WPI Campus Center Feasibility Study for LEED O+M Certification

Submitted to the Faculty of
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the Degree of Bachelor of Science.

Darius Luo, Erin Venard, Hannah Whitney
Advisors: Soroush Farzin, Shichao Liu, and Leonard Albano
March 24, 2022

Table of Contents

Abstract

To address climate change and support Worcester Polytechnic Institute's commitment to sustainability, this project analyzed the Rubin Campus Center's potential to achieve LEED Existing Building: Operations + Maintenance v4.1 certification. The team determined the existing building's performance to warrant the Silver certification level. The team evaluated the structural feasibility of proposed changes and utilized energy modeling software to analyze the potential benefits for several retrofit options to further improve sustainability. For the proposed variable changes and final proposed models, the team found the associated energy usage reductions, estimated initial costs, and yearly monetary savings. The team recommends that WPI investigate rooftop units (RTUs) with energy recovery wheels, kitchen makeup air units (MAUs) with cooling coils, and either ground source heat pumps or high efficiency electric summer boilers. These findings can guide WPI to decrease their impact on the environment, lower their operations costs, and reinforce their dedication to sustainability.

Acknowledgements

Our team would like to thank a number of people for their contributions to this project. First, we would like to thank our advisors, Soroush Farzin, Shichao Liu, and Leonard Albano for their expertise, constructive criticism, and support. Next, we thank the Facilities Office, specifically: Ron O'Brien, the Director of Facilities; Kevin McLellan, the Manager of Building Controls and Maintenance; Glenn Myers, the Associate Director of Mechanical Services; Michael Wagner, the Lead Plumber; Ted E. McCarty, the Lead Electrician; and Nick Palumbo, Director of Design and Construct. The Facilities Office provided us access to the Campus Center's mechanical rooms, building management system, and architectural documentation, along with providing us with their insight to WPI's sustainability initiatives. We would like to thank Kim Wykes, Operations Manager of the Campus Center for her support and provision of numerous policies related to the CC's operation and Paul Mathisen, Director of Sustainability, and the WPI Green Team for providing us with a variety of materials related to WPI's sustainability efforts. We thank Kenneth Neuhauser and Wesley Stanhope from Building Evolution Corporation (BEC) for their expertise and assistance on this project. We also thank every student, staff, and faculty member who took our surveys.

List of Figures

List of Tables

1. Introduction

One of the greatest challenges of our lifetime is combating climate change to ensure a livable future for the coming generations. The built environment that humanity has constructed to protect themselves from climate is also one of the world's biggest contributors to climate change, consuming more than 30% of the total energy and 60% of the total electricity used in the U.S. (Ried, 2008). While standards for sustainability in building design and construction have been developed and are usually applied to new buildings, existing buildings pose a concern in the advancement of sustainable development within the built environment. Depending on the age of the building, both the enclosure and the mechanical systems could detrimentally affect the building's energy efficiency and, therefore, its contributions to global warming through excessive use of fossil fuels and emissions of carbon. By evaluating and renovating existing buildings to become more efficient and resilient, the negative effects of these buildings on the climate can be reduced while better preparing them to handle any climate changes.

On a smaller scale, universities can pursue sustainability initiatives and green buildings to reduce the environmental and climate impacts of their operations. As a university, WPI is committed to sustainability efforts and continues to improve its campus by building more efficient buildings and addressing inefficiencies in existing ones (Worcester Polytechnic Institute, n.d.a). Since 2007, the university has been dedicated to constructing new buildings in accordance with the Leadership in Energy and Environmental Design (LEED) green building certification program. WPI must look into renovations and LEED certification of older campus buildings to further address sustainability and energy efficiency initiatives outlined by the administration. This project investigates the feasibility of certifying one of WPI's existing campus buildings under LEED and outlines the general steps for WPI to take in engaging the LEED certification process for this building and potentially others.

2. Background

2.1. Project Goal

While WPI has established sustainability goals to forward environmentally conscious initiatives, such as its continued commitment to achieving LEED standards for future buildings, the university has yet to develop a comprehensive plan for retrofits that promote the sustainability of its existing buildings. As a college campus that resides in and impacts the surrounding Worcester county, WPI has a responsibility to ensure that they are minimizing their energy usage, greenhouse gas emissions (GHGs), and harm to the local environment. This responsibility can be acknowledged through renovations to existing buildings, such as the Rubin Campus Center (CC). How can our project recommend strategies to reduce the environmental impact and energy usage to achieve LEED certification for the CC? Furthermore, would these methods, as they relate to improving the structural, mechanical, and enclosure systems, be feasible for the WPI Administration to implement?

The primary objective in addressing these research questions was to develop a LEED Existing Buildings Operations and Maintenance (LEED EBOM) v4.1 certification plan for the CC. The team investigated the building as it had currently stood for a proposed LEED scorecard. The team evaluated the building, including the current mechanical and structural systems, and the impacts of subsequent proposed changes on the building’s energy efficiency and environmental impacts to achieve LEED certification. A REVIT model, DesignBuilder energy model, and a structural model of the original building were created to benchmark the current building systems. They were then compared against models of the proposed sustainable systems.

The secondary objective of this project was to demonstrate to the WPI Administration the feasibility of achieving LEED EBOM certification for the CC. This was accomplished by developing a sustainability proposal consisting of a narrative and a variety of packages, with their associated budgets, that could achieve different levels of LEED certification.

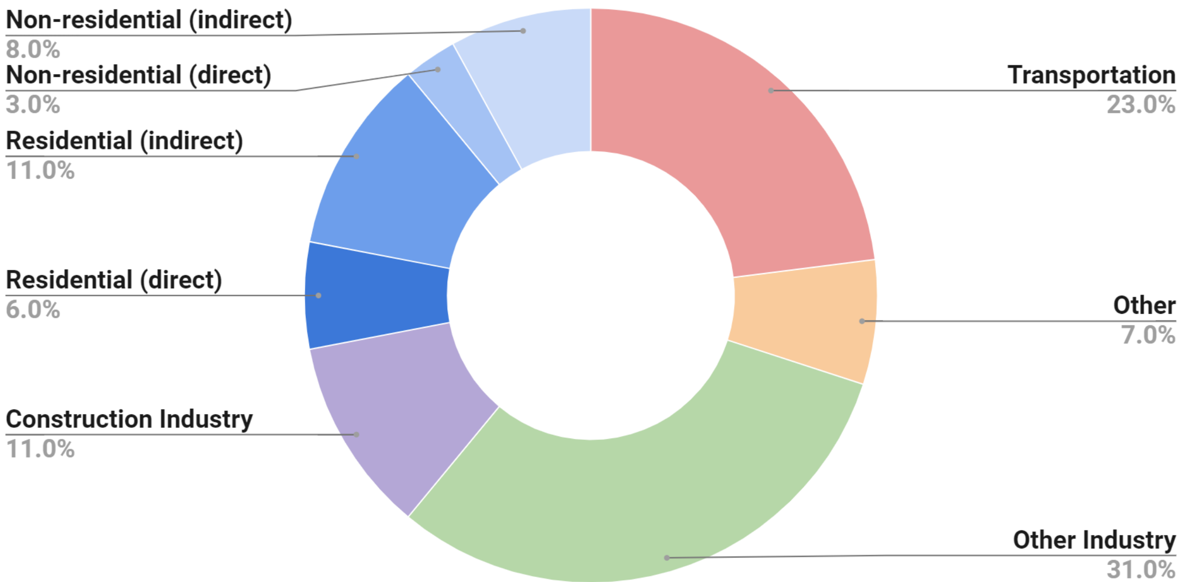
2.2. Buildings' Impact on Climate Change

Construction and building operations are traditionally not eco-friendly processes (World Green Building Council, 2017). As the world's population continues to grow, the global building stock is expected to double in quantity by 2050. Managing this consumption and prioritizing productivity is essential to control the global temperature increase from a predicted 1.5˚C over the next decade (The Intergovernmental Panel on Climate Change, 2019). Consequently, adapting building design is critical in addressing the climate crisis and its effects on the environment.

The construction and operation of buildings are a substantial contributor to global carbon emissions. As seen in Figure 1, of the 39% of energy-related CO2 emissions, 28% account for operational emissions (Global Alliance for Buildings and Construction, 2019). Operational emissions involve the energy necessary to cool, heat, and power buildings. Embodied carbon emissions, the emissions from construction activities and the total building life-cycle, make up the remaining 11% of the CO2 emissions (Global Alliance for Buildings and Construction, 2019).

Figure 1

Global Share of Buildings and Construction Carbon Emission, 2019



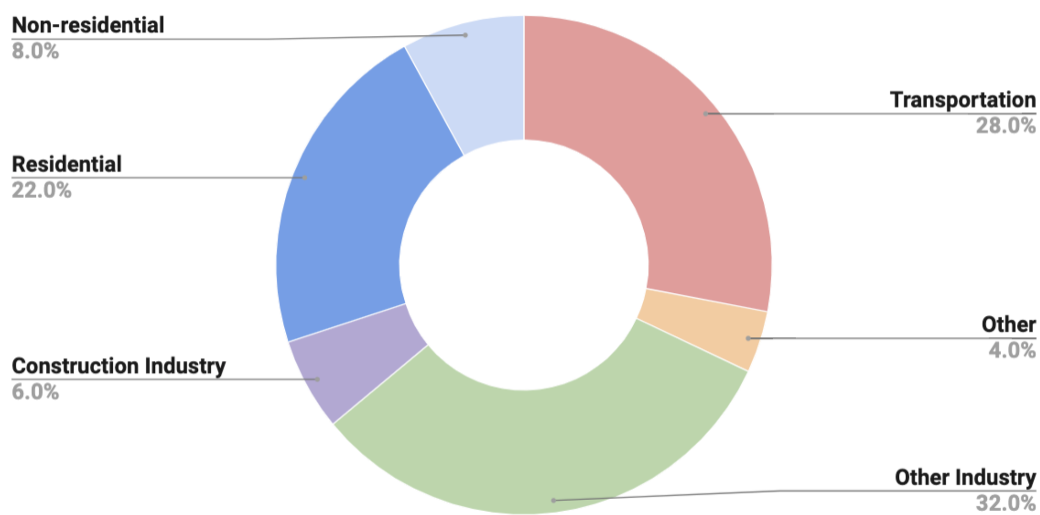
(Global Alliance for Buildings and Construction, 2019)

The utilization of water directly affects energy usage and increases the environmental impact. Water is an essential resource in the construction process as well as building operation and maintenance. During construction, water is necessary for water treatment, aggregate washing, concrete preparation and curing, and site management. Water also ensures building operation and maintenance through many systems such as drinking, toilet flushing, washing, waste, landscaping, heating, and cooling. Buildings constitute a third of global freshwater consumption and sewage waste (Bardhan, 2011).

The increase in energy use for buildings and construction accounts for 36% of global final energy use, as shown in Figure 2. Construction accounts for 6% of the global final energy use, while building systems and operations account for the remaining 30% as seen cumulatively in the Non-residential and Residential sectors in Figure 2 (Global Alliance for Buildings and Construction, 2019). Between 80-90% of energy use throughout a building's life cycle occurs during the building's operation (Brady & Abdellatif, 2017). Addressing and investing in the performance of existing buildings, such as building energy renovations, can increase energy efficiency. Of the 4.5 trillion dollars in global investments for energy efficiency in 2018, only 139 billion dollars were spent on buildings (Global Alliance for Buildings and Construction, 2019). Thus, the energy efficiency spending in buildings was 0.03% of total construction and renovation investments globally.

Figure 2

Global Share of Buildings and Construction Final Energy, 2019



(Global Alliance for Buildings and Construction, 2019)

While the construction industry supports economic growth, societal needs, and quality of life, it can also contribute negatively. The exploitation of natural resources and energy consumption continue to exacerbate carbon emissions, environmental degradation, and global warming (Doan et al., 2017). Establishing effective operation and maintenance plans is imperative for systems to perform as designed over the equipment's lifespan. Technologically and economically feasible advancements exist within the building industry to provide solutions for the impact buildings have on climate change. This includes the restructuring of the construction phase to support sustainable practices through material and location selection. Rapid progress can only occur through the implementation of these solutions into more stringent policy and partnership.

2.3. Sustainable Approaches in the Building Industry

Improving the performance and efficiency of buildings requires the integration of different strategies. These strategies reduce building energy use, positively impact the local environment, and can be measured through energy performance modeling and site investigations. These strategies range from active to passive, and can also include the use of renewable energy sources to offset the energy used on-site.

Active strategies comprise the building's mechanical systems and electrical equipment that are designed to reduce energy loads. Innovations for heating, ventilation, and air conditioning (HVAC) systems and their energy sources have led to an increase in efficiency while also reducing harmful greenhouse gases (GHGs) from fossil fuels (Fakhar et al., 2014). Traditional, separate heating and cooling systems, such as oil boilers and ducted or window-mounted air conditioners, are now competing with heat pump-based systems that can simultaneously provide heating and cooling while using more environmentally friendly energy sources such as electric, wind, or solar. Additional active systems can include motion-detection sensors for artificial lighting and activity sensors for the building plug loads to conserve energy at times of minimal or no occupancy (Karyotakis et al., 2012; Murakami et al., 2007).

Reliance on renewable energy sources is an additional strategy that many high-performance buildings employ. Such sources include on-site photovoltaics or off-site wind farms and hydropower plants. Solar, wind, and water energy have a near-zero emission of CO_2 and other air pollutants, making them sustainable sources of alternative energy compared to fossil fuels (Delucchi & Jacobson, 2016). Renewables are often used to reach net-zero or net-positive energy status, meaning that they produce equal or greater amounts of energy than is consumed by the building.

The efficiency and energy conservation of active systems is facilitated by the incorporation of passive systems into building design, such as increasing insulation in the building envelope, reducing thermal bridging, installing high performance windows, optimizing site orientation, and integrating natural ventilation (Boehm, 2011). A high-performance envelope and optimal site orientation will reduce the load on the mechanical systems and thereby reduce energy usage. Envelope design is dependent on the climate of the building's location; therefore, material choices, window placement, and the amount of insulation should be carefully considered. The consideration of site orientation is beneficial for passive heating and cooling. The placement of windows in accordance with the site orientation can contribute to solar heat gain in the winter and cross ventilation in milder months.

Understanding the impacts of both active and passive systems was necessary to perform a comprehensive energy analysis of the CC. Alterations to the building's site orientation, window placement, and building materials were not applicable, but smaller-scale adjustments, such as sun-shielding and upgrading necessary building replacements alongside the more practical replacements of the building's mechanical systems were explored. Additionally, other factors such as water use efficiency, materials choices, and purchasing policies are aspects of sustainability unrelated to energy efficiency that still has major contributions to a building's holistic engagement in sustainability.

2.4. Green Rating Systems

Architects and developers who want to go beyond code compliance and build high-performance buildings can have their sustainability efforts certified through a third-party rating system. A certified building will have a higher property value, increased marketability, and oftentimes reduced energy consumption, which may offset the higher initial costs (Soulti, 2016; Vierra, 2019; Yale, 2020). Furthermore, occupant health and well-being can be positively affected due to improved indoor environmental quality, such as increased natural daylighting and the use of healthier building materials (Vierra, 2019; Yale, 2020). The well-being of the community can also be positively impacted due to outdoor environmental changes, such as the addition of green spaces and stormwater management systems. Although not all green buildings are certified, certification can verify and quantify a building's sustainable practices.

Popular building rating systems to promote green building include Leadership in Energy and Environmental Design (LEED), Energy Star, Living Building Challenge, WELL Building Standard, Passive House, and Green Globes; these are summarized in Table 1. Each rating system has either a prescriptive approach, performance approach, or a combination of both. A prescriptive-based system utilizes a set of standards that the building components need to meet, which could involve minimum R-values and specific construction methods (Cowan, 2020). A performance-based approach focuses on achieving certain results for the overall building, such as a target energy use that could be determined using energy simulations or energy meters. It is often easier for buildings to meet prescriptive standards than performance goals as the latter method requires more planning and coordination.

Table 1

Summary of Popular Green Building Rating Systems

Certification/Rating System	Rating Type	Areas of Focus
LEED v4.1	Prescriptive and Performance	Emissions, Energy, Indoor environment, Materials and resources, Operations and maintenance, Sustainable sites, Water efficiency
ENERGY STAR	Performance	Emissions, Energy, Waste, Water
Living Building Challenge v.4	Performance	Energy, Equity, Health and wellbeing, Indoor environment, Materials and resources, Sustainable sites, Water efficiency
WELL Building Standard v.2	Prescriptive	Comfort, Indoor environment, Lighting, Health and wellbeing, Water
Passive House U.S. 2021	Performance or Prescriptive	Emissions, Energy, Indoor environment
Green Globes	Prescriptive	Emissions, Energy, Indoor environment, Materials and resources, Project management, Sustainable sites, Water

(Cowan, 2020; Energy Star, n.d.; International Living Future Institute, n.d.; International Well Building Institute, n.d.; Green Building Initiative, n.d.; Passive House Institute U.S., n.d.; USGBC, n.d.b; Vierra, 2019)

The LEED rating system was selected for investigation for this feasibility study due to its popularity and current usage on-campus. Although there is mixed research regarding the extent of energy savings, if any, for LEED-certified buildings, the team decided that LEED provided a wide variety of sustainability aspects for them to analyze (Amiri et al., 2019). The evaluation of energy savings do not necessarily have to occur in the context of obtaining LEED points.

2.5. LEED Certification

LEED is one of the front runners in green building rating systems. Created by the U.S. Green Building Council (USGBC), LEED has become the most used green building rating system globally (Awadh, 2017). The certification program, administered by the Green Building Certification Institute (GBCI), allows for distinct and recognizable verification of a building's or neighborhood's environmental design. Overall, LEED enables the design, construction, operations, and maintenance of material-efficient, powerful, healthy, and cost-efficient structures (USGBC, n.d.).

LEED Certification has many rating systems that can be applied to a variety of projects, including Building Design and Construction (BD+C) and Building Operations and Maintenance (O+M). Additional examples of these rating systems and applications are seen in Table 2 (USGBC, n.d.).

Table 2

LEED Certification Rating Systems and Applications

Building Design and Construction (BD + C)	Interior Design and Construction (ID + C)	Buildings Operations and Maintenance (O+M)	Neighborhood Development (ND)	Homes
New Construction	Commercial Interiors	Existing Buildings; Operations & Maintenance (EBOM)	Neighborhood Development Plan	Homes
Core & Shell	Retail	Schools	Neighborhood Development	Midrise
Schools	Hospitality	Retail		
Retail		Hospitality		
Hospitality		Data Centers		
Data Centers		Warehouses & Distribution Centers		
Warehouses & Distribution Centers				
Healthcare				

(USGBC, n.d.)

The accumulation of points through credit categories is used to achieve different certification levels depending on which rating system best fits the project. In ascending order, the four levels of certification are: Certified, Silver, Gold, and Platinum. These four certification levels require 40-49 points, 50-59 points, 60-69 points, and 80+ points, respectively.

LEED for Operations and Management (O+M) pertains to existing buildings and interior performance. LEED O+M certification focuses on sustainable design strategies and measuring the improved performance of buildings. LEED EBOM version 4.1 (v4.1) applies to existing buildings that have been completely operational and occupied for a minimum of one year (USGBC, n.d.). LEED EBOM highlights how retrofits can increase sustainability without demolishing the existing building. This ensures the longevity and improved life cycle of high-performance buildings. LEED EBOM has eight distinct credit categories which encompass essential green building elements as shown in Figure 3. The scorecard, as seen in Figure 4, depicts the credit categories and associated possible points that can be gained for LEED certification.

