greenhouse Gas Emissions.' Scientific American. Accessed January 28, 2021. https://www.scientificamerican.com/article/limits-on-greenhouse-gas-emissions/."

[19] "CDC - Indoor Environmental Quality - NIOSH Workplace Safety and Health Topic," Jul. 02, 2019. https://www.cdc.gov/niosh/topics/indoorenv/default.html (accessed Jul. 06, 2021).

[20] "Green Building 101: What is indoor environmental quality? | U.S. Green Building Council." https://www.usgbc.org/articles/green-building-101-what-indoor-environmental-quality (accessed Jul. 06, 2021).

[21] P. Wargocki *et al.*, "Ventilation and Health in Non-industrial Indoor Environments: Report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN)," *Indoor air*, vol. 12, pp. 113–28, Jul. 2002, doi: 10.1034/j.1600-0668.2002.01145.x.

[22] O. US EPA, "Introduction to Indoor Air Quality," *US EPA*, Aug. 14, 2014. https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality (accessed Jul. 07, 2021).

[23] G. Brager and S. Borgeson, "Comfort standards and variation in exceedance for mixed-mode buildings.," p. 18.

[24] O. Seppänen and W. J. Fisk, "Association of ventilation system type with SBS symptoms in office workers," *Indoor Air*, vol. 12, no. 2, pp. 98–112, Jun. 2002, doi: 10.1034/j.1600-0668.2002.01111.x.

[25] "Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature | Elsevier Enhanced Reader." https://reader.elsevier.com/reader/sd/pii/S2212609016300140?token=E04F32A15AB598AD108636646CAE91C67DDD2BED51D164496A0E09A9198E33DB2509AA9716A49FD6B92CB55A156A5A1A&originRegion=us-east-1&originCreation=20210706062203 (accessed Jul. 06, 2021).

[26] U. Landström, E. Åkerlund, A. Kjellberg, and M. Tesarz, "Exposure levels, tonal components, and noise annoyance in working environments," *Environment International*, vol. 21, no. 3, pp. 265–275, Jan. 1995, doi: 10.1016/0160-4120(95)00017-F.

[27] R. V. Andersen, J. Toftum, K. K. Andersen, and B. W. Olesen, "Survey of occupant behaviour and control of indoor environment in Danish dwellings," *Energy and Buildings*, vol. 41, no. 1, pp. 11–16, Jan. 2009, doi: 10.1016/j.enbuild.2008.07.004.

[28] "NR Acoustic Comfort," *NJ Green Building Manual*. http://greenmanual.rutgers.edu/acoustic-comfort/ (accessed Jul. 08, 2021).

[29] J. Veitch, J. Bradley, L. Legault, S. Norcross, and J. Svec, "Masking Speech in Open-Plan Offices with Simulation Ventilation Noise: Noise-Level and Spectral Composition Effects on Acoustic Satisfaction," Jan. 2002, doi: 10.4224/20386334.

[30] A. MBC (Myriam), "Human lighting demands:healthy lighting in an office environment," 2005, doi: 10.6100/IR594257.

[31] "Document Display | NEPIS | US EPA." https://nepis.epa.gov/Exe/ZyNET.exe/901A0E00.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1991+Thru+1994&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C91thru94%5CTxt%5C00000019%5C901A0E00.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-

&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL (accessed Jul. 09, 2021).

[32] P. Preziosi, S. Czernichow, P. Gehanno, and S. Hercberg, “Workplace air-conditioning and health services attendance among French middle-aged women: a prospective cohort study,” *International Journal of Epidemiology*, vol. 33, no. 5, pp. 1120–1123, Oct. 2004, doi: 10.1093/ije/dyh136.

[33] D. T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, and J. Tookey, “A critical comparison of green building rating systems,” *Building and Environment*, vol. 123, pp. 243–260, Oct. 2017, doi: 10.1016/j.buildenv.2017.07.007.

[34] “U.S. Energy Flow - U.S. Energy Information Administration (EIA).” https://www.eia.gov/totalenergy/data/flow-graphs/total-energy.php (accessed Feb. 14, 2021).

[35] “Top 12 Green Building Rating Systems Sustainable Investment Group.” https://sigearth.com/top-12-green-building-rating-systems/ (accessed Feb. 14, 2021).