Figure 3

LEED v4.1 EBOM Scorecard

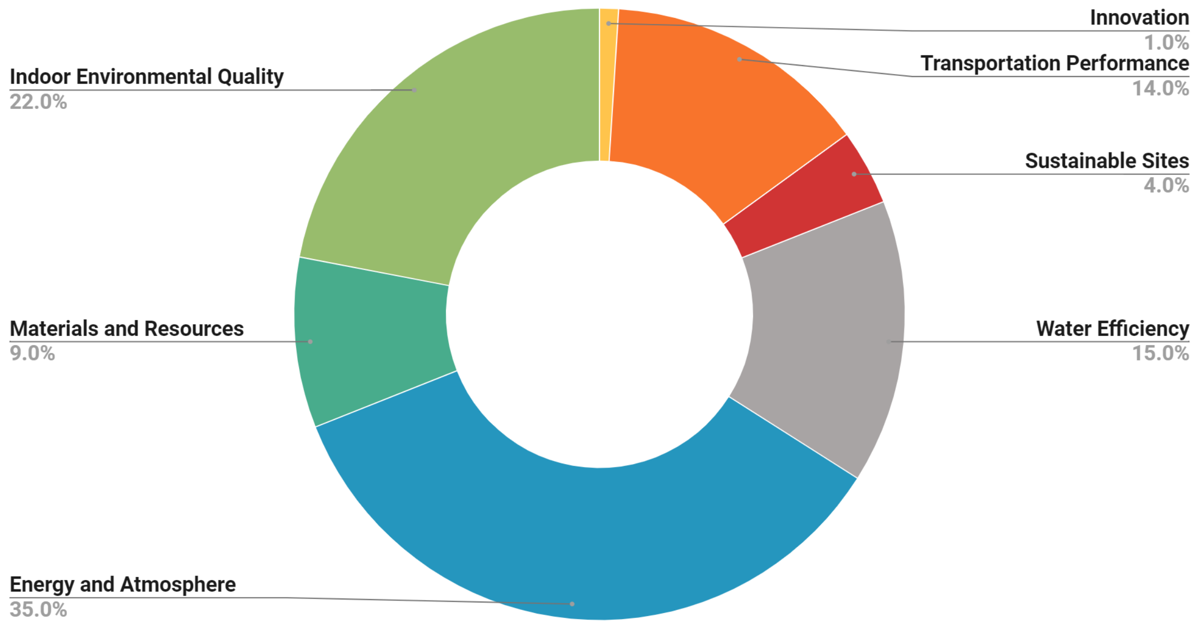
LEED v4.1 for Operations & Maintenance: Existing Buildings
Scorecard

Y	?	N			Points	
0			**Location and Transportation**		**14**	
0			Prereq	Transportation Performance	14	
0	**0**	**0**	**Sustainable Sites**		**4**	
			Credit	Rainwater Management	1	
			Credit	Heat Island Reduction	1	
			Credit	Light Pollution Reduction	1	
0			Credit	Site Management	1	
0	**0**	**0**	**Water Efficiency**		**15**	
0			Prereq	Water Performance	15	
0	**0**	**0**	**Energy and Atmosphere**		**35**	
Y			Prereq	Energy Efficiency Best Management Practices	Required	
Y			Prereq	Fundamental Refrigerant Management	Required	
			Prereq	Energy Performance	33	
			Credit	Enhanced Refrigerant Management	1	
			Credit	Grid Harmonization	1	
8	**0**	**0**	**Materials and Resources**		**9**	
Y			Prereq	Purchasing Policy	Required	
Y			Prereq	Facility Maintenance and Renovations Policy	Required	
8			Prereq	Waste Performance	8	
			Credit	Purchasing	1	
1	**0**	**0**	**Indoor Environmental Quality**		**22**	
Y			Prereq	Minimum Indoor Air Quality	Required	Yes
Y			Prereq	Environmental Tobacco Smoke Control	Required	Yes
Y			Prereq	Green Cleaning Policy	Required	Maybe
0			Prereq	Indoor Environmental Quality Performance	20	
0			Credit	Green Cleaning	1	
1			Credit	Integrated Pest Management	1	
0	**0**	**0**	**Innovation**		**1**	
			Credit	Innovation	1	
9	**0**	**0**	**TOTALS**	Possible Points:	**100**	

Certified: 40-49 points, **Silver:** 50-59 points, **Gold:** 60-79 points, **Platinum:** 80+ points

Figure 4

LEED v4.1 O+M Credit Distribution of Eight Categories



(USGBC, n.d.)

2.6. College Campuses and Sustainability

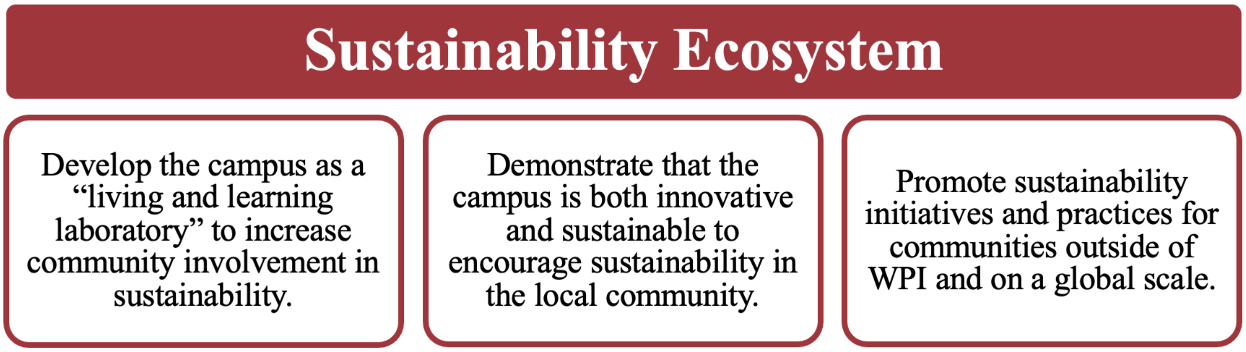
There is significant value in investing in energy efficient campus buildings for college administrations, particularly as colleges are single entity, long-term landholders with a significant stake in the welfare and longevity of their building stock (Ried, 2008). Due to the contributions that buildings have on climate change, college administrators need to evaluate and reduce their impacts. Built environment specialist Cathy Jackson states that "large institutions like a university...have the expertise, they have staff, and they have resources to hire really talented consultants" (Yale, 2020). This role is recognized by the 662 North American universities, including Worcester Polytechnic Institute (WPI), that participate in the Association for the Advancement of Sustainability in Higher Education (AASHE, n.d.). Engaging in new construction and pursuing the renovation of older campus buildings to improve the energy efficiency of college campuses not only reduce harm to the environment, but can lead to increasing the value of the university for prospective faculty, staff, and students (Ried, 2008). Construction and renovation efforts have the added benefit of supporting the local community's economic infrastructure through the use of local materials and labor. College administrations who want to advance the sustainability of their campus can develop an energy policy or sustainability plan to establish their goals and the steps they will take to achieve it (Agdas et al., 2015).

Under this perspective, the project team explored WPI's existing position on sustainability and efforts towards energy reduction. The team would then use this information to determine how this project could advance those positions and efforts to make a more significant impact on the energy conservation and sustainability of the campus.

To gauge WPI's potential interest and willingness to invest in this project, the institution's dedication to sustainability was evaluated. WPI develops a new sustainability plan every few years to establish goals using the guiding principles of environmental stewardship, economic security, and social justice. According to the current Sustainability Plan for 2020 to 2025, WPI has three primary objectives that serve as a sustainability ecosystem to address local and global issues, as shown in Figure 5 (Worcester Polytechnic Institute, 2020b).

Figure 5

WPI's Primary Objectives of the Sustainability Ecosystem



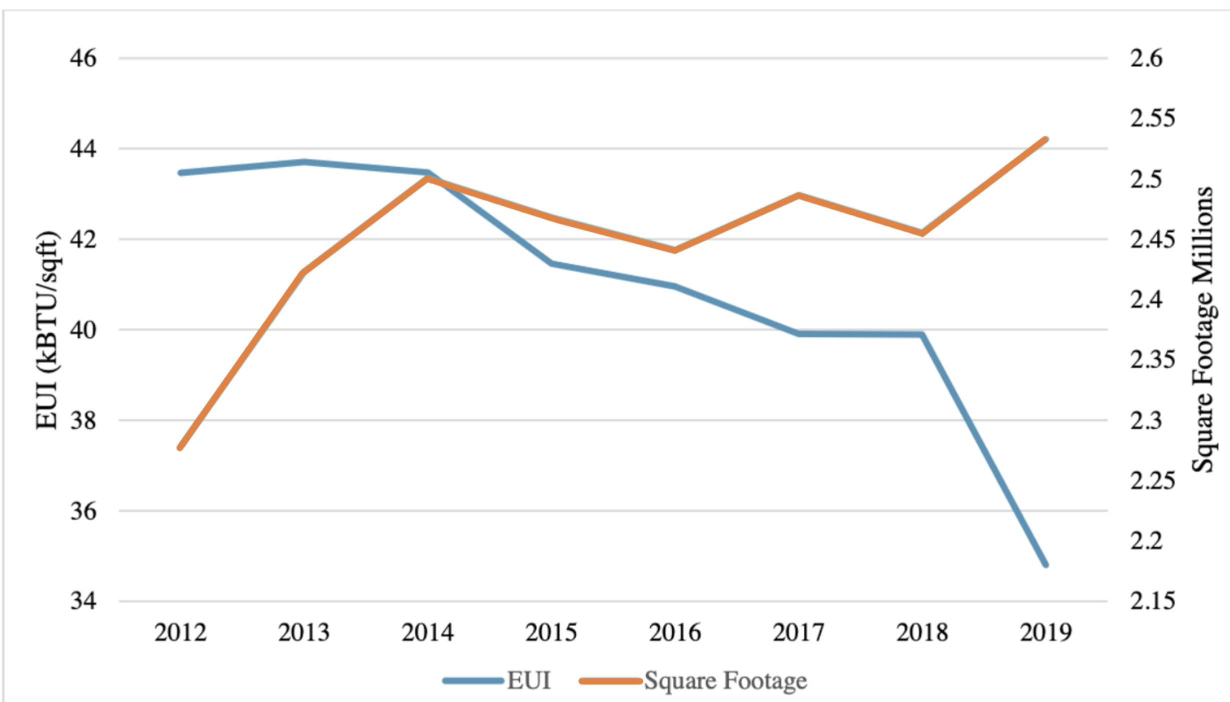
To highlight how WPI's sustainability initiatives are in line with these three objectives, WPI produces an annual sustainability report. The 2019-2020 Sustainability Report features WPI's commitments to sustainability through four focus areas: academics, research/scholarship, community engagement, and campus operations (Worcester Polytechnic Institute, 2020a). The first three focus areas include sustainability topics in academics, green research projects, and student clubs promoting sustainable practices.

Campus operations, the fourth focus area, encompasses site plan, construction, building design, maintenance, and operation procedures. In 2007, the Board of Trustees voted that all future buildings must be certifiable under LEED. Whether or not these buildings have to become officially LEED certified is not specified. As of March 2022, there are six LEED-certified campus buildings at varying certification levels: Bartlett Center (Certified), East Hall (Gold), Recreation Center (Gold), Faraday Hall (Silver), Innovation Studio/Messenger Hall (Gold), and Unity Hall. Retrofits have been completed for buildings constructed before 2007, but they have been mostly limited to improving lighting systems. Partly due to these retrofits, WPI campus's water consumption, natural gas usage, electricity usage, and greenhouse gas emissions, which are tracked on a campus level at the minimum, have all been reduced since the 2014 fiscal year.

After the implementation of more energy efficient systems starting in 2014, overall campus energy usage has reduced by one to two percent each year (Howell et al., 2021). WPI's energy consumption can also be expressed with its energy usage intensity (EUI), which represents the average energy used per square foot of campus buildings. As existing buildings are retrofitted with more energy efficient systems and the square footage increases with the construction of new, LEED-certified buildings, the campus EUI has been decreasing by an average of 4.5 percent from 2014 to 2019, as seen in Figure 6. Although WPI has identified goals for increasing campus sustainability with new construction and existing buildings, additional efforts are needed to significantly address climate change.

Figure 6

Comparison of Campus EUI and Total Square Footage



Note. Edited colors to make them more distinct. (Howell et al., 2021)

2.7. Rubin Campus Center

The CC was chosen to accomplish the project goal for many reasons, primarily of which is its significance to student life. Completed in March 2001, the CC stands three stories tall and is approximately 71,000 square feet (WPI, n.d.c). The building is located in the center of the WPI campus and houses multiple services essential to the student body and staff (WPI, n.d.b; WPI, n.d.c). The 1970 report, *The Future of Two Towers Part Four: A Plan*, brought attention to the lack of unity between individuals and community life on campus (van Alstyne et al.). The Faculty Planning Committee recognized the need for a physical space on campus where students and faculty could meet, have meals, and engage in extracurriculars that would support the idea of a healthy, immersive, and well-balanced life at WPI. The CC has fulfilled that need, becoming a center for student activities. Students come to the CC to study, relax, access the mailroom or bookstore, eat at the food court or Dunkin' Donuts, attend large events in the flexible meeting spaces, or work in the office spaces for student organizations. Multiple administrative offices, including the Dean of Students and Chartwells Dining & Catering, are also housed within the building. These amenities and services intertwine the CC with student life and university operations.

The CC was chosen for its significance to the students and faculty in addition to more practical reasons, namely age, access to drawings, and collected utility data. The age of the CC likely enhances the financial feasibility of the renovations for WPI when compared to the campus's older buildings. First, the building was constructed at the turn of the twenty-first century, where modern construction practices more often incorporated centralized HVAC systems. Older campus buildings would need a more comprehensive retrofit because they would more likely require the installation of a completely new centralized HVAC system. Furthermore, the required drawing sets and models were available to the team to determine the existing systems while the utility data helped establish the systems' efficiencies.

The team will evaluate and recommend strategies to improve the building's functions so that it both adheres to WPI's sustainability goals and continues to serve the needs of the WPI community. Retrofitting such a pivotal building to achieve LEED standards would further establish WPI's dedication to sustainability and align with the objectives outlined in WPI's Sustainability Plan.

3. Methodology

The team employed a number of methods to obtain information on the current mechanical and structural systems in the CC, as well as to develop alternative models that would explore different sustainability improvements. This included analyzing the building's documentation, understanding the LEED requirements for certification, and developing building energy and structural models. These methods are expanded upon in detail in the following sections.

3.1. Existing Conditions of the CC

To understand the design and intent of the CC, drawing sets were acquired from facilities. Prior to reviewing the drawing sets, the team was required to sign a nondisclosure agreement to ensure that any proprietary information is kept confidential. Although the team used the available data and information for the research and development of the project, not all of the information can be shared within this report. The team reviewed the architectural, structural, plumbing, mechanical, landscaping, food service, fire protection, electrical, and civil plans. The team investigated and evaluated the structural system with the intent of collecting information on the composition, structural notes, and enclosure details for structural analysis of the existing structure. The team also reviewed the as-designed MEP systems for later comparison to the existing systems.

The team examined the models of existing MEP equipment in mechanical rooms and used the information for the energy simulations. Photos of equipment and interior space of the mechanical room were obtained to collect relevant information during a tour led by members of the Facilities Office. The team then compared the information from the site investigation with that in the architectural and mechanical drawings to ensure the input accuracy of the energy and structural analyses.

Issues were brought to the team's attention by the Facilities Office for consideration. The roof is projected to be renovated during the 2023 fiscal year, providing opportunities to improve the roof or implement a new system. The current rooftop air handling units (RTUs) and summer boilers will also need to be replaced as they have reached the end of their lifespans. In terms of comfort, the make-up air unit (MAU) in the kitchen does not have a cooling coil, making the environment uncomfortable for the staff during the summer months.

The team then investigated the latest versions of the LEED rating system to determine which version would best apply to the feasibility study of the CC. The latest version of the system is 4.0, with a subsequent version 4.1 in beta as of 2021. LEED v4.1 presents the first opportunity for LEED to use both prescriptive and performance-based approaches. All previous versions of LEED, including version 4.0, solely use prescriptive-based measures to improve sustainability. A member of the GBCI's Technical Customer Service Team informed the team that LEED v4.1 is the "best bet for longevity" as LEED v4.0 will eventually be retired (T.

Staheli, personal communication, September 30, 2021). With all these factors, the team chose to pursue LEED v4.1 certification for the feasibility study.

The team utilized LEED's online performance tracking platform Arc to manage the documentation and determine the number of points that the project is eligible to earn. The points for all seven categories, as previously shown in Figure 4, rely on data or documentation that is uploaded to the program. Progress of the project is easily managed and observed through a dynamic scoring visualization that simplifies the seven categories into five, as seen in Figure 7:

Figure 7

Dynamic Graphic that Tracks a Project's LEED Score

Due to the limited timeline of the project and the team's own capabilities, the priorities for investigating the feasibility of LEED certification were limited to those credits that are educationally valuable and currently feasible based on their access to the building, its operations, and its data. The team prioritized the following credit categories: Location and Transportation, Water Efficiency, Energy and Atmosphere, and Indoor Environmental Quality. Waste performance within the Materials and Resources category as well as heat island reduction within the Sustainable Sites category were also prioritized. These credits and credit categories were isolated because they connected with the educational requirements and goals of the MQP. They also corresponded with the application of different modeling programs that the team has learned in previous courses. The team acquired the necessary data for input into the Arc LEED online scoring program from the facilities office and other stakeholders. The remaining credits from the Materials and Resources, Sustainable Sites, and Innovation categories were identified by the team as secondary priorities. The team collected existing information to determine what current practices and policies are not LEED certifiable to recommend actions that the WPI Administration could take to achieve those credits.

3.2. Data Collection

Multiple surveys were conducted for the purpose of collecting data from both transitory and full-time occupants of the CC regarding their perceptions of the indoor environmental quality (IEQ), their transportation methods to the building, and their visits to the building. A summary of these survey methods can be seen in Table 3.

Table 3

Data Collection Methods Summary

	Arc Transportation and Human Experience Survey	Full-Time IEQ Survey	Visit Frequency and Length Survey
Intended Participants	Transitory and full-time building occupants (i.e., students, visitors, staff, etc.)	Regular building occupants (i.e., office workers)	Transitory building occupants (i.e., students, visitors, etc.)
Purpose of Study	Transportation methods occupants use to arrive at the CC and their comfort while there	Regular occupants' perception and control on IEQ (i.e., thermal comfort, air quality, and lighting)	Average # of visitors the building a day and the average length of each visit
Sample Size	210	21	37
Methodology	Distributed through email aliases, social media, flyers, display screens, and in-person promotion. Survey questions can be seen in Appendix _	Distributed through email to office workers. Survey questions can be seen in Appendix _	Counted # of people entering in an hour during a weekday afternoon and asked, "How much time do you spend in the CC on an average day?"
Usage	Obtain LEED points in Arc program in Transportation and Human Experience categories	Analyze and address current needs of affected population	Input into Arc program to calculate performance score of categories

3.2.1. Arc Transportation and Human Experience Survey

The first survey encompassed transitory and full-time occupants, as seen in Appendix A, and was generated by the Arc program to be automatically implemented for LEED points. This survey allowed the team to develop an understanding of the transportation methods occupants use to arrive at the CC and their comfort within the building. The team distributed the information for the survey through social media platforms and email aliases. Flyers with a QR code to the survey were placed on tables and bulletin boards throughout the CC in addition to being displayed on television screens across campus. Furthermore, the team promoted the survey through in-person interactions at a display table in the CC.

3.2.2. Full-time IEQ Survey

The second survey was sent out through email to the office workers in the building, representing the regular occupants. The survey questions can be seen in Appendix B. This survey allowed the team to determine the perception and control of the regular occupants on the indoor environmental quality of the CC, with a focus on thermal comfort, air quality, and lighting. The survey highlights occupants' satisfaction with their environment, both physically and psychologically. The team utilized this information to understand the occupants' perspectives and the effects the CC has with regard to productivity, comfort, and satisfaction. This data was then analyzed to address the current needs of the affected population.

3.2.3. Visit Frequency and Length Survey

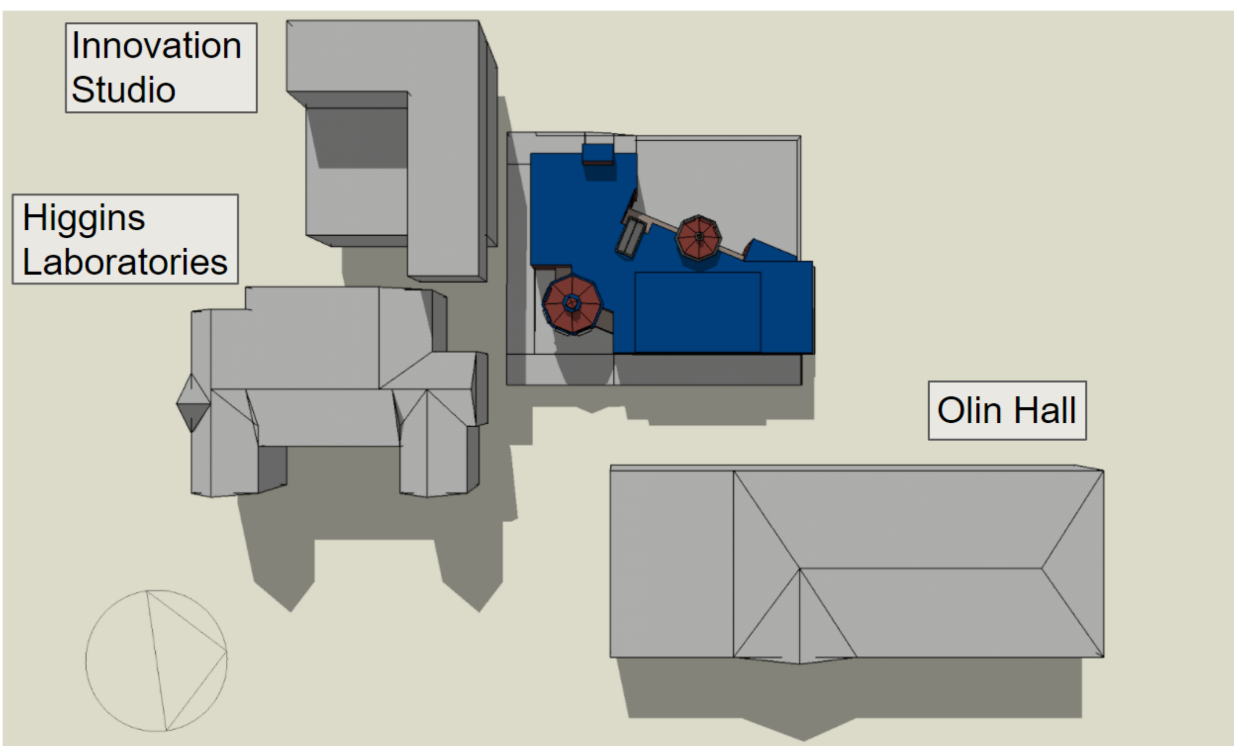
Additionally, the team determined the average number of visitors the building receives each day and the average length of each visit, which was needed for point calculations in the Arc program. For the first metric, the team recorded the number of people entering the building for an hour on a weekday afternoon and used this number as the hourly average. It was estimated that the increased visitors from the many events that take place in the CC could balance out the decreased number of visitors during the weekends. With the building's operating schedule, the team could then calculate the average number of visitors each day. For the second metric, the team surveyed people as they entered and left the building to determine how much time they spend in the CC. The responses were then aggregated and the average visit duration was calculated. Both of these metrics were inputted into the Arc program, as they affected how the performance scores of each category is calculated.