[36] “annualreport2020.pdf.” Accessed: Apr. 05, 2021. [Online]. Available: https://finance.uw.edu/uwar/annualreport2020.pdf

[37] “sustainability-action-plan-at-a-glance-v070120.pdf.” Accessed: Apr. 05, 2021. [Online]. Available: https://green.uw.edu/files/plan/sustainability-action-plan-at-a-glance-v070120.pdf

[38] “Energy.” https://green.uw.edu/dashboard/energy (accessed Apr. 08, 2021).

[39] K. Mazhukhina, “Uncovering the HUB’s sustainable features,” *In Our Nature*, Aug. 20, 2015. https://green.uw.edu/blog/2015-08/uncovering-hubs-sustainable-features (accessed Apr. 06, 2021).

[40] “UW - Husky Student Union (HUB) | U.S. Green Building Council.” https://www.usgbc.org/projects/uw-husky-student-union-hub (accessed Apr. 06, 2021).

[41] “Controllability of systems - thermal comfort | U.S. Green Building Council.” https://www.usgbc.org/credits/new-construction/v2009/eqc62 (accessed Apr. 06, 2021).

[42] “Thermal comfort - design | U.S. Green Building Council.” https://www.usgbc.org/credits/new-construction-commercial-interiors-retail-nc-retail-ci/v2009/eqc71 (accessed Apr. 06, 2021).

[43] “SeaTac, WA Weather History | Weather Underground.” https://www.wunderground.com/history/daily/us/wa/seatac/KSEA/date/2014-8-20 (accessed Apr. 19, 2021).

[44] “extRemes.pdf.” Accessed: Apr. 19, 2021. [Online]. Available: https://cran.r-project.org/web/packages/extRemes/extRemes.pdf

[45] “Assessing Distribution Fit,” *Vortarus Technologies LLC*, Jan. 02, 2019. https://vortarus.com/assessing-distribution-fit/ (accessed May 19, 2021).

[46] “Air-Conditioning Was Once Taboo in Seattle. Not Anymore. - The New York Times.” https://www.nytimes.com/2021/06/25/us/western-heat-wave.html (accessed Jul. 18, 2021).

[47] “Seattle is a lot more air-conditioned than it used to be,” *The Seattle Times*, Jun. 25, 2021. https://www.seattletimes.com/seattle-news/data/seattle-is-a-lot-more-air-conditioned-than-it-used-to-be/ (accessed Jul. 18, 2021).

[48] “Definition of ROOM TEMPERATURE.” https://www.merriam-webster.com/dictionary/room+temperature (accessed Jul. 12, 2021).

[49] "Risk Analysis and the Acceptable Probability of Failure - PDF Free Download." https://docplayer.net/28565109-Risk-analysis-and-the-acceptable-probability-of-failure.html (accessed Jul. 15, 2021).

[50] "en.1990.2002.pdf." Accessed: Jul. 15, 2021. [Online]. Available: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1990.2002.pdf

[51] "C11. Aleatory and Epistemic Uncertainty.pptx.pdf." Accessed: Dec. 03, 2020. [Online]. Available: http://www.ce.memphis.edu/7137/PDFs/Notes/C11.%20%20Aleatory%20and%20Epistemic%20Uncertainty.pptx.pdf

[52] A. Mahdavi *et al.*, "Necessary Conditions for Multi-Domain Indoor Environmental Quality Standards," *Sustainability*, vol. 12, p. 8439, Oct. 2020, doi: 10.3390/su12208439.