3.3. Energy Analysis

The team utilized the energy modeling software DesignBuilder to determine the energy usage intensity (EUI) for the building's current conditions and analyze potential areas for improvement. The architectural drawing sets, in combination with site visits, were used to accurately recreate the geometry within the software. Any measurements for the building's geometry that were unclear from the drawings were determined using Bluebeam Revu. All glazing and doors were also included in the geometry. Any windows that could not be drawn accurately due to software limitations were modified to retain the same glazing area. Component blocks were created for the buildings surrounding the CC as shown in Figure 8. Their purpose was to provide more accuracy in examining the effects of the sun and shading on the daylighting of the building's interior. Additionally, ground blocks were created around and under the building to represent the topography. The wall, roof, and slab assemblies were constructed in the software using section cuts in the architectural drawing sets to establish the approximate R-value. Glazing assemblies were constructed using the descriptions within the drawing sets and datasheets of similar products.

Figure 8

Plan View of the CC and Surrounding Buildings



To assist in the verification of data inputs, the team was granted access to *Webctrl*, the building management system (BMS) that WPI uses to monitor and adjust the mechanical and electrical systems of various buildings on-campus. The team was able to view the BMS data of the CC and the campus electric meters, and this informed various inputs to the model that are described in the following paragraphs. Separate from *Webctrl*, the team also had access to natural gas usage data from FY2015-2019 for the CC which were later used for model simulation comparisons in the results section.

The building model's three floors were divided into zones based on how they are separated in the *Webctrl* system, as seen in Figure 9. The activity types for each zone were defined based on the available templates within the Activity tab. Some assumptions and simplifications of the activities were made to reflect a more accurate occupant density rather than activity type. The occupant density for each zone was left as the default from the chosen activity template. The three operating hour schedules were applied to the zones based on how they are defined in the *Webctrl* system. Due to the complexity of the model and the large number of zones, zones of similar activity types and mechanical equipment were merged as shown in Figure 10, reducing the original number of zones by a third.

Figure 9

Zone Division of First Floor CC in Webctrl

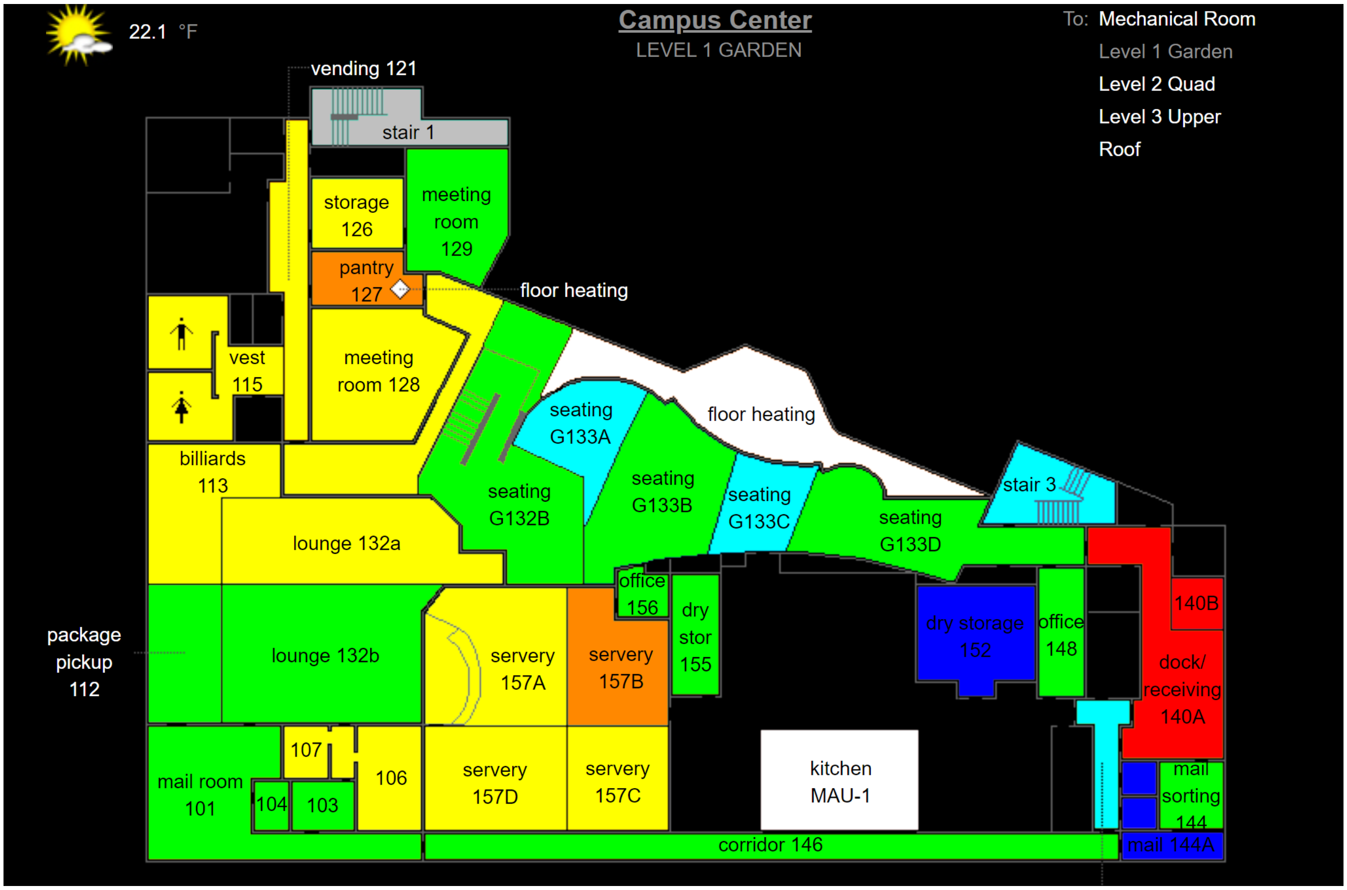
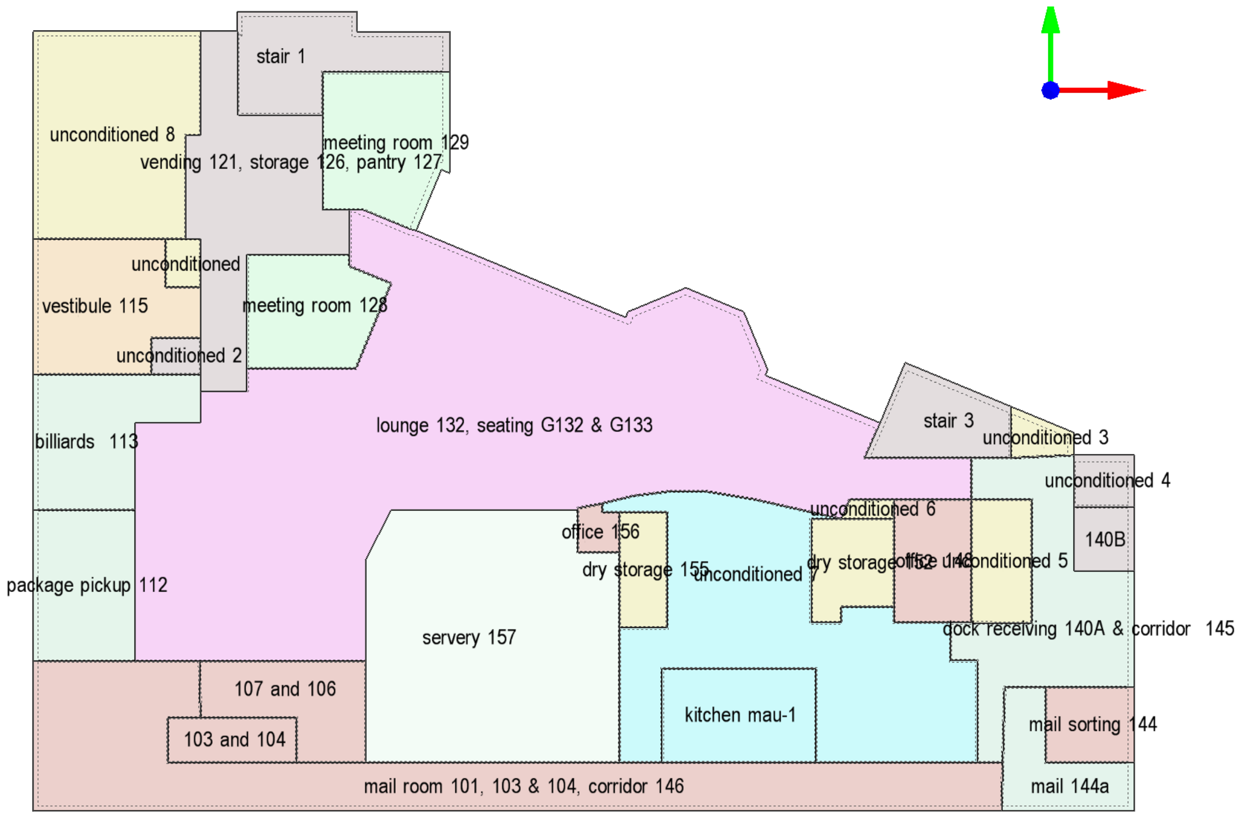


Figure 10

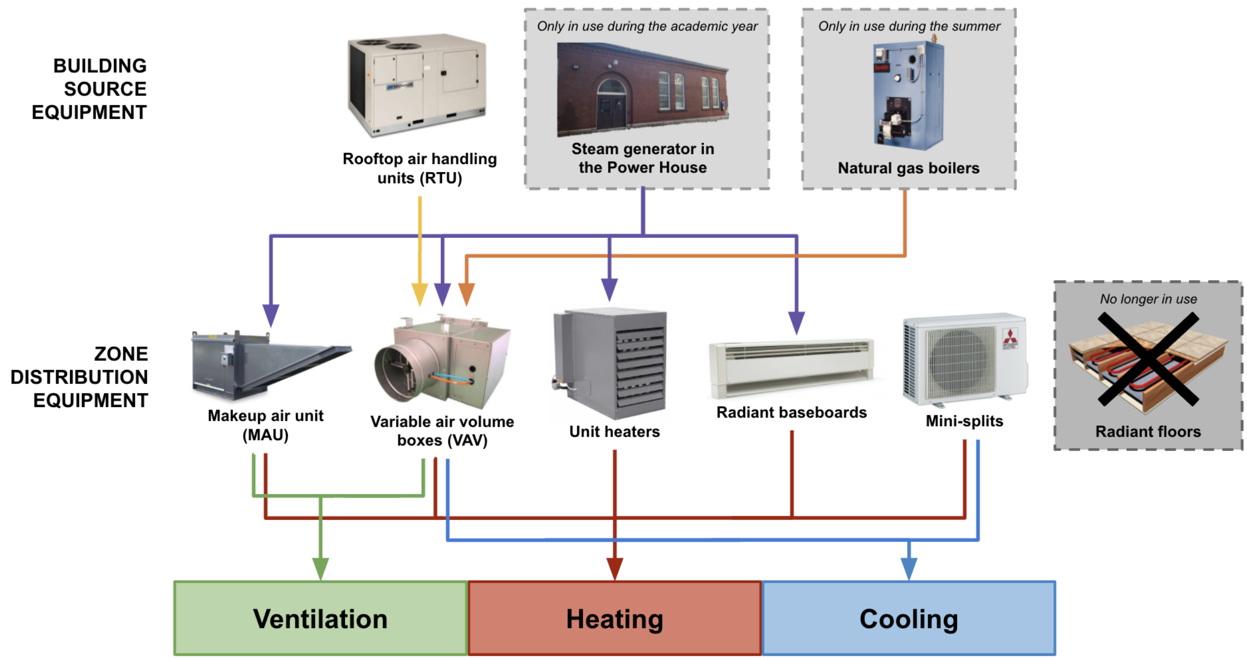
Simplified Zone Division of First Floor CC in DesignBuilder



To evaluate the efficacy of the existing mechanical systems, the team needed to understand and accurately simulate them. An overview of the HVAC system is shown below in Figure 11. The CC utilizes a Variable Air Volume (VAV) system with two Mammoth rooftop air handling units (RTUs) and a steam heating system fueled by the Power House, which runs at 80-85% efficiency. During the summer months, the steam loops are not operational and two Smith gas-fired boilers are used instead with a calculated efficiency of 81%. The RTUs, summer boilers, and most of the original VAV boxes have not been replaced in the twenty years since the building was completed. Some VAV boxes were more recently installed after replacing all of the building's constant air volume (CAV) boxes from the original mechanical design. The VAV boxes include standard VAV boxes, fan powered terminals (FPTs), and parallel powered induction unit (PIUs). Some spaces, such as data rooms and the mailroom, use Mitsubishi mini-split systems. For additional heating, there are radiant baseboards and unit heaters. The radiant floor heating system on the ground floor is no longer in use.

Figure 11

Relationships between the Building Source and Zone Distribution Equipment



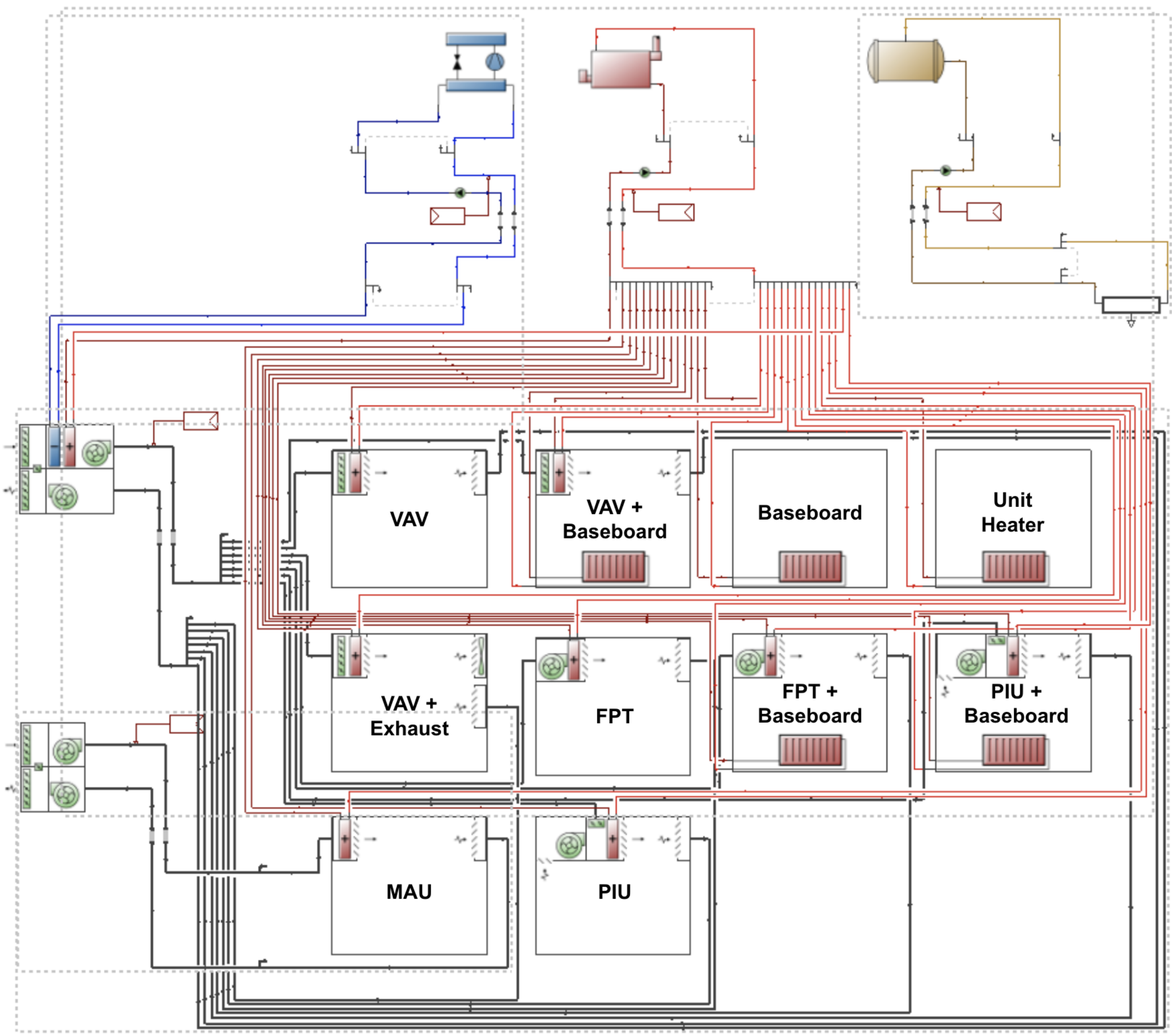
The team also obtained information regarding the electrical and plumbing systems to simulate the associated energy usage and their subsequent impacts on the building's EUI. Approximately 90% of the building's lighting was replaced with energy efficient LEDs during a past retrofit, and five daylighting sensors were placed along the north curtainwall by the food court. The remaining energy inefficient lighting is within mechanical spaces. To provide domestic hot water to the building, two Lochinvar gas-fired water heaters are used.

In DesignBuilder, the two RTUs were modeled as a single air handling unit (AHU) with the combined design flow rate of the two units, 51615 CFM. The simulated AHU also contains an exhaust fan. All of the data inputs for the AHU were left at default or autosized values because the model numbers for the two RTUs were not acquired by the team and datasheets could not be found to verify inputs. The mechanical plans indicated that a direct expansion (DX) coil may be responsible for cooling, but the equipment was modeled with a cooling coil connected to a chiller. Similarly, the heating of the hot water coil comes from the campus's steam heating system, but the equipment was modeled to be connected to a boiler. This modification most accurately recreates the efficiency rates of the steam system and the summer boilers, which have a negligible difference in efficiency.

Zone groups were created to categorize the different combinations of heating and cooling systems used by the zones. A total of ten zone groups were created, with their combinations as depicted in DesignBuilder shown in Figure 12. Each zone group uses one or a combination of the following: variable air volume (VAV) box, fan powered terminal (FPT), parallel powered induction unit (PIU), radiant baseboard, unit heater, make-up air unit (MAU), and exhaust fan. The zones in which no mechanical systems are modeled are considered to be unconditioned spaces, and are not included in the zone groups. The team organized the spaces based on the components included within each space's system.

Figure 12

CC Mechanical Systems and Zone Groups



All VAV, FPT, PIU, radiant baseboard, and unit heater settings in DesignBuilder correspond to the mechanical schedules and/or datasheets. This information includes air flow, water flow, heating capacities, and efficiencies. If information could not be found, the equipment was left to be autosized by DesignBuilder.

The team then outlined the proposed building scenarios to be simulated. Changes to the existing building would include replacements for different mechanical equipment that addressed issues identified by the facilities team and would aim to reduce energy consumption. The team tested all replacements individually to isolate which variables had the greatest positive impact across an entire year. Table 4 outlines the single-variable changes that took place. While product data from certain brands were used to analyze changes to the existing building, the team in no way directly recommends the use of these particular brands or products mentioned, only the ways in which they save energy or promote campus electrification.