Appendix & Additional Graphs

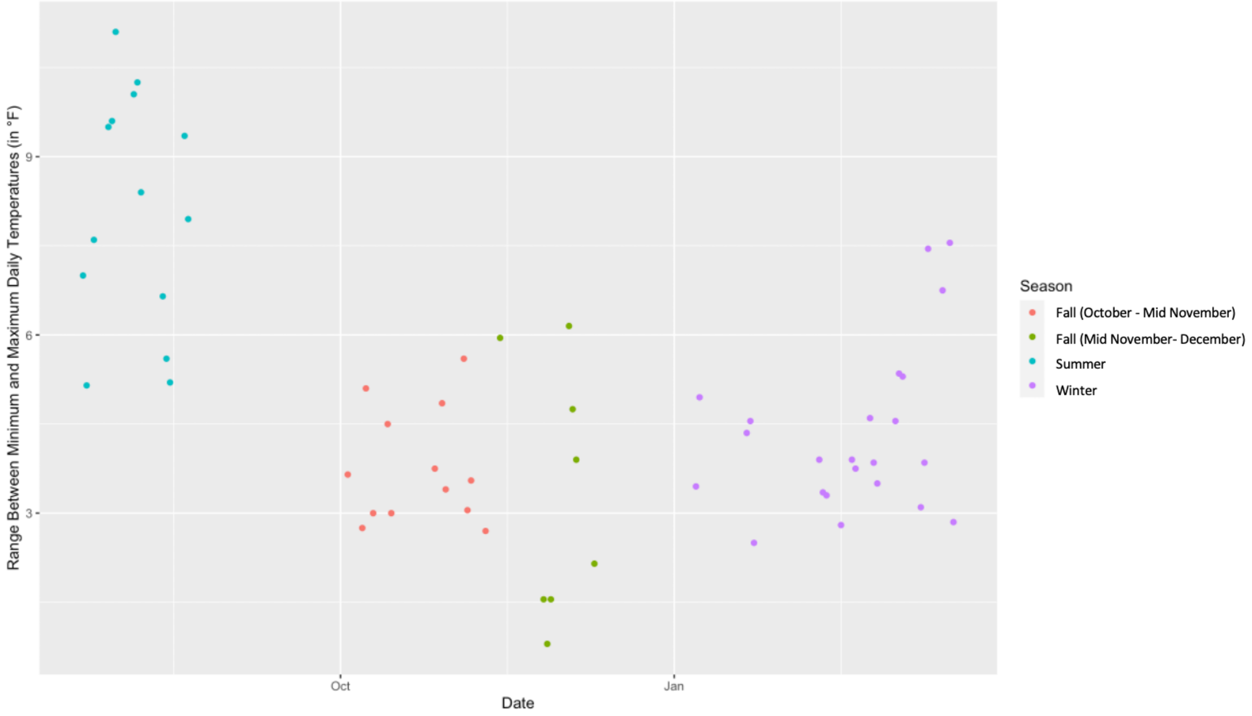

Figure 15. Range of Global Indoor Temperature Time Series Data (in °F)

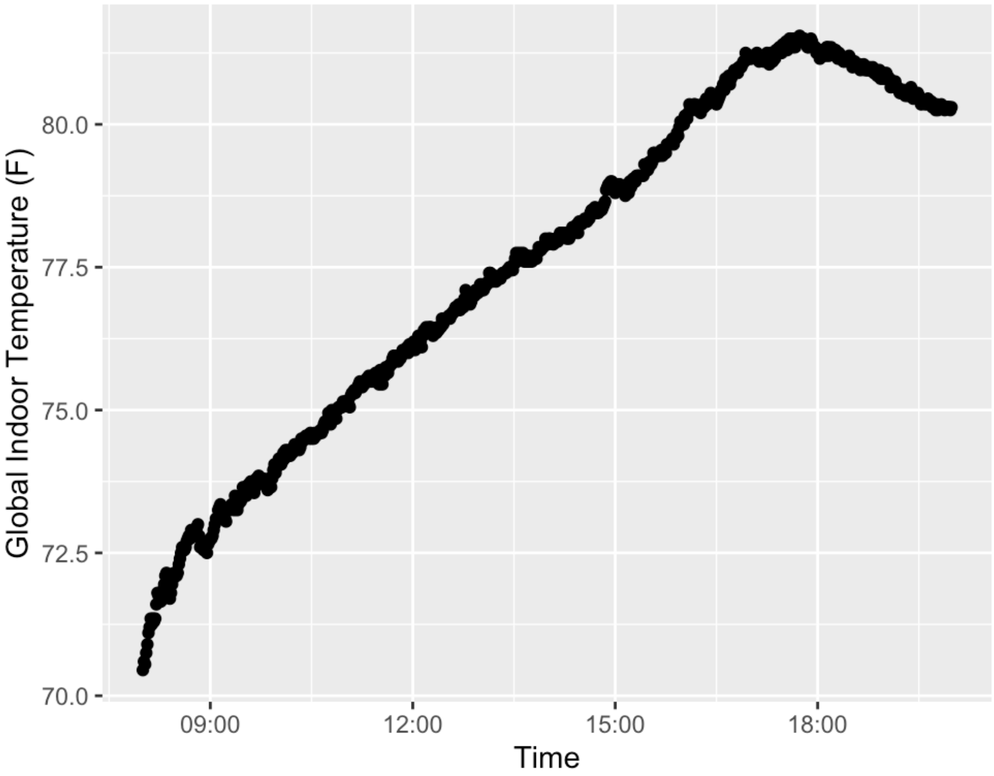

Figure 16. Time series plot for the date with the largest indoor temperature range (July 31st, 2014)