Table 4

Comparison of Existing Mechanical Systems and Replacements for Proposed Building Model

<table>
<tr><th>Targeted IEQ Function</th><th>Existing:</th><th>Replaced With:</th></tr>
<tr><td rowspan="3">Heating, Cooling, & Ventilation</td><td rowspan="3">Mammoth RTUs</td><td>Option 1: Trane</td></tr>
<tr><td>Option 2: Trane RTU + Renewaire ERV</td></tr>
<tr><td>Option 3: Daikin RTU with Energy Recovery Wheel</td></tr>
<tr><td rowspan="2">Heating (& Cooling for Option 2)</td><td rowspan="2">Smith Natural Gas Boilers + Steam System</td><td>Option 1: Laars Electric Boilers (Remain on Steam System)</td></tr>
<tr><td>Option 2: ClimateMaster Heat Pumps</td></tr>
<tr><td>Heating, Cooling, & Ventilation</td><td>Greenheck MAU (Only Heating Coil)</td><td>Annexair MAU w/ Both Heating and Cooling Coils and Heat Recovery Plate</td></tr>
<tr><th>Targeted Energy Source:</th><th>Existing:</th><th>Replaced With:</th></tr>
<tr><td>All Electric</td><td>District Steam System, Summer Boilers, DHW Water Heater</td><td>Heat Pumps & Lochinvar Electric Water Heater</td></tr>
</table>

Once the variables with the greatest impact were identified, they were combined to form the final proposed model. Within this model, the team then updated the roof to have more insulation and weather protection, and simulated it for different rooftop scenarios. The rooftop options were as follows: a green roof, a photovoltaic (PV) panel array optimized for energy production, and a PV panel array optimized for LEED certification, and a combination green roof and PV panel array.

3.4. Green Design Strategies

Specific green design strategies were evaluated based upon LEED credit point potential as well as spatial availability, feasibility, and overall design. RTUs, photovoltaic (PV) panels as well as a green roof were chosen and designed with placement in mind. These strategies were then analyzed structurally depending on their chosen location to ensure the building structure could withstand the loading.

A sun study was conducted to determine the sun path and position in relation to the CC through DesignBuilder as shown in Figure 13. Additionally, an analysis of the available solar radiation was conducted in Revit. As seen in Figure 14, this analysis provided the annual solar energy through a visualization of the most efficient placement of PV panels. This function calculated the PV energy production per year and associated energy savings. It also determined the building energy offset with the required PV panel area needed and the payback time.

Figure 13

Sun Path Diagram of the CC from DesignBuilder

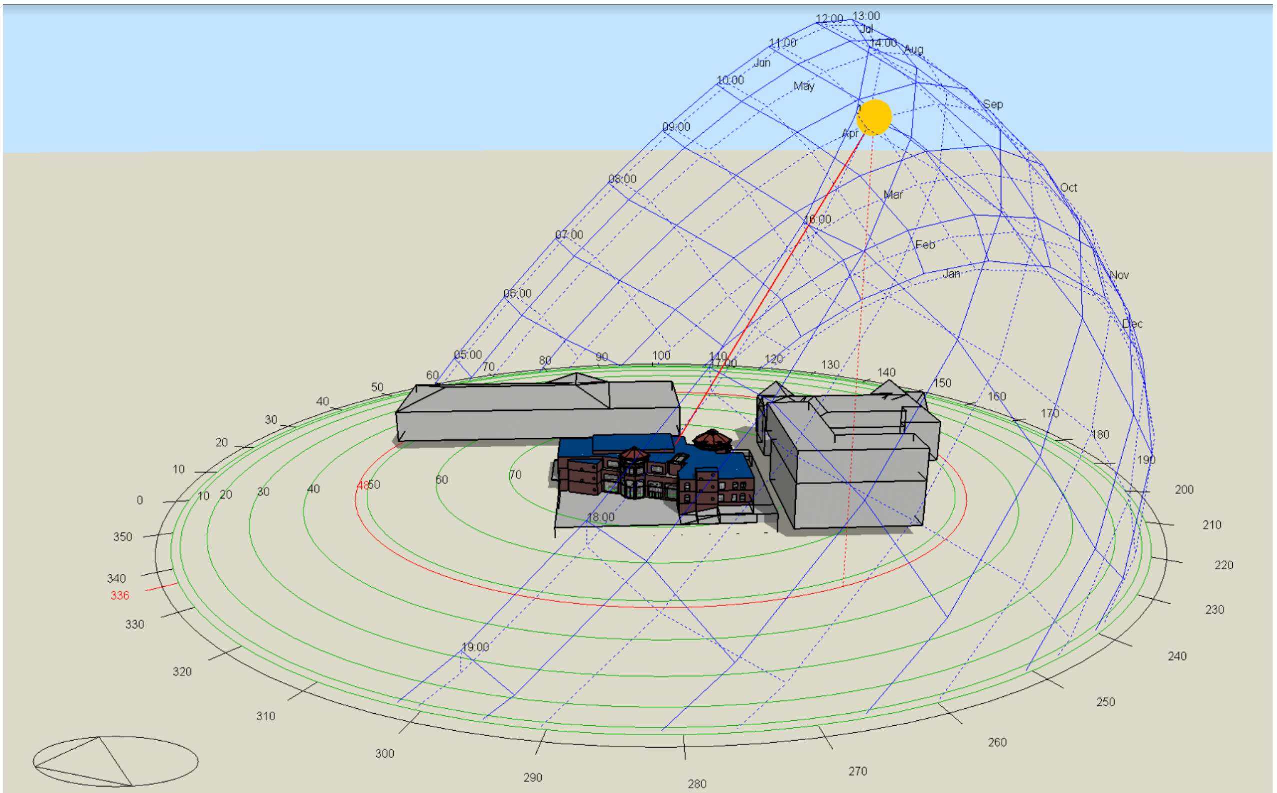
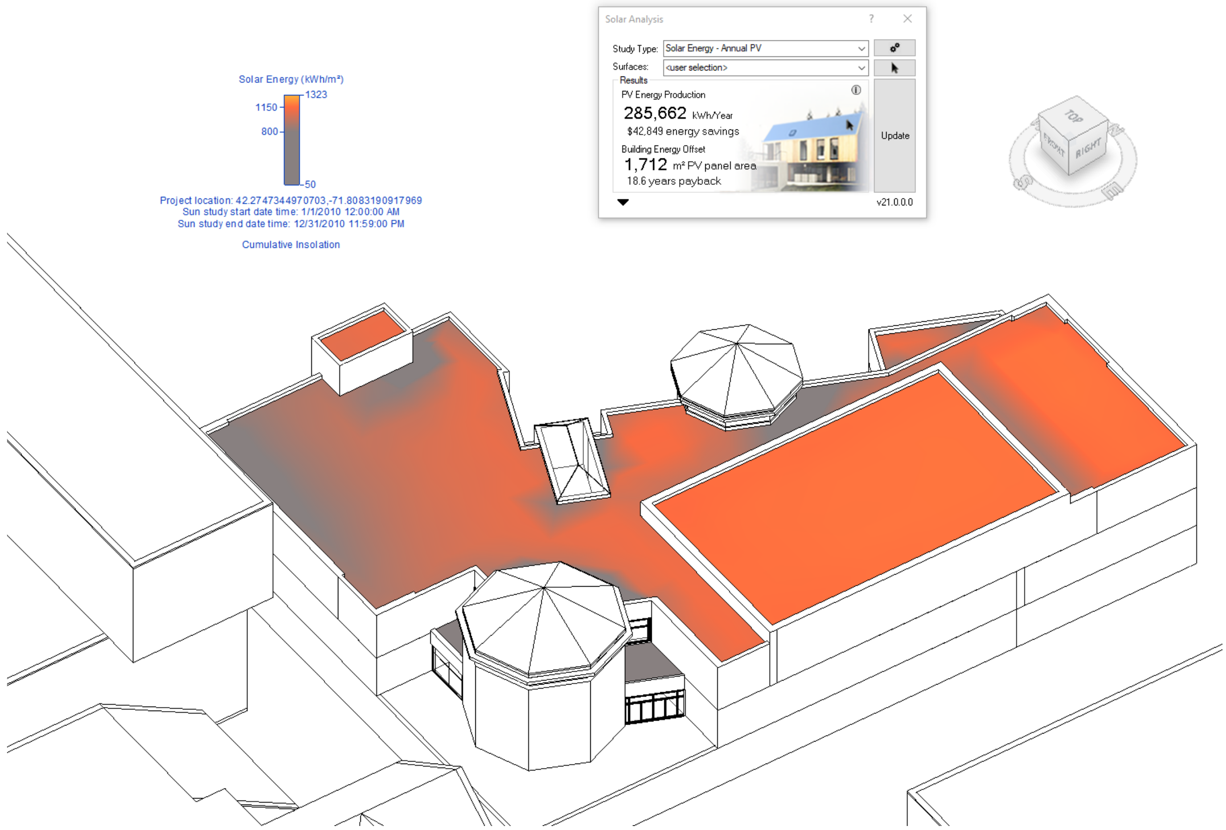


Figure 14

Revit Model PV Potential Visualization of the CC



For the PV panel green design strategy, variations of solar arrays were developed based on the angle selected for maximum efficiency as well as location. Of the variations, the option with the largest load was selected for analysis. To find the loads associated with the PV panels, the quantities and exact locations of the panels had to be determined. The team found the optimal tilt angles, sun elevation level, and azimuth correction angle based on the location of the building (De Rooij, n.d.; University of Oregon, 2015). Using the standard commercial 78" x 39" PV panels, the team calculated the most efficient inter-row spacing and followed the Massachusetts state guidelines to appropriately distance the panels from the roof edge (DHCD Massachusetts, 2014; Diehl, 2020; Quick Electricity, n.d.).

The green roof was designed with climate and low maintenance as priorities. Case studies at WPI and Whipple Riverview Ipswich (WRI) were utilized for their feasibility due to precedence and location in the Massachusetts humid continental climate zone (MassDEP, n.d.). The East Hall green roof was examined as an established green roof within the university setting, and the WRI was referenced for its detailed demonstration as a retrofitted green roof on an existing building. A green roof design was decided based upon an extensive green roof model, as it requires little maintenance and is most feasible for a roof retrofit in comparison to an intensive green roof. The roof construction design details include a waterproof membrane, plastic drainage mat, filter fabric, soil medium, and low growing drought-tolerant plants similar to that of the WRI. Additional considerations include specific herbaceous plants native to the local environment, and their survivability.

3.5. Structural Analysis

An investigation of the current building's structural system was done first to analyze the current capacities and compare them against proposed systems. The CC is composed of a structural steel framing system, with braced frames and a non-composite galvanized metal roof deck. A variety of wide flange shapes are within the building which were analyzed as seen in Table _. Hollow Structural Sections (HSS) are present and conform to American Society for Testing and Materials (ASTM) specification A500 Grade B steel within the system. The exterior of the building consists of a load-bearing masonry wall system with cast stone masonry.

Table 5

Wide Flange Shapes Investigated for Roof Structural Analysis

W-Shapes Investigated			
High Roof		Level 4 Roof	
Girders/Beams	Columns	Girder/Beams	Columns
W8X18	W10X77	W14X22	W10X77
W36X135	W12X87	W16X26	W12X87
		W18X40	
		W18X50	
		W21X44	
		W21X68	

To determine the loading capacity of the whole building, a structural analysis of the roof was conducted starting with the beams, girders, and then columns. By calculating the upper and lower thresholds for building capacity, the acceptable levels for superimposed loads were found, and the feasibility of adding new mechanical systems was evaluated with regard to the available structural capacity. The provided structural and architectural drawings sets were used as a baseline for analysis. Additionally, assumptions were made for both the beam/girder and column analysis and design based on the drawing sets as seen in Table 5 .

Table 6

General and Specific Assumptions for Roof Structural Analysis

Assumptions	
General	
• Simply supported structure • Load and Resistance Factor Design (LRFD) • Fy = 50 ksi • Roof – snow zone 3, 35 psf + drifting • Wind load – zone 2 exposure B, 17 psf • Seismic load: Massachusetts code requirements • Non-composite beam • AISC Table 3-23, Uniformly distributed load • Establish initial member sizes based on tributary areas and gravity loads (D, L, S, etc.) • Floor LL = 100 psf	
Beams + Girders	Columns
Design flexural strength φ_b = 0.90 (LRFD)	Effective Length Factor, K = 1 used for both the major and minor axes
Load Combination Equations: 1.4D 1.2D + 1.6L	Load Combination Equations: 1.4D 1.2D + 1.6 (Lr or S or R) + (.5L or .5W) 1.2D + 1.6L + .25 (Lr or S or R)
Zx found using AISC Specification equation F2-1	Column capacity determined with ASIC Specification E1, E2, E3
W shape choice AISC Table 3-2	Table 4-1a for compressive design strength, (φcPn) and associated W-shape properties
Maximum deflection limits LL = L/360, no greater than 1in * find location	
Maximum deflection limits DL + LL = L/240	
Ix, AISC Table 1-1 based off W shape	
W shape found, AISC Table 3-2 based off Ix	

Within those systems, certain members were highly repetitive; thus, a diverse sample of beam and column schemes were chosen to be analyzed to ensure coverage of overall variations. The roofing system contains two separate levels of roofing and analysis was focused on a variety of beam member sizes. The considerations for the members investigated included factors such as member sizes and member spans. The investigation was concentrated on applications that involved longer member spans, members in the proximity of stairwells, and mechanical/anticipated mechanical equipment. As seen in Figure 15, beam and girder schemes were also designated based upon interior and exterior regions as well as dispersion across the different regions to ensure proper representation of the roofing system loading capacity. Typical columns in defined areas of interest, being interior, exterior, or corner columns were investigated for a full range of column types within the system, following chosen members as seen in Figure 16. The column bearing capacities were investigated and determined.

Figure 15

Selected Beams and Associated Tributary Areas for the Level 4 Roof and High Roof

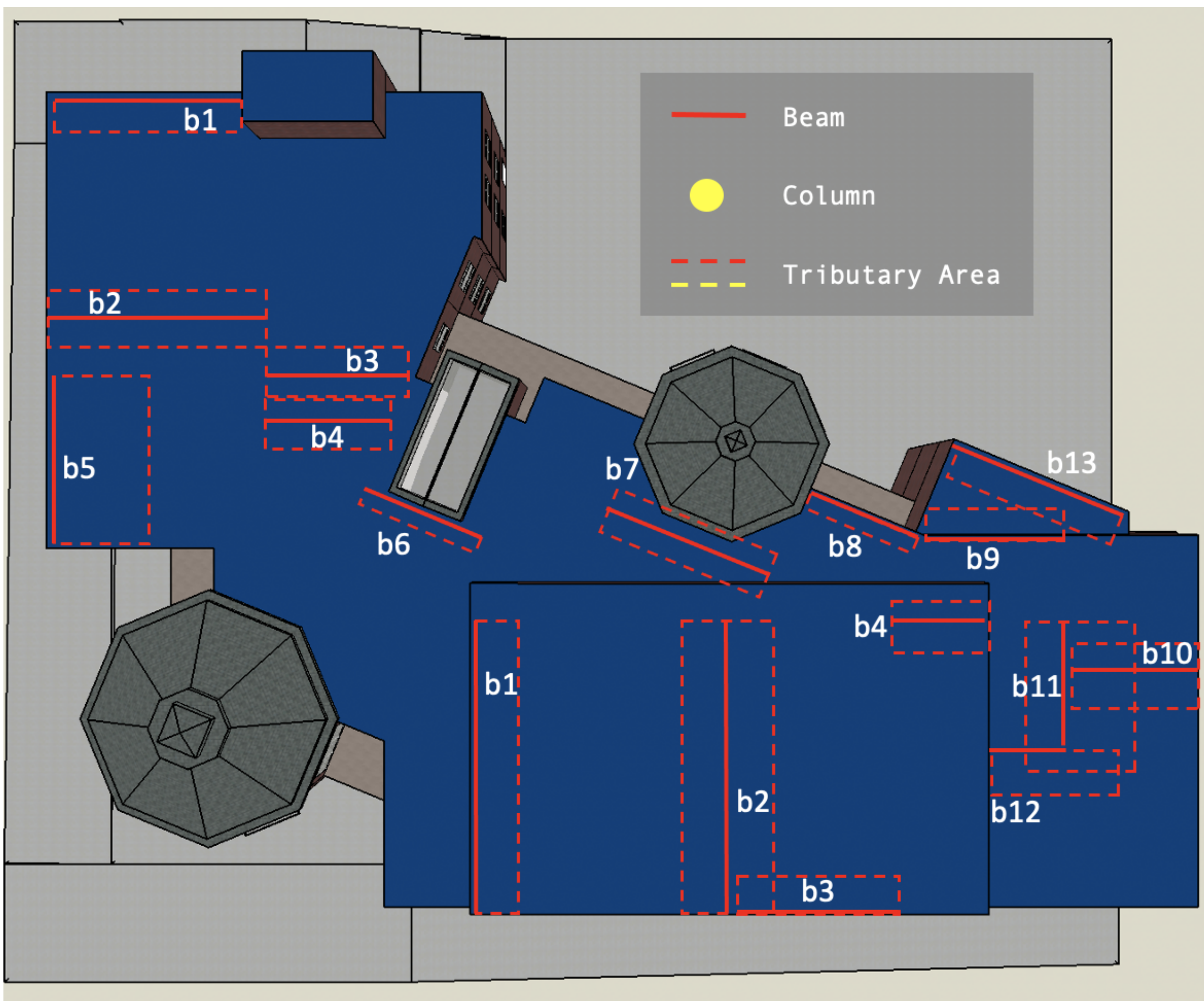
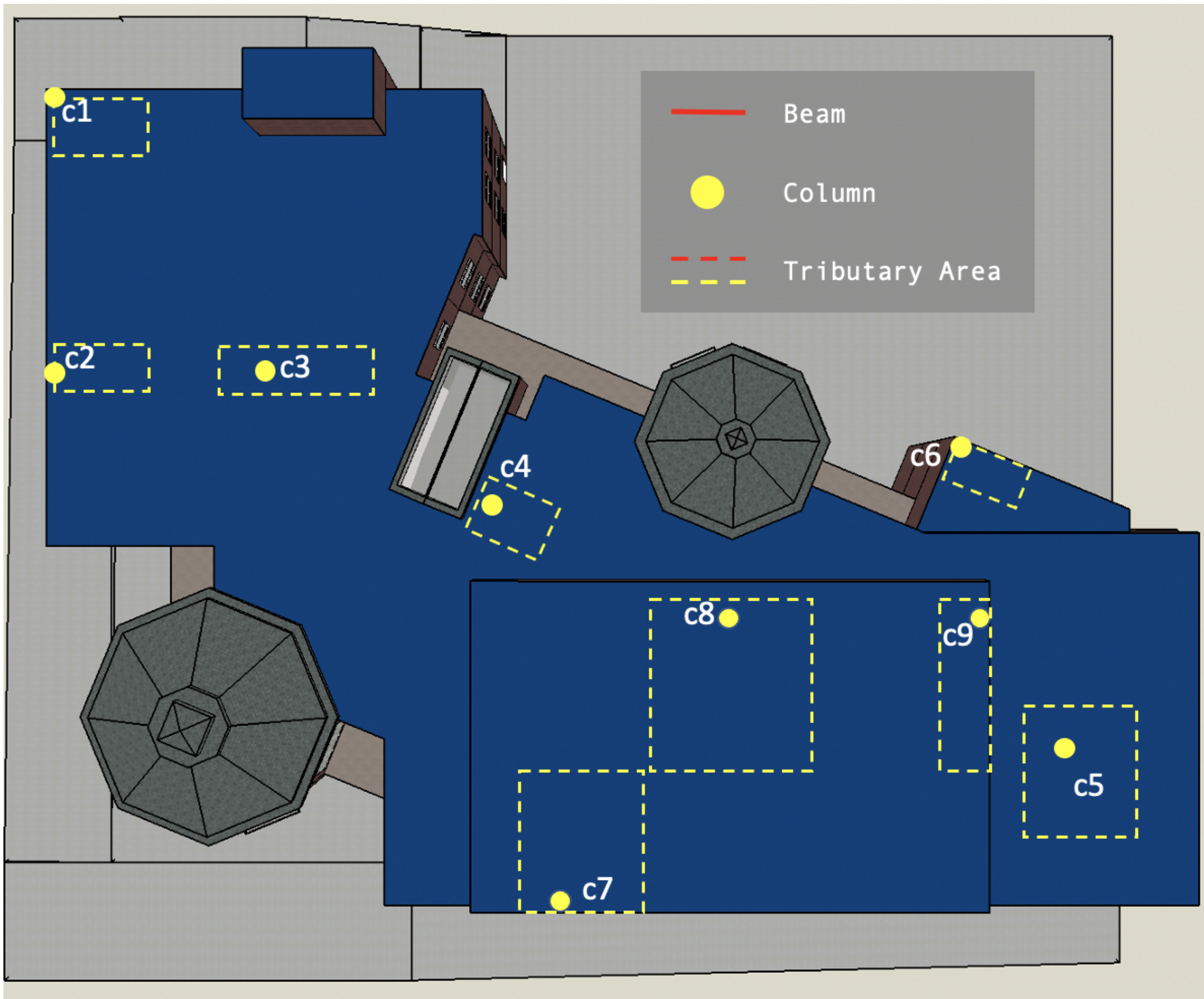


Figure 16

Selected Columns and Associated Tributary Areas for the Level 4 Roof and High Roof

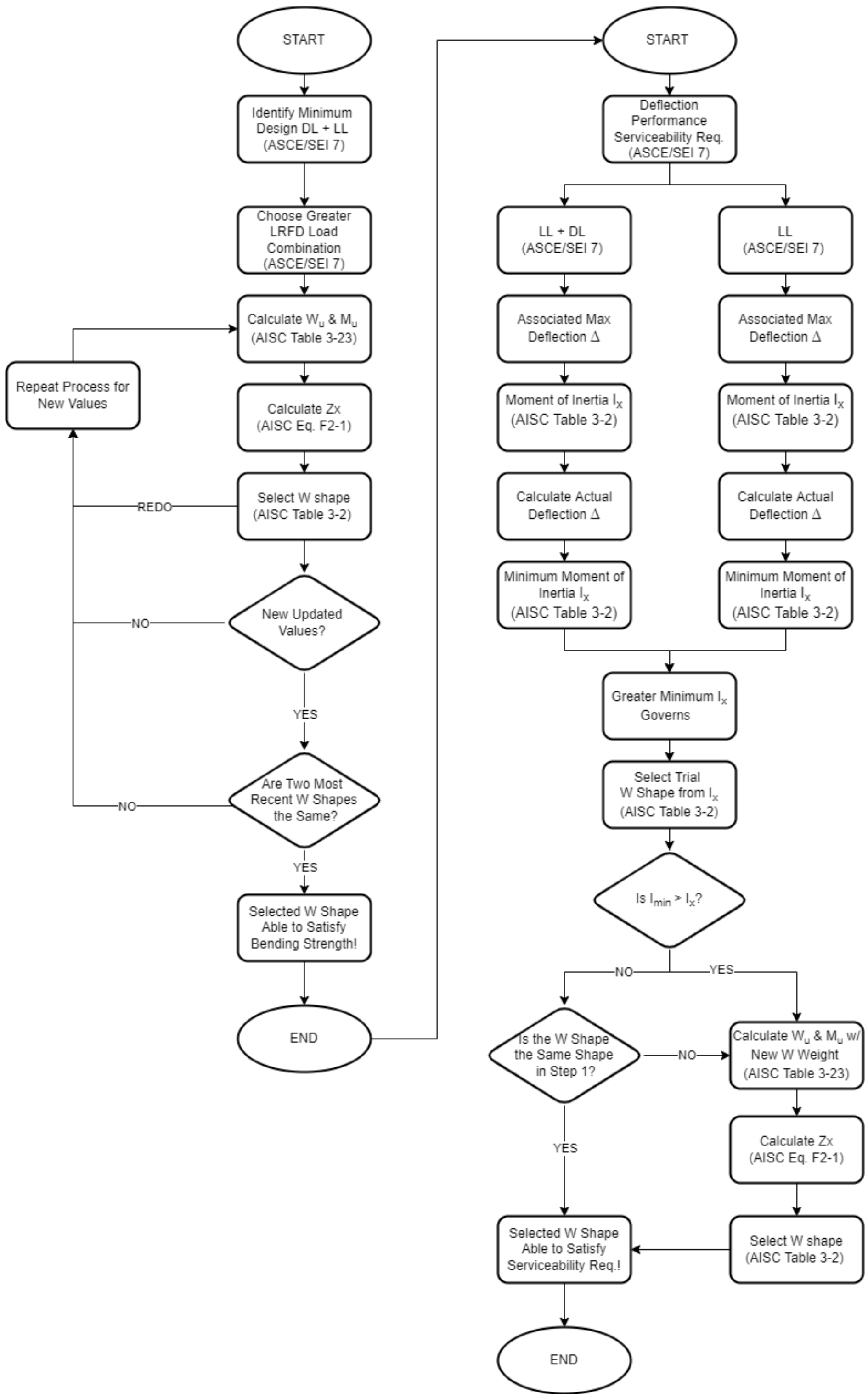


3.5.1. Analysis of Available Capacity

To begin, the lower and upper thresholds for the strength and serviceability requirements of the specified simply supported beam and girder sections were determined, as summarized in Figure 17. The identification of roofing and exterior construction materials were found within the architectural and structural drawing sets to calculate dead loads. The minimum design dead loads were identified per the ASCE/SEI 7 standard *Minimum Design Loads for Buildings and Other Structures*.

Figure 17

Strength and Serviceability Flow Chart Diagram for Beam Design



As seen in Appendix C, load combinations were calculated based upon the given beam parameters, such as dead and live loads and girder length. The larger of the two load combination values per the Load and Resistance Factor Design (LRFD) method was used as the governing value for the remaining strength calculations. For the lower end of the necessary W-shapes to withstand the loading capacity, the governing distributed load was used to calculate the respective required bending strength M_u. The plastic section modulus, Z_x, was then calculated and used to select a new W-shape. Based upon the weight of the newly selected W-shape, an updated load combination, ultimate bending moment, and plastic section modulus Z_x were calculated. If the resulting Z_x was found to be greater than the original, the process occurred again until an appropriate shape per the strength parameters was selected.

After selecting an appropriate W-shape based upon the strength requirements, deflection performance was investigated for each scheme presented per the given serviceability criteria as summarized in Table 5. The maximum deflection limit for the floor live load (LL) and the combined superimposed dead and floor live load (LL + DL) were utilized. The moment of inertia was obtained from Table 1-1 or 3-2 based on the chosen W-shapes. The actual deflection value was then determined for the LL and the LL + DL for every chosen scheme. The minimum moment of inertia values is then calculated to find the lightest W-shape. If $I_x \geq I_{min}$, then the previously selected W-shape from which satisfied the bending strength is determined appropriate. The required capacities w_u and M_u were recalculated to reflect the current values as necessary. This process was repeated to analyze the upper range of the beam loading capacity.

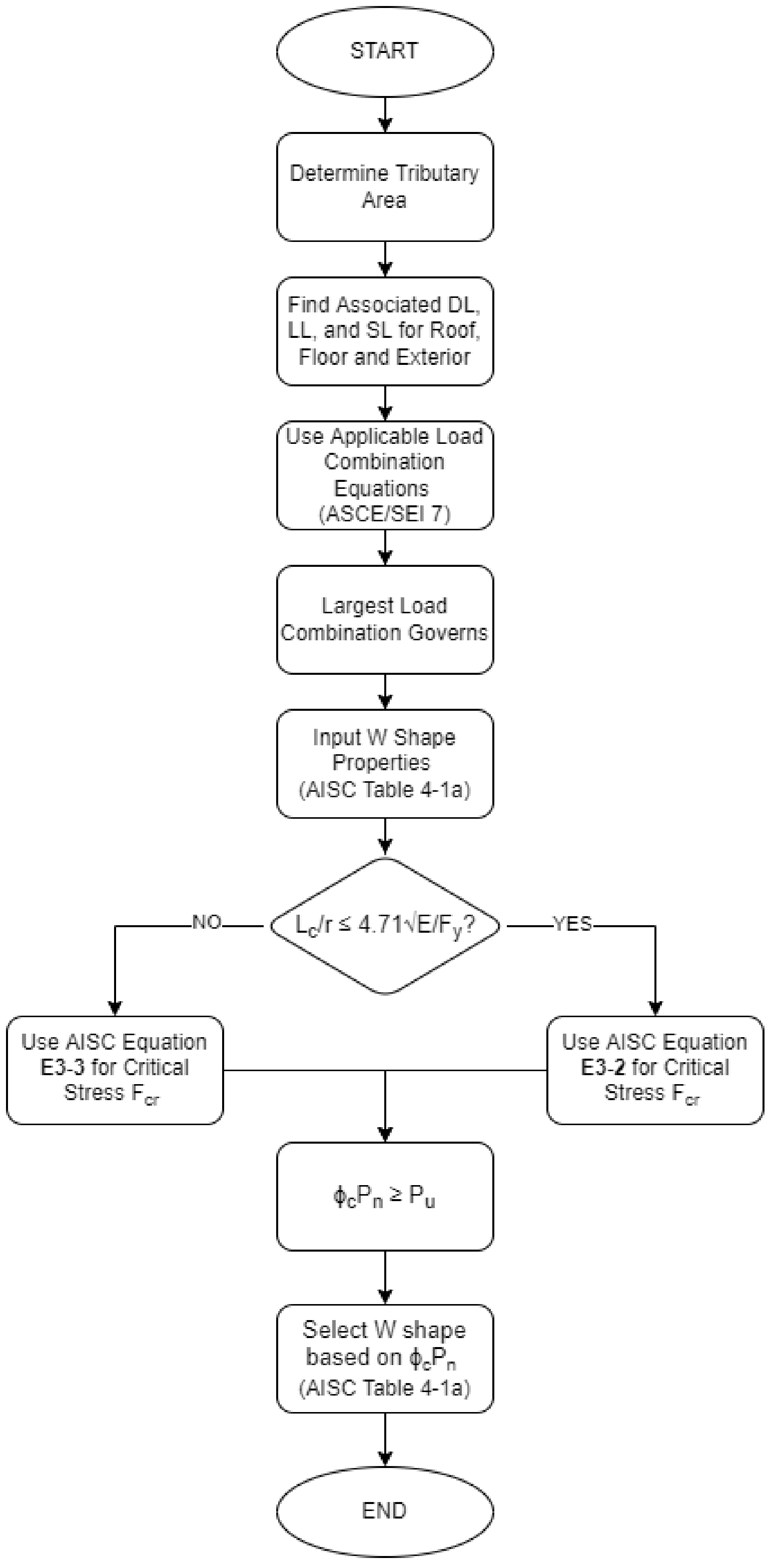
To determine the allowable column loading on the CC, the column design investigation began, as shown in Figure 18, by determining the tributary areas and loading information which were calculated based upon the drawing sets. Both the lower and upper range of the column compressive design strength (ϕcPn) were determined by utilizing calculated load factors and structural drawing sets for W-shapes selection, respectively. This process provided both a minimum and maximum threshold.

To determine the lower end of the column scheme capacities, a range of values suitable to resist the compressive loads for the given interior, exterior, and edge columns were confirmed by using the calculated dead loads previously found. This range of values includes the floor dead and live loads as well as the exterior façade dead loads depending on the chosen column location. The relevant load combination equations were identified, and the total factored loads were calculated. The greatest of the calculated total factored loads (P_u) were then used to select a W-shape. Properties based upon the selected W-shape were found, and the lower-end capacities of the selected columns were verified utilizing specified provisions. By finding the compressive design strength (ϕcPn) for each scheme, the W-shape was then confirmed by comparing ϕcPn to P_u.

While the lower end of the capacity was found utilizing the P_u to choose a W-shape at the start, the upper end of the capacity was found by utilizing the given column W-shapes provided within the structural drawing sets. Similarly, properties for the selected W-shapes were identified and the upper capacity of the chosen column shapes were verified through the specified provisions. The compressive design strength (ϕcPn) for the chosen W-shape was found and confirmed through the comparison of the previously determined P_u.

Figure 18

Strength and Serviceability Flow Chart Diagram for Column Design



3.5.2. Structural Feasibility of New Green Design Strategies

The building load capacities of the beams, girders, and columns were analyzed for all three green design strategies. Multiple iterations were investigated to determine if they were structurally suitable. The RTU options, PV panel system, and green roof were individually implemented into the structural design to confirm structural permissibility against the available capacity for both girders/beams and columns. Additional loading was implemented based upon the different green design strategies, and strength and serviceability analysis occurred for the girder/beams and columns as previously summarized in Figure 17 and Figure 18, respectively. They were verified by comparing these values with the original building's load capacity threshold. Comparisons were made by examining each schemes' factored ultimate uniform load (w_u), compressive design strength (ϕcPn), and required axial compressive load (P_u) for permissibility.

4. Results

The existing building's energy usage, and unmet setpoint hours for heating and cooling were used, along with other data, to establish the original LEED scorecard and a baseline comparison against the proposed variable changes and final proposed models. The four final proposed building models were developed from a combined analysis of the structural and mechanical design calculations. This analysis isolated the variables that used less energy and were structurally feasible. The four proposed buildings were developed from seven initial energy models that simulated six different, single-variable changes and 26 structural schemes that tested changes and external additions to the roof. All of the results from the four proposed models were compared, and the results were then inputted into the Arc program to develop the proposed buildings' LEED scorecards. Opportunities for improving the score are explored, and recommendations for the WPI Administration to engage in this process are made. The project's outcomes and limitations are discussed.

4.1. LEED

The existing building's LEED score was calculated by the online program Arc based on information the team obtained from various sources. Certain information, such as IEQ measurements for CO2, Volatile Organic Compounds, and other air contaminants, and prerequisites for all of the categories were not conducted or confirmed by the team and did not influence the calculation of the score in Arc. The final performance score was calculated by Arc to be 57/100 and is shown in Figure 19 and Figure 20, indicating that the existing building is certifiable as LEED Silver. A breakdown of this score by points per category is discussed below.

Figure 19

Existing Building LEED Points Achieved

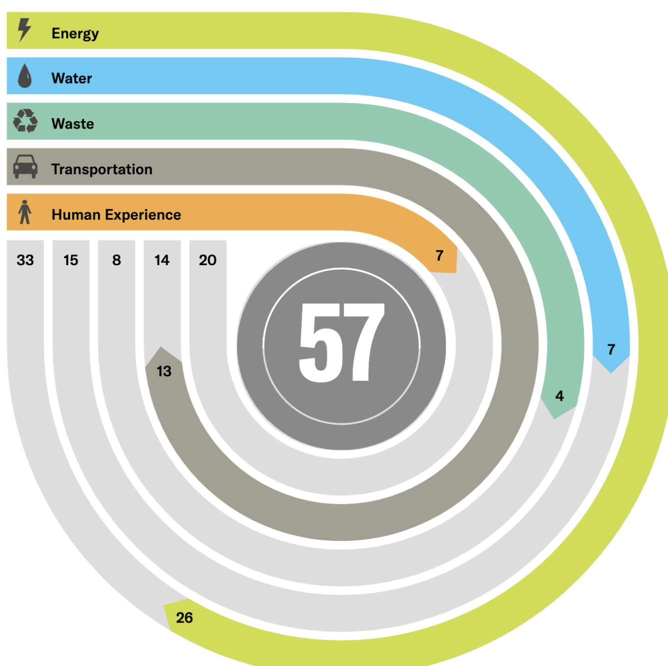


Figure 20

Existing Building LEED Certification Level

4.1.1. Building Settings

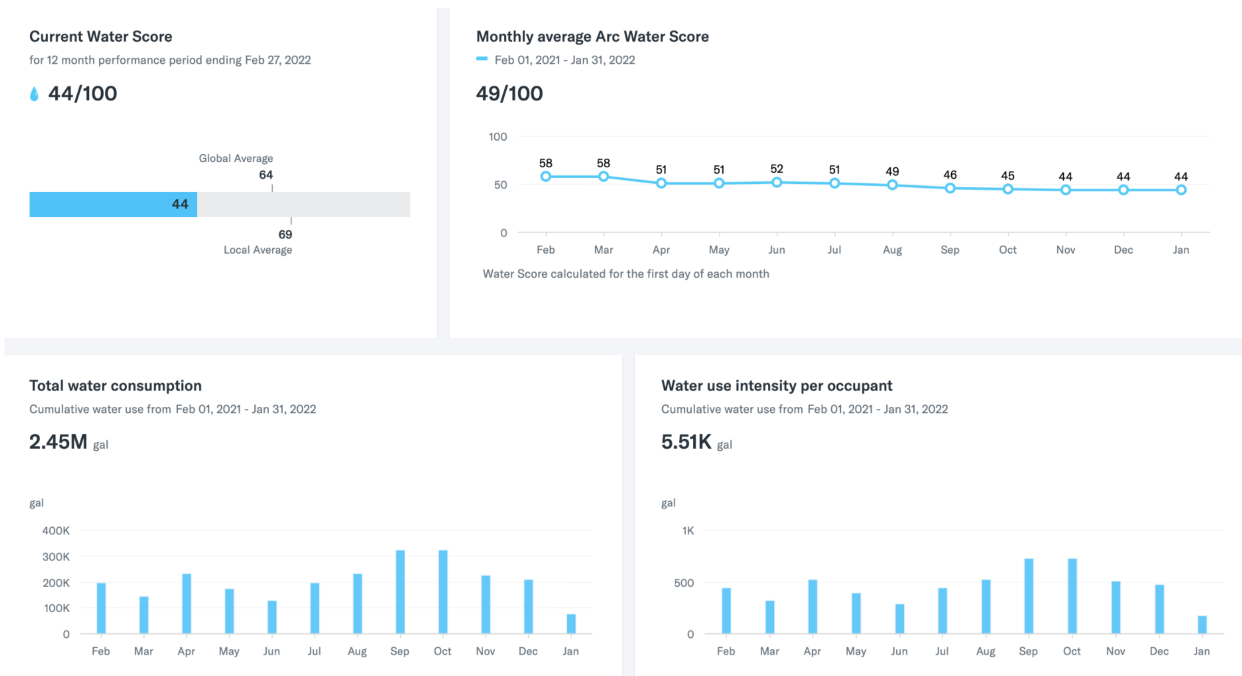
Before points could be calculated for any of the LEED categories, information regarding the CC building needed to be inputted into Arc under the building settings. The gross floor area was determined to be 71,148 square feet based on the architectural floor plans. The building was assumed to be in operation 365 days per year with 121 operating hours weekly, based on normal hours of operations (WPI, n.d.b). Multiple data points were needed to determine the time-weighted occupancy, which affects the calculated efficiency or number of responses needed for all LEED categories. There are an estimated 60 regular occupants, including the 25 office workers, Chartwells employees, Dunkin' Donuts cashiers, and the mailroom workers. Based on our study conducted in the CC, there are 501 visitors every hour or 8,660 visitors on an average day, and each visit has an average duration of 46 minutes. The time-weighted occupancy was determined to be 444 total daily occupants.

4.1.2. Water Performance

The water performance score was calculated by utilizing the building settings and total monthly water consumption, determined by the water bills from fiscal years 2021 and 2022. The building must achieve a minimum of six LEED points in the water performance category as a prerequisite for certification. After inputting the existing total water usage as seen in Figure 21, the building achieved a current water score of 44, which equates to seven LEED points.

Figure 21

Water Performance Graphs from Arc



4.1.3. Waste Performance

Waste performance results were defined utilizing the data seen in Figure 22 to determine the waste performance score for the CC. The total cumulative weight of the waste generated and total cumulative weight of the waste diverted was found from the annual waste audit conducted by the WPI Green Team. The current waste score was calculated to be 49/100, giving the CC four LEED points out of the available eight points as seen in Figure 23.

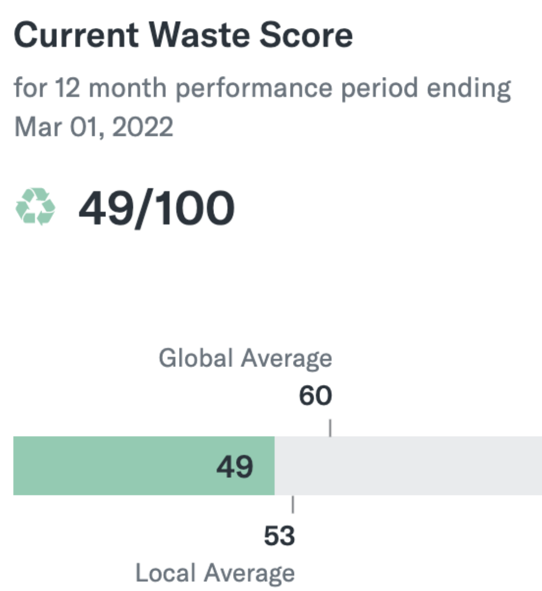
Figure 22

Determined Recycling Rates, Waste Generated and Waste Diverted for the CC through Annual Waste Audit

2019 Waste Audit Results	
Recycling Rate	14.03%
Total Waste Generated (lb)	215350
Diverted (lb)	30213

Figure 23

Current Waste Score Within Arc for the CC



4.1.4. Transportation

By analyzing the results from the Arc survey distributed to occupants, it was found that almost 75% of occupants walk to the CC, while almost 20% take a car as a single rider as seen in

Figure 24. This may represent people who drive to the WPI campus in general, and chose to distinguish themselves from individuals that live on or near campus. The transportation score from the CC was 94/100 as seen in Figure 25. The CC was awarded 13 out of a total 14 LEED points.