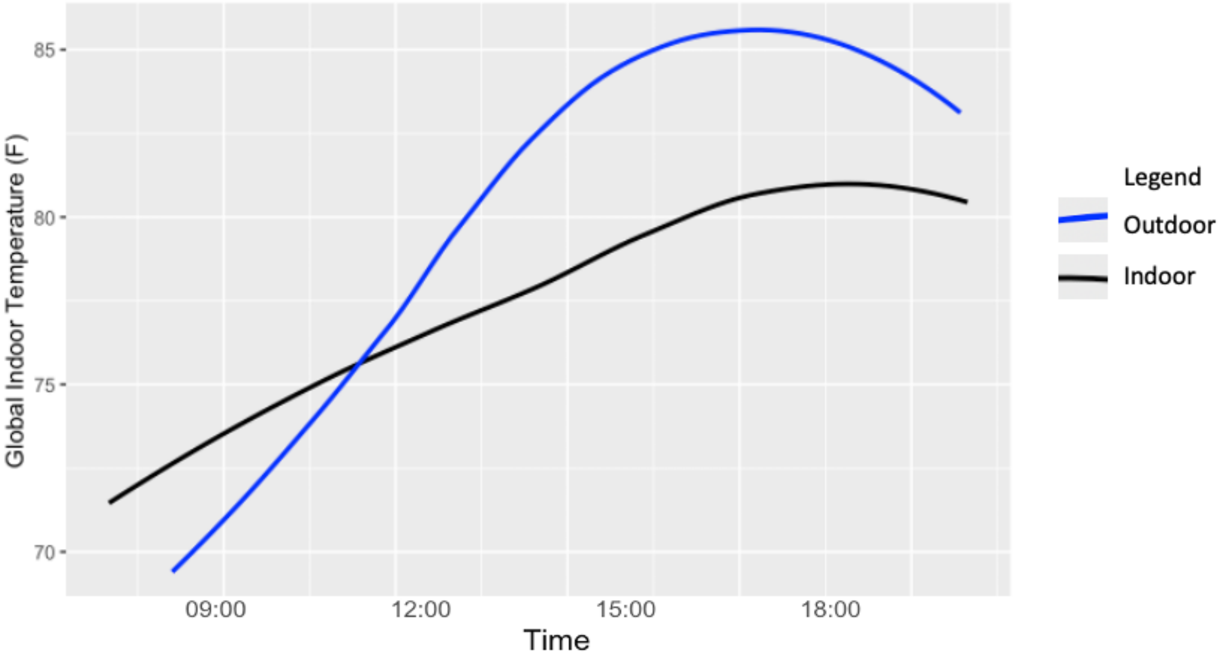

Figure 17. Time series plot for the date with the largest indoor temperature range (July 31st, 2014)

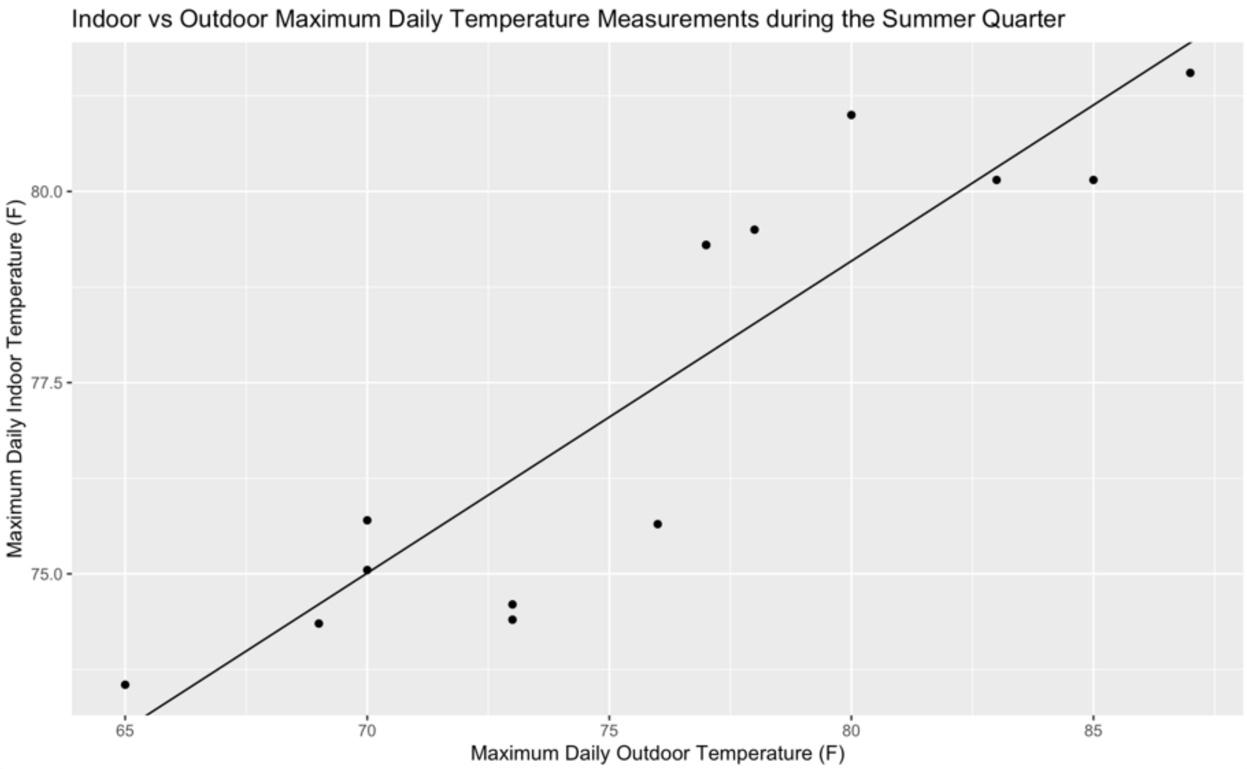

Figure 18. Summer Quarter Indoor vs Outdoor Maximum Daily Temperature Measurements