Figure 24

Transportation Mode Popularity for CC Occupants

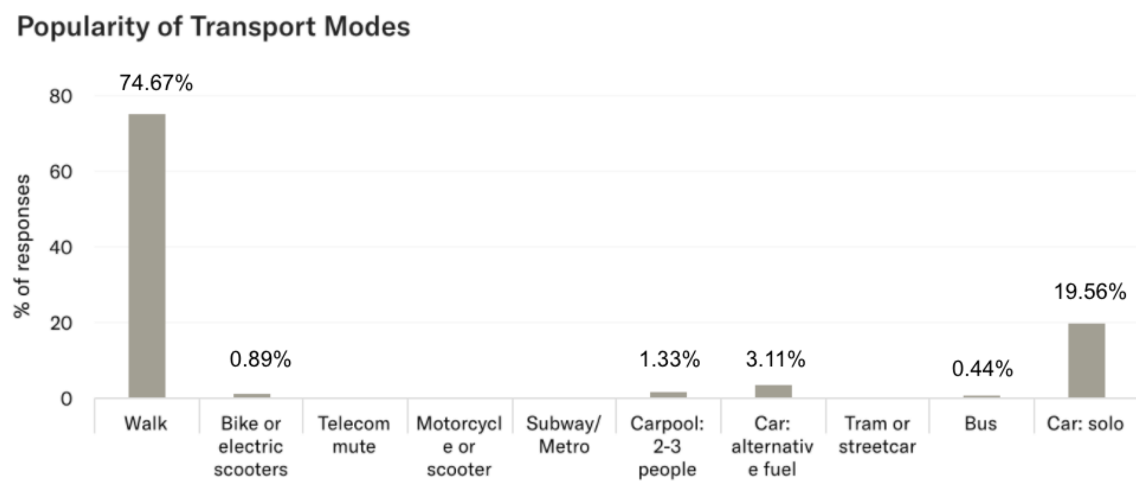
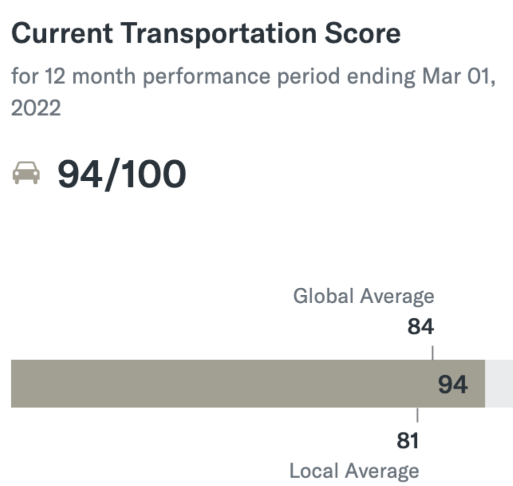


Figure 25

Current Transportation Score Within Arc for the CC



4.1.5. Human Experience

The Arc survey also gathered information from occupants regarding their comfort levels for the human experience category. About ¾ of respondents indicated they were satisfied, very satisfied, or extremely satisfied, as depicted in Figure 26. The human experience score was 34/100 as seen in Figure 27, and the CC was awarded seven out of a total 20 points.

Figure 26

Occupant Satisfaction of Indoor Environmental Quality of the CC

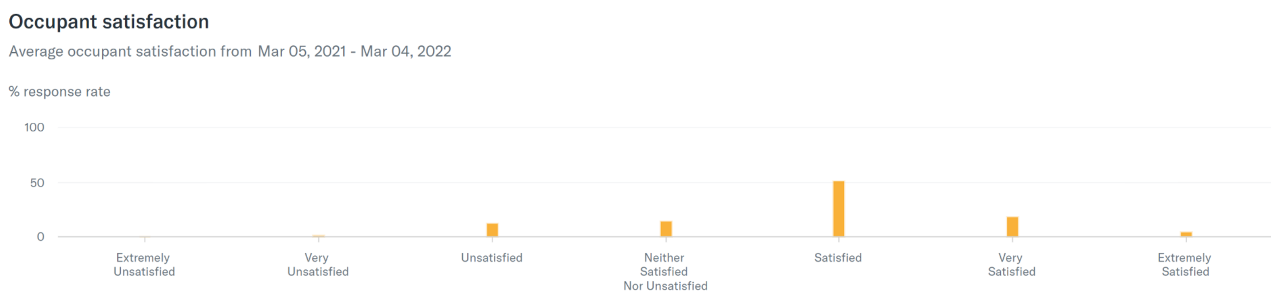
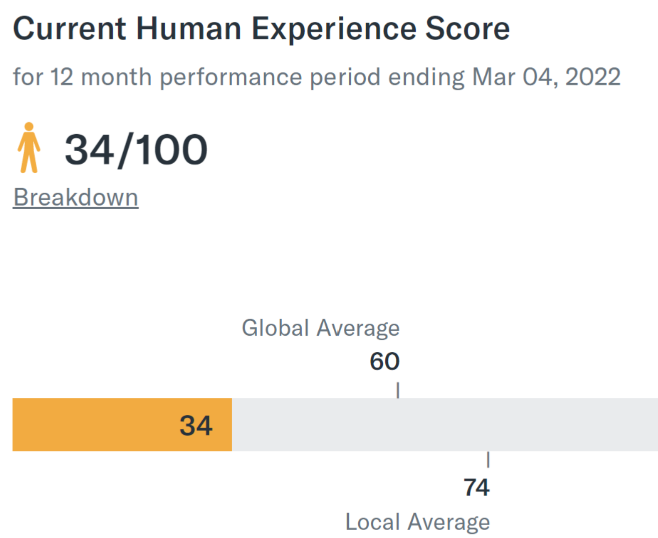


Figure 27

Current Human Experience Score Within Arc for the CC



4.1.6. Energy Performance

After the completion of the DesignBuilder model for the existing building, the monthly energy usage data could be extrapolated based on the recently metered electrical data and past natural gas bills. The monthly electricity usage and natural gas usage can be seen in Figure 28 and Figure 29, respectively. The electricity consumption for the existing building is composed of any heating during the summer months, cooling, lighting, equipment, fans, and motors. The natural gas consumption is composed of heating, domestic water, and kitchen equipment. The existing building's EUI was estimated to be 156 kBtu/sf.

Figure 28

Monthly Electricity Usage as Inputted in Arc

Energy 26 / 33
PV Panels
Natural Gas Meter
Electricity Meter

Automated meter:
Portfolio Manager
For more help with syncing a new property, please review this guide .

READING START DATE	READING END DATE	READING (kWh)
Feb 01, 2022	Feb 28, 2022	83,107.25
Jan 01, 2022	Jan 31, 2022	82,712
Dec 01, 2021	Dec 31, 2021	79,641
Nov 01, 2021	Nov 30, 2021	104,578.4
Oct 01, 2021	Oct 31, 2021	95,439
Sep 01, 2021	Sep 30, 2021	110,572.52
Aug 01, 2021	Aug 31, 2021	130,848.99
Jul 01, 2021	Jul 31, 2021	132,108.09
Jun 01, 2021	Jun 30, 2021	117,420.64
May 01, 2021	May 31, 2021	109,813.48
Apr 01, 2021	Apr 30, 2021	90,258.37
Mar 01, 2021	Mar 31, 2021	87,950.28

Figure 29

Monthly Natural Gas Usage as Inputted in Arc

Energy 26 / 33
PV Panels
Natural Gas Meter
Electricity Meter

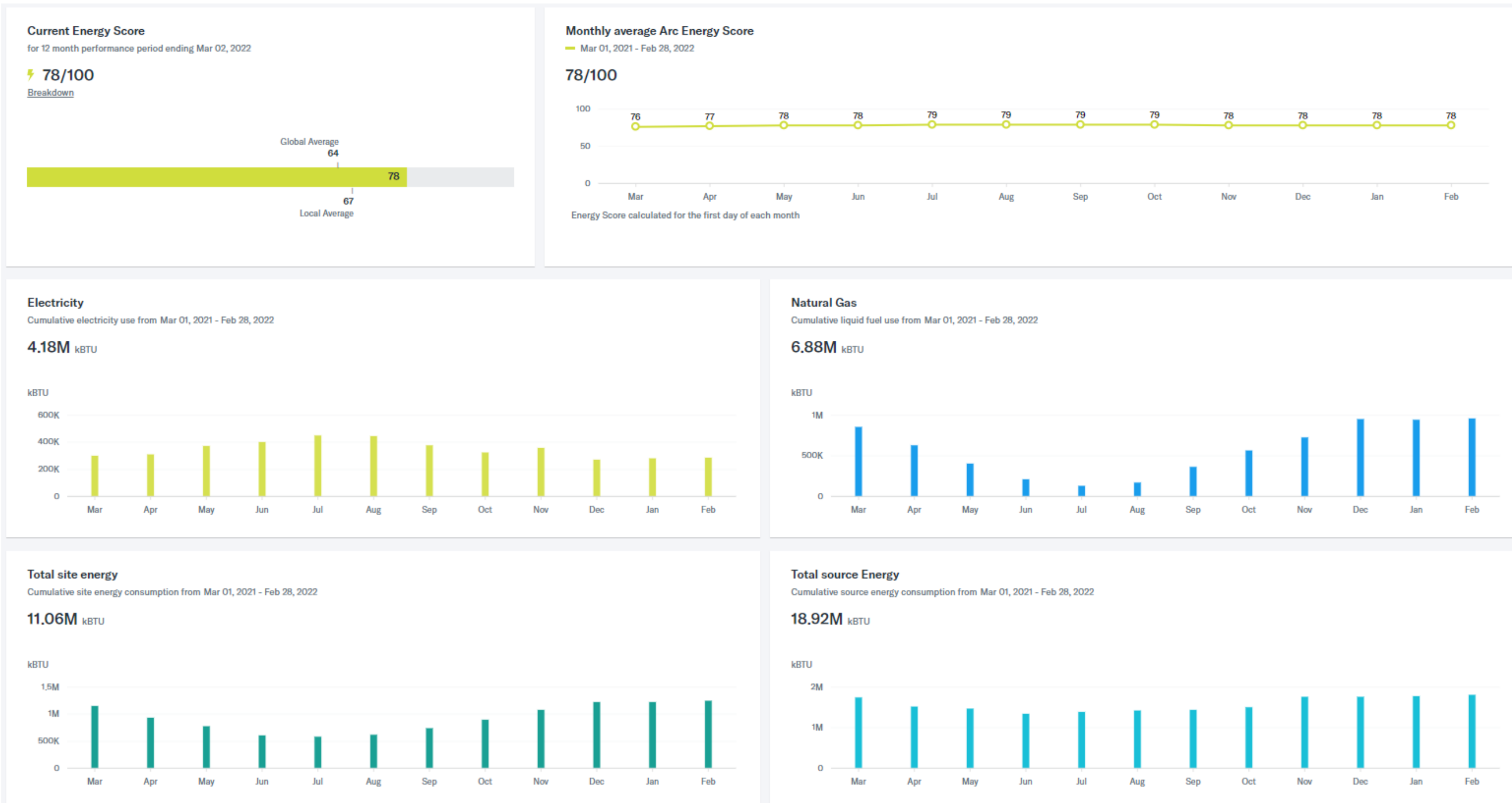
Automated meter:
Portfolio Manager
For more help with syncing a new property, please review this guide .

READING START DATE	READING END DATE	READING (kWh)
Feb 01, 2022	Feb 28, 2022	280,943.96
Jan 01, 2022	Jan 31, 2022	275,398.4
Dec 01, 2021	Dec 31, 2021	277,957.45
Nov 01, 2021	Nov 30, 2021	212,350.28
Oct 01, 2021	Oct 31, 2021	165,959.71
Sep 01, 2021	Sep 30, 2021	105,960.05
Aug 01, 2021	Aug 31, 2021	48,765.9
Jul 01, 2021	Jul 31, 2021	37,087.6
Jun 01, 2021	Jun 30, 2021	60,557.58
May 01, 2021	May 31, 2021	117,523.38
Apr 01, 2021	Apr 30, 2021	184,169.98
Mar 01, 2021	Mar 31, 2021	249,965.56

As a prerequisite for any level of certification, the building needed to achieve a minimum of 6.5 points. The Arc program calculated a current energy score of 78, as seen in Figure 30, which equates to 26 points out of the possible 33.

Figure 30

Energy Performance Graphs from Arc

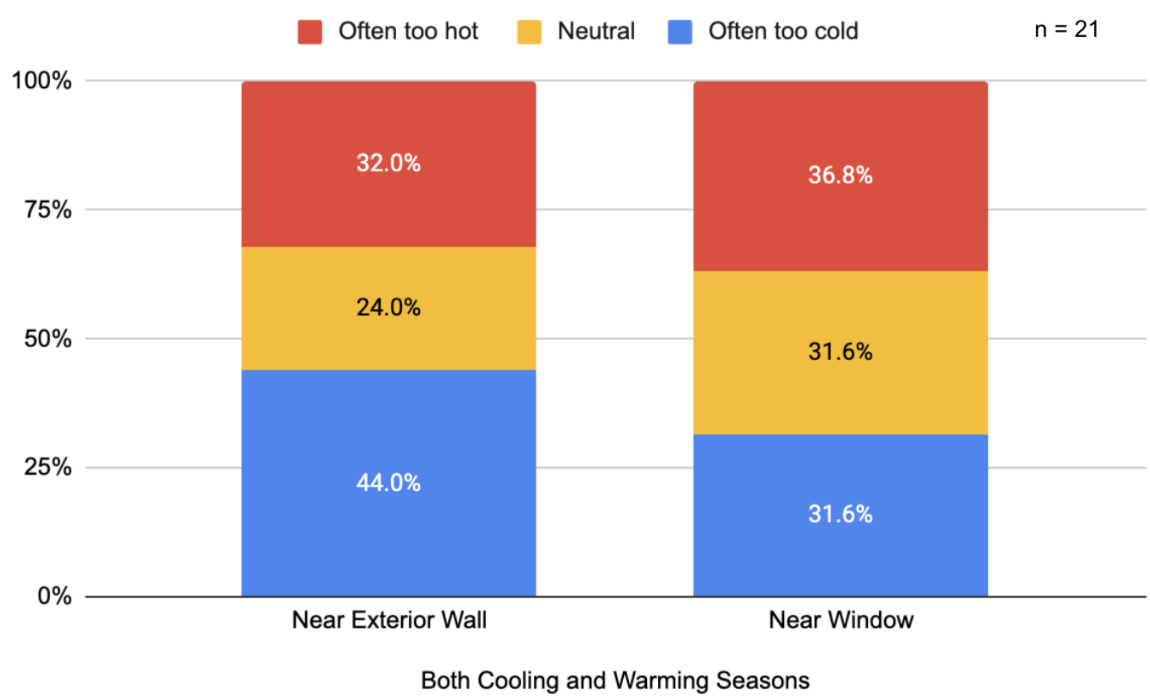


4.2. Full-time IEQ Survey Results

Results regarding personal environmental comfort specific to thermal, air, and lighting quality were found through the IEQ survey distributed to full-time occupants of the CC with a sample size of n = 21. From this data, it was found that while about half of occupants in the CC were either often too hot or too cold, the other half, 47.8%, were found to be neutral in their comfort levels during both the cooling and warming season, as seen in Figure 31. Additionally, 33.3% of occupants found their environment to be often too cold in the warming season which was an increase of 7.2% in comparison to the cooling season. In contrast, 20.8% of occupants found their environment often too hot in the warming season, which decreased by 5.3% from the cooling season.

Figure 31

Occupant Comfort Levels During Cooling and Warming Seasons in CC



The comfort levels of occupants during the warming and cooling seasons were compared in contrast to the occupant's location to an exterior wall and/or a window within their workspace as seen in Figure 32 and Figure 33, respectively. It was found that occupants in the CC have more thermal discomfort near exterior walls than that of windows with around a 10% increase in feeling neutral near windows in both the warming and cooling seasons. Additionally, occupants were found to be often too hot more frequently than often too cold in the exterior walls in both warming and cooling seasons at 37.5% and 33.3% respectively.

Figure 32

Occupant Comfort Levels During Warming Season Based On Location in CC

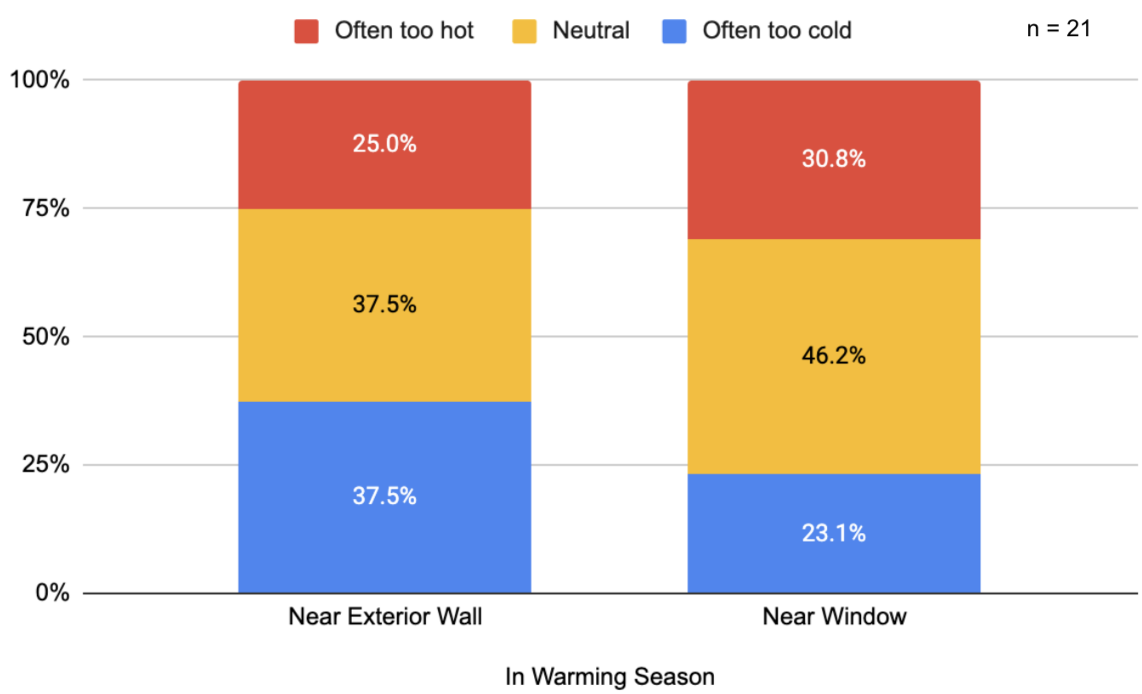
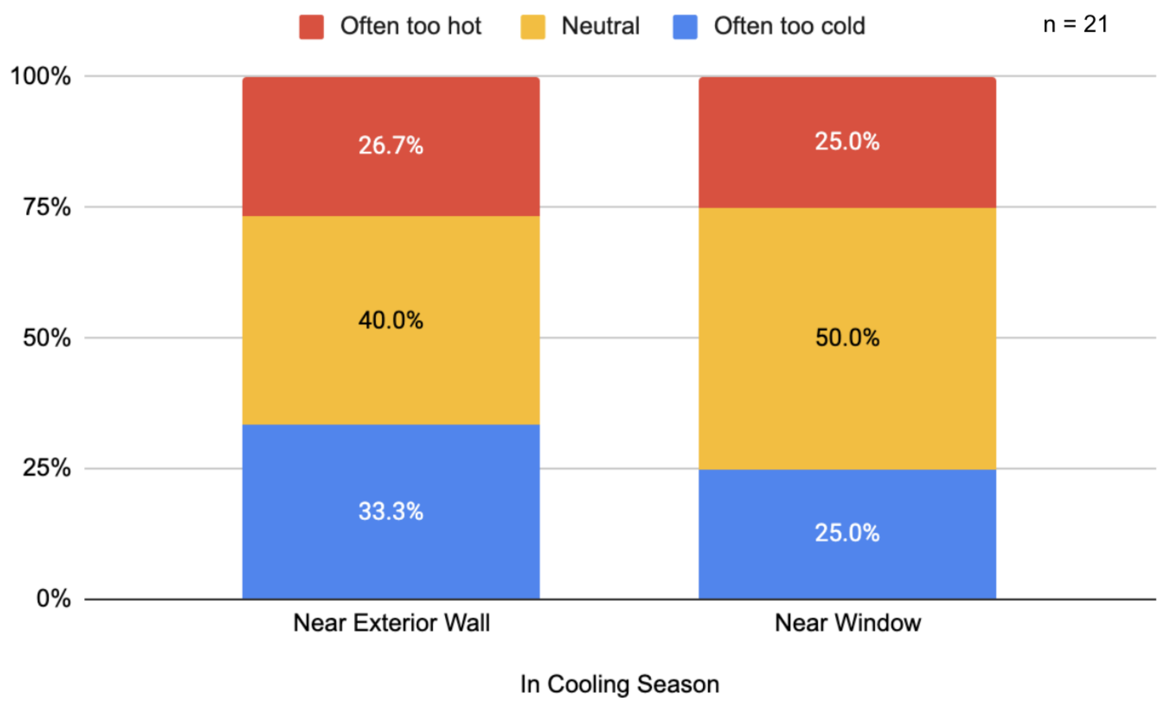


Figure 33

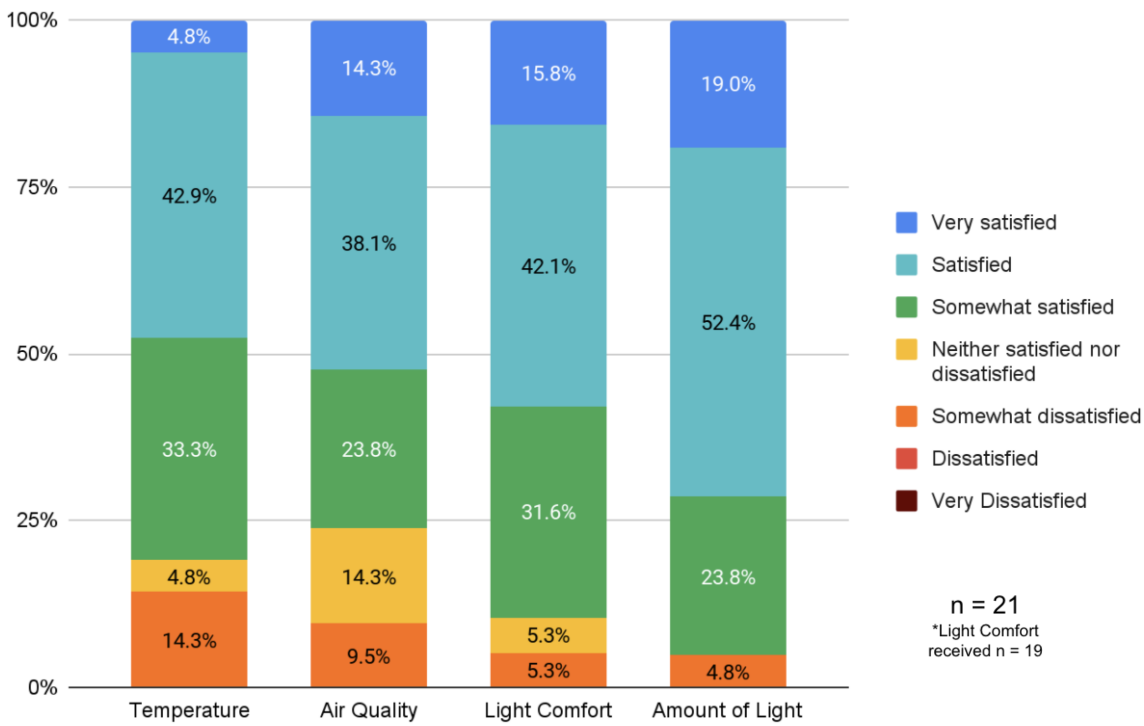
Occupant Comfort Levels During Cooling Season Based On Location in CC



Comparisons of the temperature, air quality, amount of light, and light comfort for occupant satisfaction were made as seen in Figure 34. A majority of occupants were satisfied with all four factors. None of the occupants were dissatisfied or very dissatisfied with any of the four factors. The temperature quality was found to accrue both the greatest percentage of somewhat dissatisfied occupants as well as the least percentage of very satisfied occupants. The amount of light for occupants yielded the largest portion of satisfaction, including very satisfied, satisfied, and somewhat satisfied. Following the amount of light satisfaction was light comfort, temperature, with the least amount of satisfaction for occupants being air quality within the CC. The total satisfaction was found to be 95.2%, 89.5%, 81%, and 76.2%, respectively.

Figure 34

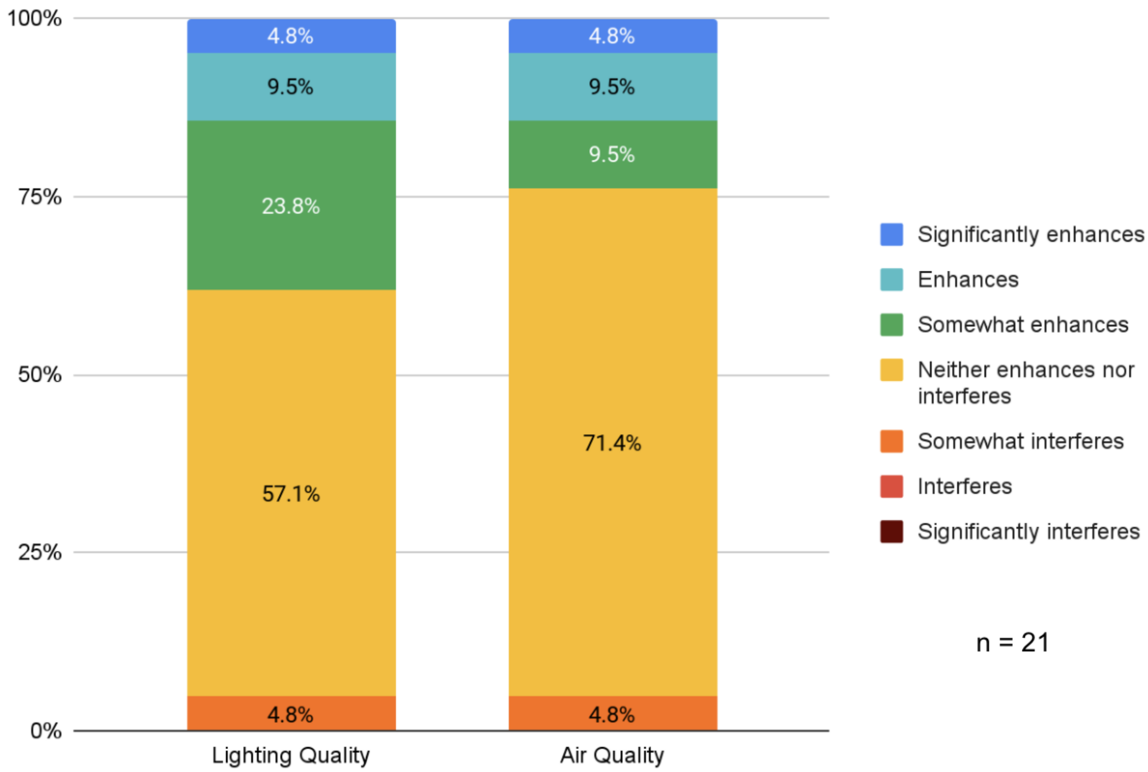
Comparison of Occupant Satisfaction Between Temperature, Air Quality, Amount of Light, and Light Comfort Within the CC



The workspace effects on work performance for occupants were also compared as seen in Figure 35. The lighting and air quality within the workspace for occupants was found to neither enhance nor interfere with job ability as reported by 57.1% and 71.4% of the respondents, respectively. Almost 25% of occupants believe lighting quality was found to somewhat enhance job ability. Lighting quality and air quality were also found to have similar results for occupants who believed it significantly enhances, enhances, interferes, and significantly interferes with job ability at 4.8%, 9.5%, 4.8%, and 0%, respectively.

Figure 35

Comparison of Light Quality and Air Quality Effects on Work Performance for Occupants in CC



It must be recognized that the IEQ survey results had limited participants within its sample size of n = 21. Occupants who were surveyed were specifically office workers within the CC. The survey did not include potential occupant data regarding contracted employees, mailroom workers, facilities staff, as well as student employees. Occupant locations were varied for both the floor levels as well as specified rooms in the data, however, more variability is possible with the inclusion of other staff. For example, those in the mailroom could have a different environmental experience within the CC than office workers on other floors, considering the lack of daylight within mailroom space, and its adjacency to the food court may affect air quality.

The annual hours of daylighting present within the first, second, and third floors of the CC were found using DesignBuilder as seen in Figure 36, Figure 37, and Figure 38, respectively. It was found that while the second and third floors received daylight to internal spaces within the westernmost portion, eastern side, and northeastern side of the CC, the first floor received daylight within only the northeastern side. Daylight was able to come in through windows for the second and third floors that do not exist for the first floor.

Figure 36

Annual Hours of Daylighting in DesignBuilder: First Floor

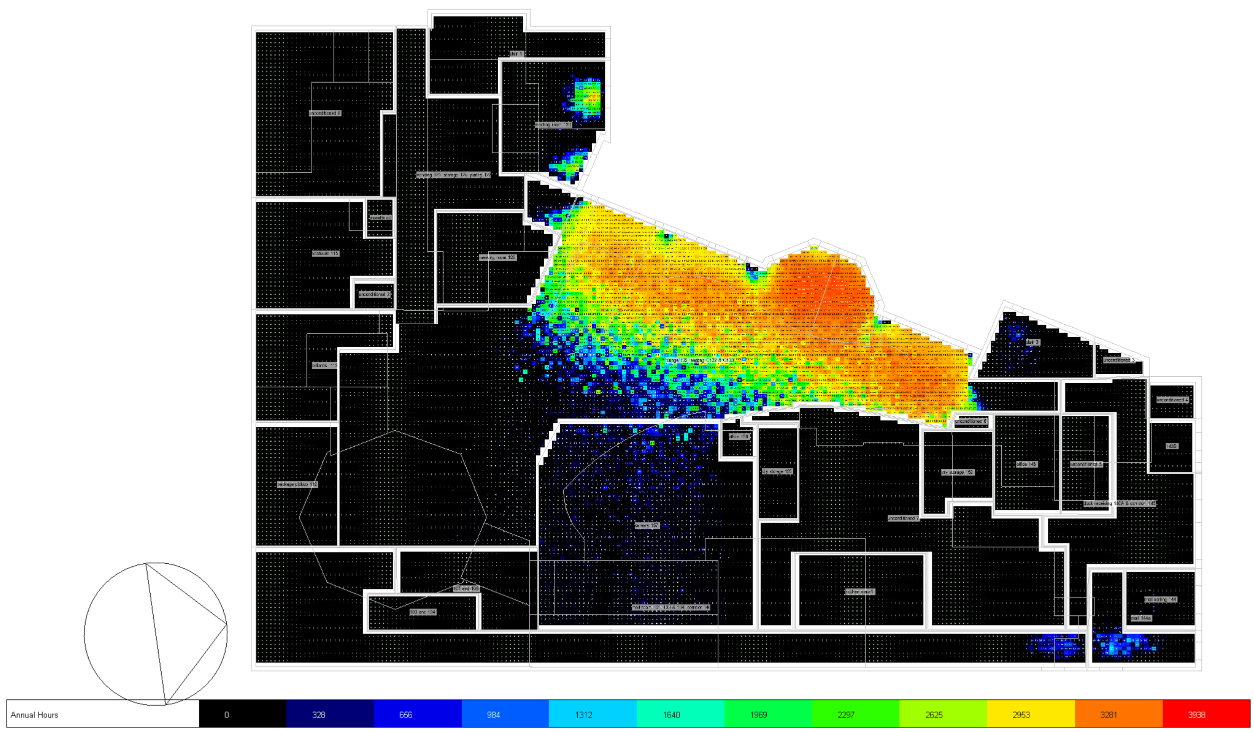


Figure 37

Annual Hours of Daylighting in DesignBuilder: Second Floor

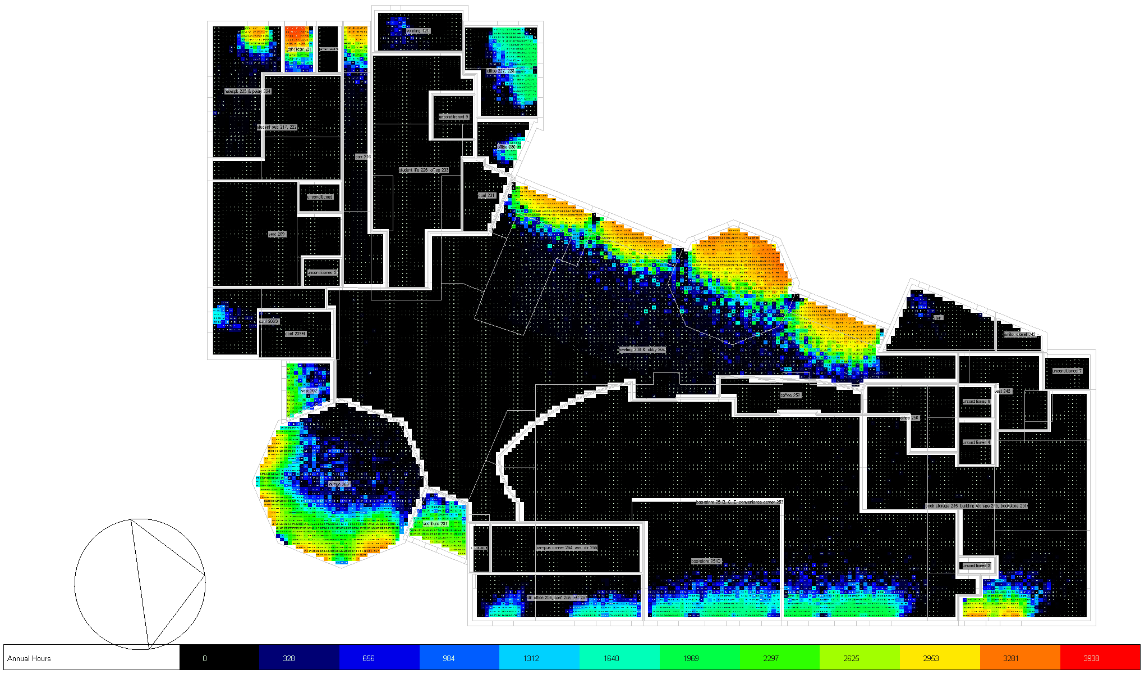
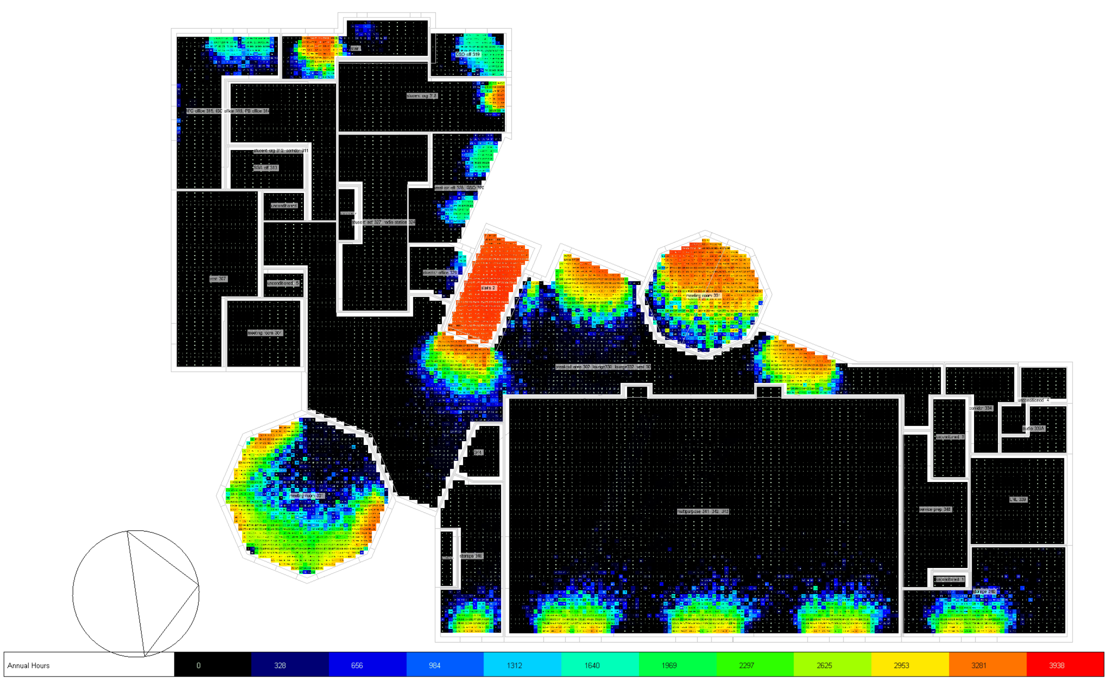


Figure 38

Annual Hours of Daylighting in DesignBuilder: Third Floor



4.3. Energy and Structural Model Analyses

4.3.1. RTU Evaluations

The team first compared the impacts of the three different RTU or RTU and ERV combinations with the baseline. As shown in Figure 39, the Trane RTU option demonstrated an increase of 2.3% in total energy usage, whereas the Trane RTU + Renewaire ERV combination and the Daikin RTU with energy recovery wheel demonstrated reductions of 2.4% and 2.2%, respectively. The Trane RTU reduced unmet heating and cooling setpoint hours by 6.8% and both the Trane RTU + Renewaire ERV and Daikin RTU reduced the unmet hours by 6.2%, which is shown in Figure 40.

Figure 39

Energy Usage of RTU and ERV Option Energy Models Compared to Baseline

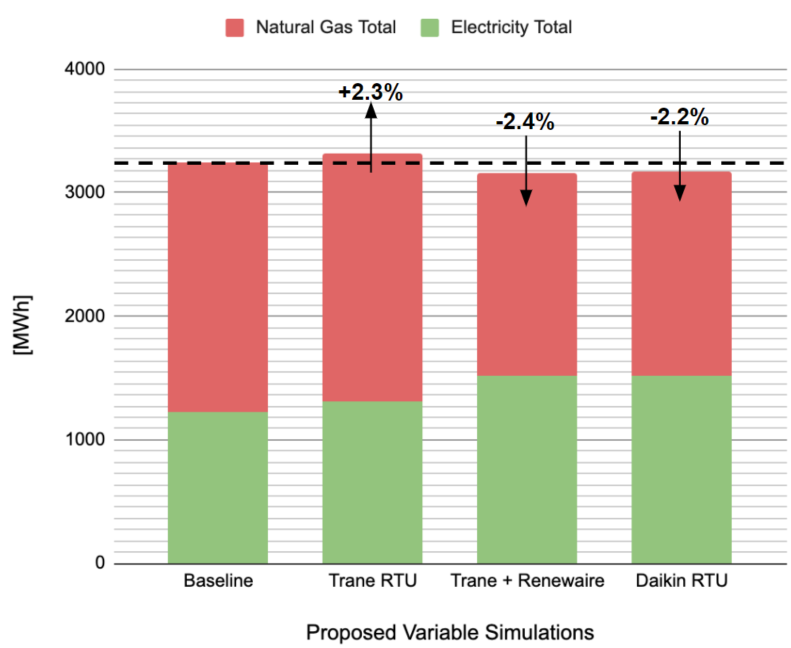
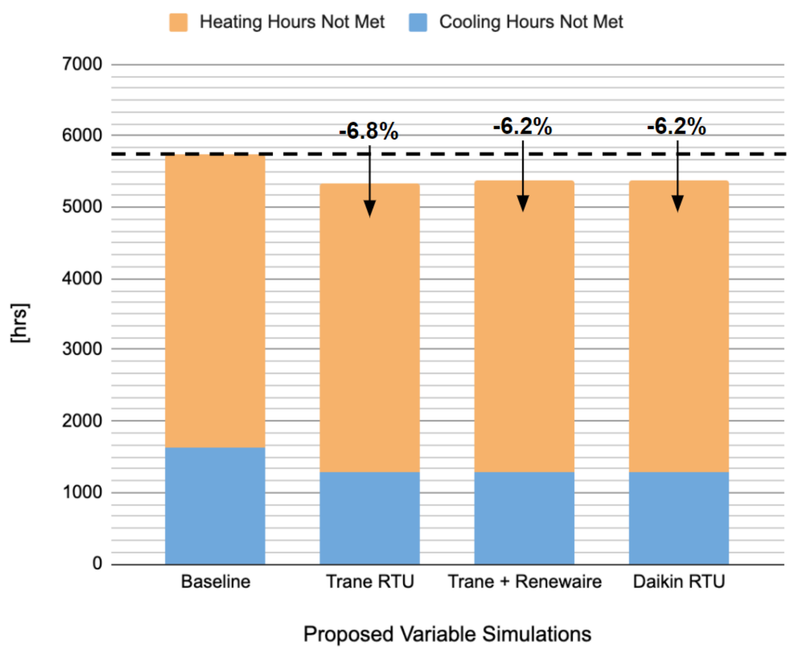


Figure 40

Yearly Unmet Heating and Cooling Setpoint Hours of RTU and ERV Option Energy Models Compared to Baseline



The loading capacity impacts were found through structural analysis of the additional loading for two Daikin RTU's sized differently with an energy recovery wheel. The smaller and larger options were defined as RTU 1 and RTU 2, respectively. The approximate weights of both units were found by using different Daikin RTU models with similar CFM ranges. The roof and associated columns were found to be able to support the additional RTU 1 loads based upon the determined threshold. For example, the beam scheme 2 had a minimum factored ultimate uniform load (w_u) of 1.57 kip/ft and a maximum w_u of 3.08 kip/ft as seen in Figure 41. The w_u for the RTU 1 replacement was found to be 2.05 kip/ft. Similarly for the column scheme 2, the compressive design strength, ϕcPn, had a minimum and maximum threshold between 342 lbs and 925 lbs. The RTU 1 option was calculated to have a compressive design strength of 380 lbs. Based upon the minimum and maximum thresholds for beam, girder, and column loading capacities for the roof, the RTU 2 option loading was compared. It was found that the associated beams/girders and columns were able to withstand the RTU 2 loading by performing similar calculations to that of RTU 1.