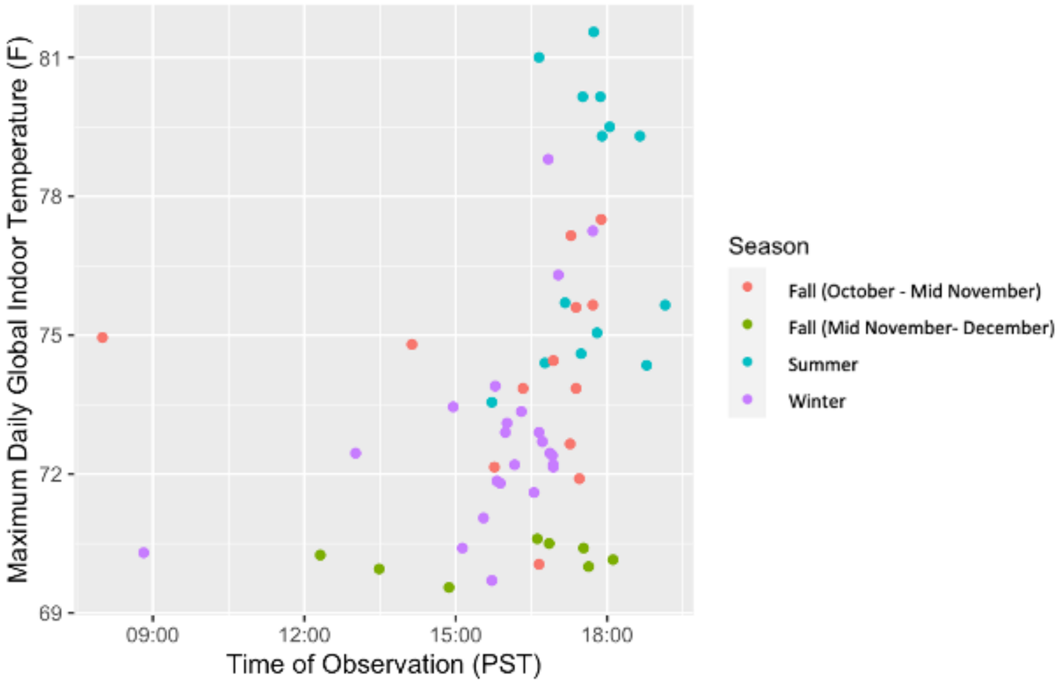

Figure 19. Time of Observation for Maximum Daily Indoor Temperature Measurements

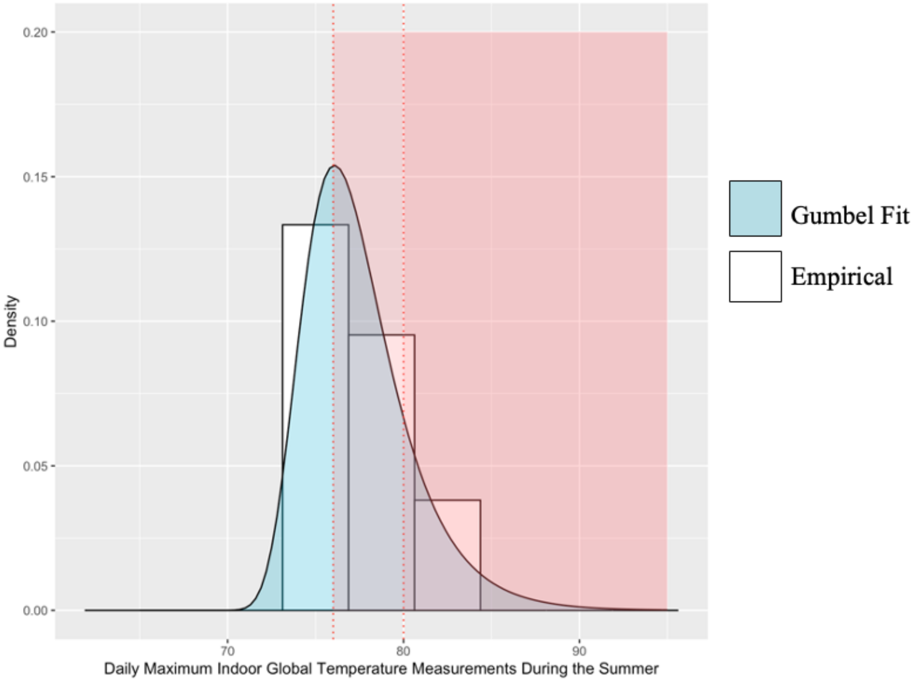

Figure 20. Maximum Daily Indoor Temperature Measurements Empirical Observations and Gumbel Fit

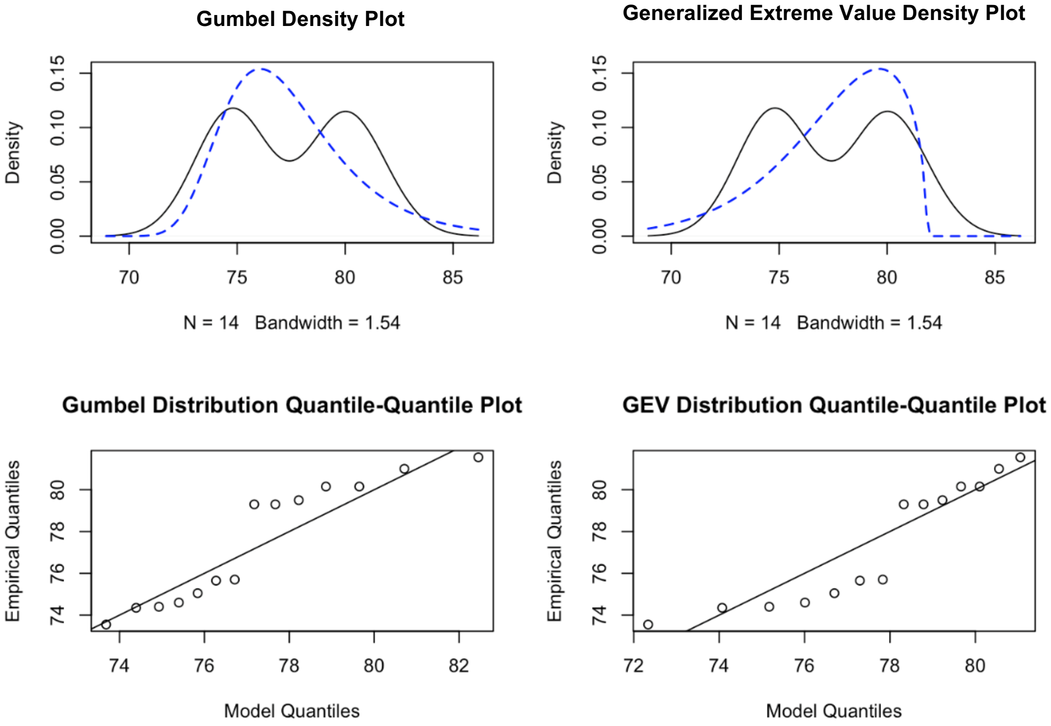

Figure 21. Density distribution and Q-Q plots examining summer extreme value indoor temperature data

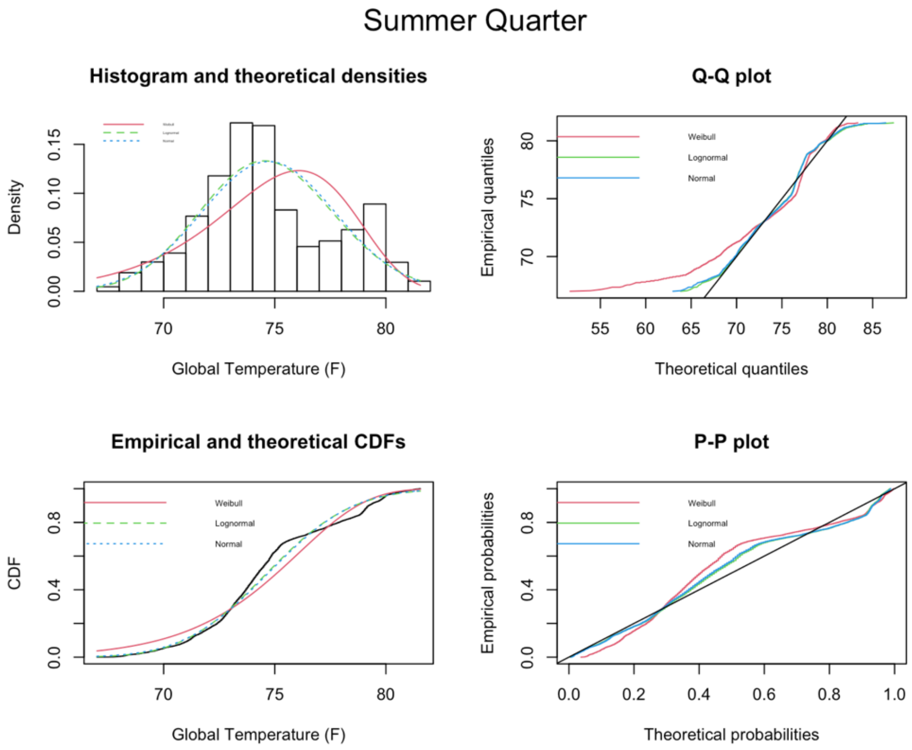

Figure 22. Summer Quarter Analysis to Normal, Weibull, and Lognormal Distributions

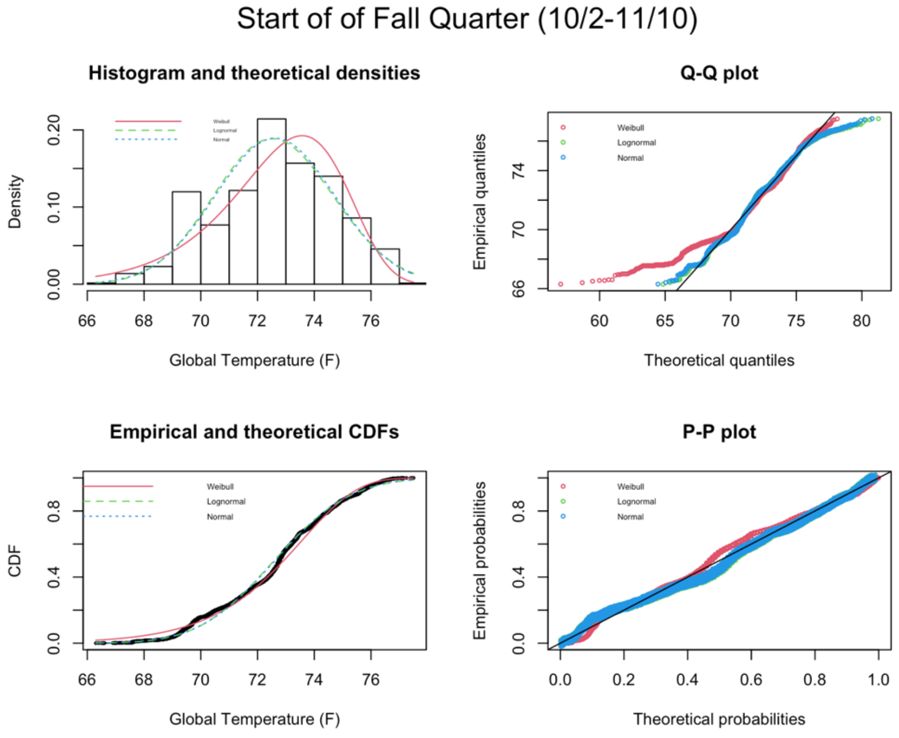

Figure 23. Start of Fall Quarter Analysis to Normal, Weibull, and Lognormal Distributions

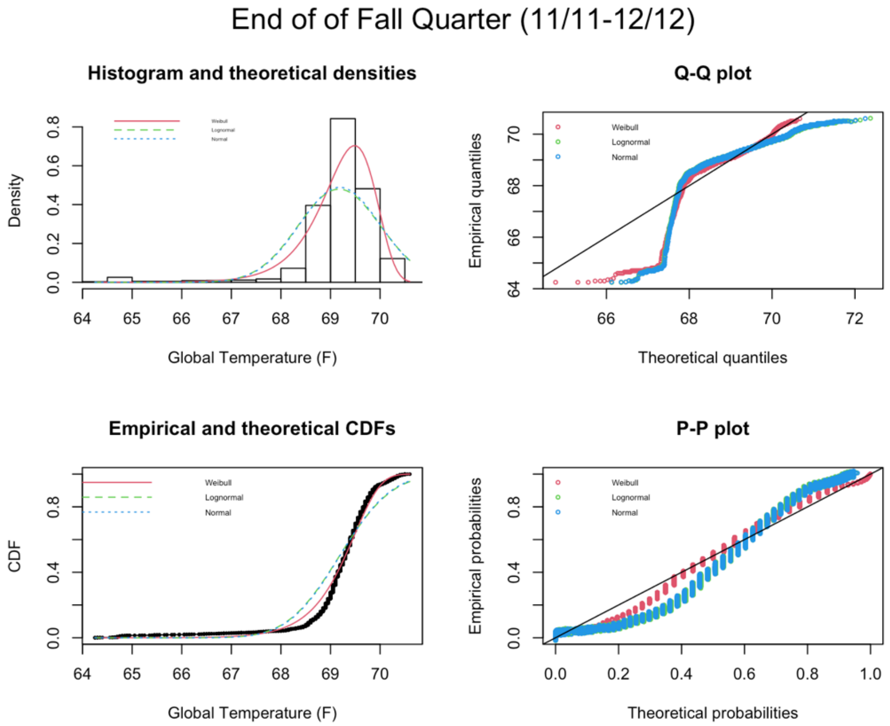

Figure 24. End of Fall Quarter Analysis to Normal, Weibull, and Lognormal Distributions

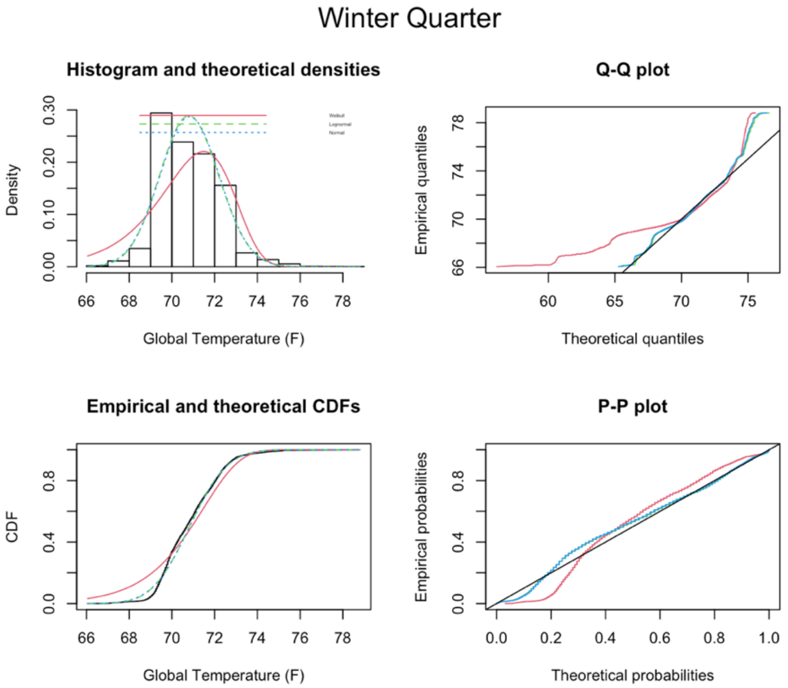

Figure 25. Winter Quarter Analysis to Normal, Weibull, and Lognormal Distributions