Figure 41

Structural Analysis and Threshold Comparison of RTU options for Level 4 Roof of CC

Level 4 Structural Analysis: RTU Options						
Beam/Girder Scheme	Min	Threshold	Max	RTU 1	RTU 2	Unit
b2	1.57	-	3.08	2.05	2.22	kip/ft
b3	1.84	-	4.04	2.56	2.67	kip/ft
b10	1.27	-	5.02	1.78	1.84	kip/ft
b11	1.89	-	3.92	2.60	2.70	kip/ft
b12	1.29	-	12.57	1.77	1.84	kip/ft
Column Scheme	Min	Threshold	Max	RTU 1	RTU 2	Unit
c2	342	-	925	380	380	ϕcPn, lb
c3	253	-	753	306	306	ϕcPn, lb
c4	253	-	753	253	253	ϕcPn, lb

Although the schemes are able to structurally support both RTU options, the option with both the RTU and a separate ERV was deemed unfeasible. All ERV units with the appropriate CFM capabilities investigated by the team were indoor units and, based on the mechanical plans, there was no space for such a large unit to be placed in the mechanical rooms. Therefore, despite having the greatest energy reduction, the Trane RTU + Renewaire ERV option was eliminated.

4.3.2. Boiler and Heat Pumps Evaluations

The first single-variable change to the heating system to be discussed is the most conservative option. The Laars electric, 100% efficient, condensing boilers were selected as an example to replace the Smith natural gas, approximately 80% efficient, non-condensing boilers for summer usage. The CC would continue to be on the steam heating system from the Power House for the remaining months. The impact of the Laars electric boiler was simulated from

April to September. As shown in Figure 42, the boilers used 6.1% more energy, and Figure 43 depicts a reduction in unmet setpoint thermal comfort hours of 2.9% with the new boilers.

The team decided to model the potential energy savings using two ground source heat pump models after a representative from the Facilities Office expressed interest in installing one to take the building off the steam loop system. As shown in Figure 42, the ClimateMaster TMW600 and ClimateMaster TMW840 models reduced the total simulated energy consumption by 34% and 33%, respectively. All energy consumption for the heating system is based on electricity rather than natural gas, making these options more environmentally friendly compared to the existing system. Furthermore, the TMW600 model and TMW840 model also decreased the yearly unmet heating and cooling setpoint hours by 9.9% and 10.2%, respectively, as shown in Figure 43. The difference between the two models is relatively negligible, but the reduction in energy consumption and unmet setpoint hours show that the geothermal heat pumps are an energy-efficient and thermally effective alternative to the current steam loop system.

Figure 42

Energy Usage of Laars Electric Boiler and ClimateMaster Heat Pumps Compared to Baseline

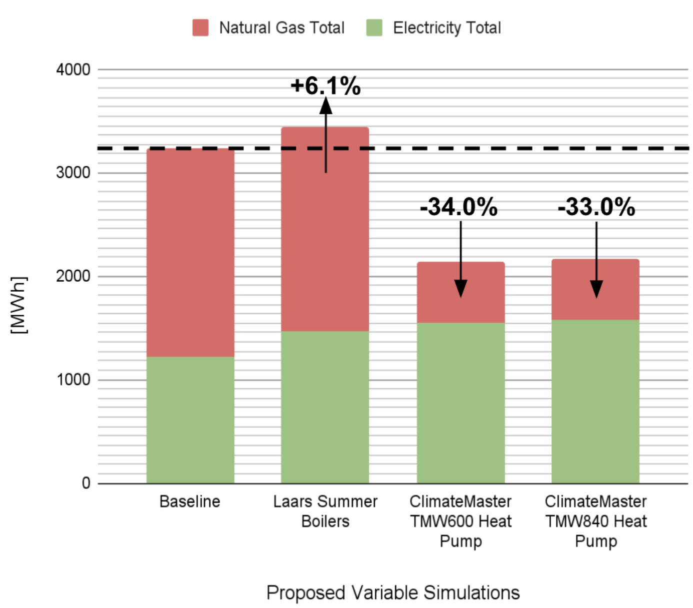
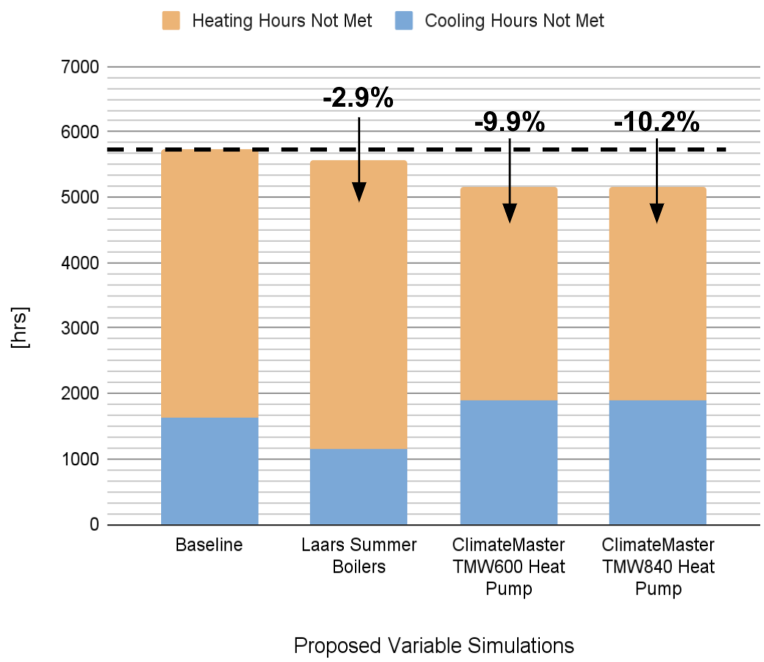


Figure 43

Yearly Unmet Heating and Cooling Setpoint Hours of Laars Electric Boiler and ClimateMaster Heat Pump Compared to Baseline



4.3.3. MAU Option

Lastly, the Annexair MAU replacement for the kitchen was simulated. As shown in Figure 44, the new MAU used 2.0% more energy when compared to the baseline and Figure 45 shows a reduction of 8.6% for unmet thermal comfort setpoint hours. The impact of the heat recovery plate in the MAU was simulated from April to September, as the Annexair product sheet indicated that heat recovery was only available during the summer months.

Figure 44

Energy Usage of Annexair MAU Compared to Baseline

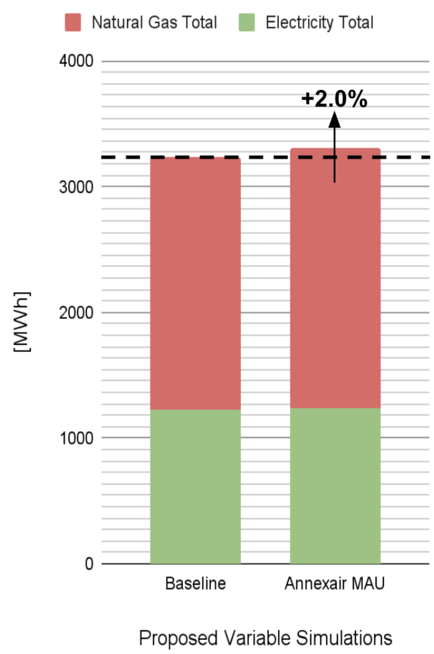
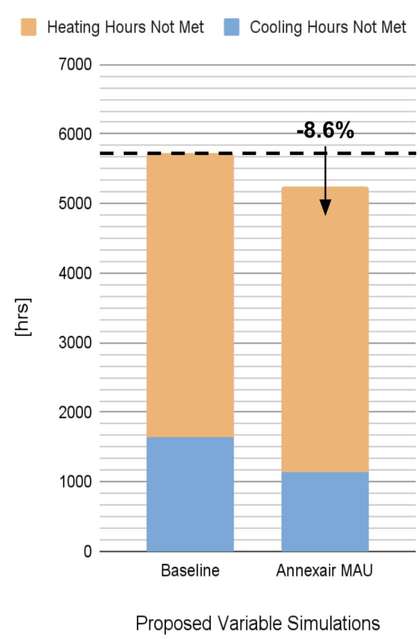


Figure 45

Yearly Unmet Heating and Cooling Setpoint Hours of Annexair MAU Compared to Baseline



4.3.4. Summary of Variable Changes

The team also developed two graphs comparing the energy usage and unmet setpoint hours of all simulated changes, as seen in Figure 46 and Figure 47.

Figure 46

Comparisons of Single Variable Changes in Energy Usage

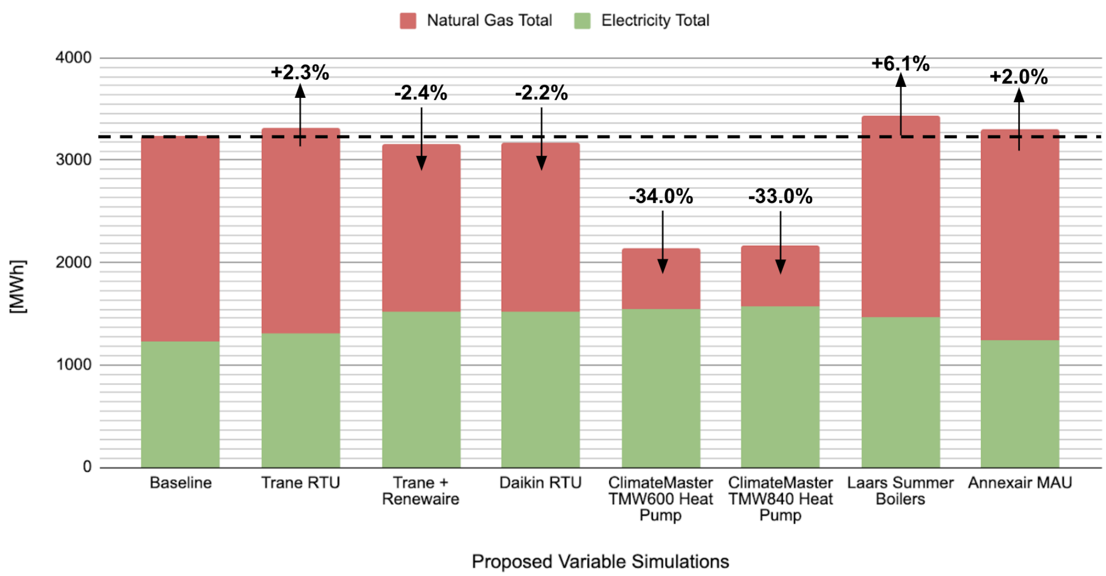
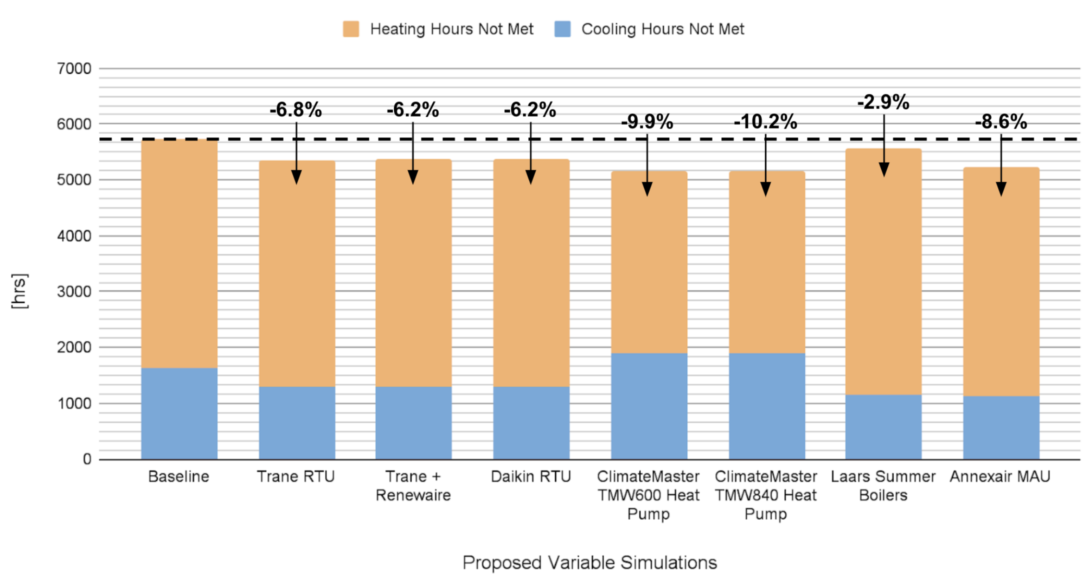


Figure 47

Comparisons of Single Variable Changes in Unmet Setpoint Hours



4.3.5. Roof Evaluations

The team structurally evaluated potential roof changes and analyzed the options for potential energy savings. This first involved ensuring the structural capacity of the additional loads present on the roof before investigating the resulting efficiency. Ballasted PV panels were chosen to be placed on the High Roof, also known as the Odeum, as seen in Figure 48.

To determine the optimal tilt angle for the PV panels, the team simulated three tilt angles: 57º to optimize generation in the winter, 42º to match the building's latitude, and 10º to minimize tilt angle while still allowing the panels to self clean. Although the higher tilt angles had the potential to generate more electricity per panel, the lower tilt angles allowed more PV panels to fit onto the high roof due to the smaller inter-module spacing. The team simulated the electricity generation for each tilt angle for the month of January and found that the 57º, 42º, 10º generated 1400 kWh, 1500 kWh, and 1900 kWh, respectively. The 10º tilt angle was, therefore, determined to yield the most electricity generation. The team did not simulate any additional months because the month of January would have theoretically allowed the higher tilt angles to generate more per panel compared to the lower tilt angles, yet the lowest angle still generated the most.

Based upon the PV panel tilt angle and specified PV panel array, the factored ultimate uniform load (w_u) and compressive design strength (ϕcPn) were compared to ensure the beams/girders and columns could withstand the new potential additions as seen in Figure 49. Both the 10º and 42º tilt angles were analyzed, however, the 10º tilt angle was considered to be most optimal. It was found that beam scheme 14, 15, and 16 for both the 10º and 42º PV panel arrays could withstand the new loads. However, beam scheme 17 was unable to withstand the calculated w_u for the 10º and 42º PV panel arrays. The w_u calculated for the 10º and 42º PV panel arrays surpassed the maximum threshold by .0183 kip/ft and .0134 kip/ft respectively.

Figure 48

Visual of PV Panels on High Roof/Odeum of CC in DesignBuilder

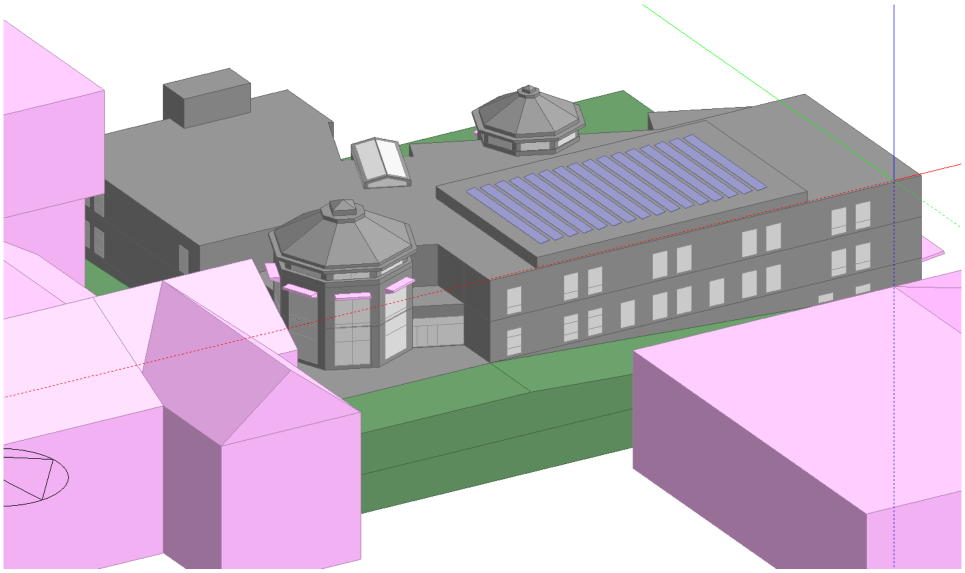


Figure 49

Structural Analysis and Threshold Comparison of PV Panels Options for High Roof/Odeum of CC

High Roof/Odeum Structural Analysis: PV Panel Options						
Beam/Girder Scheme	Min	Threshold	Max	PV Panels 10˚	PV Panels 42˚	Unit
b14	1.93	-	53.6	1.97	1.97	kip/ft
b15	1.34	-	59.7	1.40	1.38	kip/ft
b16	0.968	-	5.13	2.12	2.12	lb/ft
b17	0.194	-	0.622	0.640	0.635	lb/ft
Column Scheme	Min	Threshold	Max	10˚	42˚	Unit
c7	304	-	925	304	304	ϕcPn, lb
c8	253	-	753	253	253	ϕcPn, lb
c9	253	-	753	253	253	ϕcPn, lb

Structural analysis of the potential green roof addition for the level 4 roof was conducted. Based upon the factored ultimate uniform load (w_u) and compressive design strength (ϕcPn) thresholds, a comparison was made with the green roof loads as seen in Figure 50. The beam/girder and column schemes were found to be able to withstand the additional loading. An example would be beam scheme 1 with the green roof addition, which was found to have a w_u of 0.839 kip/ft, meeting the determined threshold capacity between 0.713 kip/ft and 1.84 kip/ft. The column scheme 1 with the green roof addition was determined to have a ϕcPn of 304 lbs and was found to be within the determined threshold of 304 lbs to 925 lbs as seen in Figure 50.

Figure 50

Structural Analysis and Threshold Comparison of Green Roof Addition for Level 4 Roof

Level 4 Structural Analysis: Green Roof Addition					
Beam/Girder Scheme	Min	Threshold	Max	Green Roof Addition	Unit
b1	0.713	-	1.84	0.839	kip/ft
b2	1.57	-	3.08	1.75	kip/ft
b3	1.84	-	4.04	2.18	kip/ft
b4	0.595	-	5.75	0.797	kip/ft
b5	3.00	-	4.77	3.27	kip/ft
b6	0.241	-	4.60	0.306	kip/ft
b7	0.508	-	1.80	0.676	kip/ft
b8	0.602	-	3.91	0.662	kip/ft
b9	0.462	-	1.94	0.536	kip/ft
b10	1.27	-	5.02	1.52	kip/ft
b11	1.89	-	3.92	2.22	kip/ft
b12	1.29	-	12.6	1.52	kip/ft
Column Scheme	Min	Threshold	Max	Green Roof Addition	Unit
c1	304	-	925	304	ϕcPn, lb
c2	342	-	925	384	ϕcPn, lb
c3	253	-	753	306	ϕcPn, lb
c4	253	-	753	253	ϕcPn, lb
c5	253	-	753	253	ϕcPn, lb
c6	304	-	925	304.27	ϕcPn, lb

4.4. Final Proposed Models

After simulating and calculating the most effective and feasible variables of the ones considered, the team assembled four final models to propose to the WPI Administration, as shown in Figure 51, Figure 52, and Figure 53. Although the team used the ClimateMaster TMW840 model for the final proposed model simulations, either the TMW600 or the TMW840 model could have been used with minor differences in the final energy usage and unmet setpoint hours. Each of these options were also evaluated in Arc, and it was determined that the changes had no impact on the LEED score and certification level that the CC is able to achieve.

Option 1: Daikin RTU, Laars Electric Boiler, and Annexair MAU. The first option only addresses the need to replace the existing RTUs and summer boilers due to age as well as the kitchen MAU due to comfort issues. It is the most conservative option. This option reduces the total energy consumption by 13.0%, reduces the yearly unmet hours by 18.1%, and has an EUI of 135 kBtu/sf.

Option 2: Daikin RTU, ClimateMaster Heat Pump, and Annexair MAU. The second option includes the replacement of the existing RTUs and MAU, but also includes the installation of a ground source heat pump. It takes the building off the steam loop, pushing the campus closer to electrification and significantly increasing energy savings. This option reduces the total energy consumption by 31.7%, reduces the yearly unmet hours by 26.6%, and has an EUI of 106 kBtu/sf.

Option 3: Daikin RTU, ClimateMaster Heat Pump, Annexair MAU, PV Panels, and Green Roof. The third option encompasses the second option with the addition of PV panels and the green roof for more energy savings and LEED points. This option reduces the total energy consumption by 32.7%, reduces the yearly unmet hours by 27.5%, and has an EUI of 103 kBtu/sf.

Option 4: Daikin RTU, ClimateMaster Heat Pump, Annexair MAU, and Lochinvar Electric Water Heater. The fourth option also encompasses the second option with the addition of replacing the existing natural gas water heaters with electric water heaters. It completely electrifies the building, setting an example for the rest of the campus. This option reduces the total energy consumption by 29.9%, reduces the yearly unmet hours by 18.9%, and has an EUI of 109 kBtu/sf.

Figure 51

Comparisons of Final Proposed Models in Energy Usage

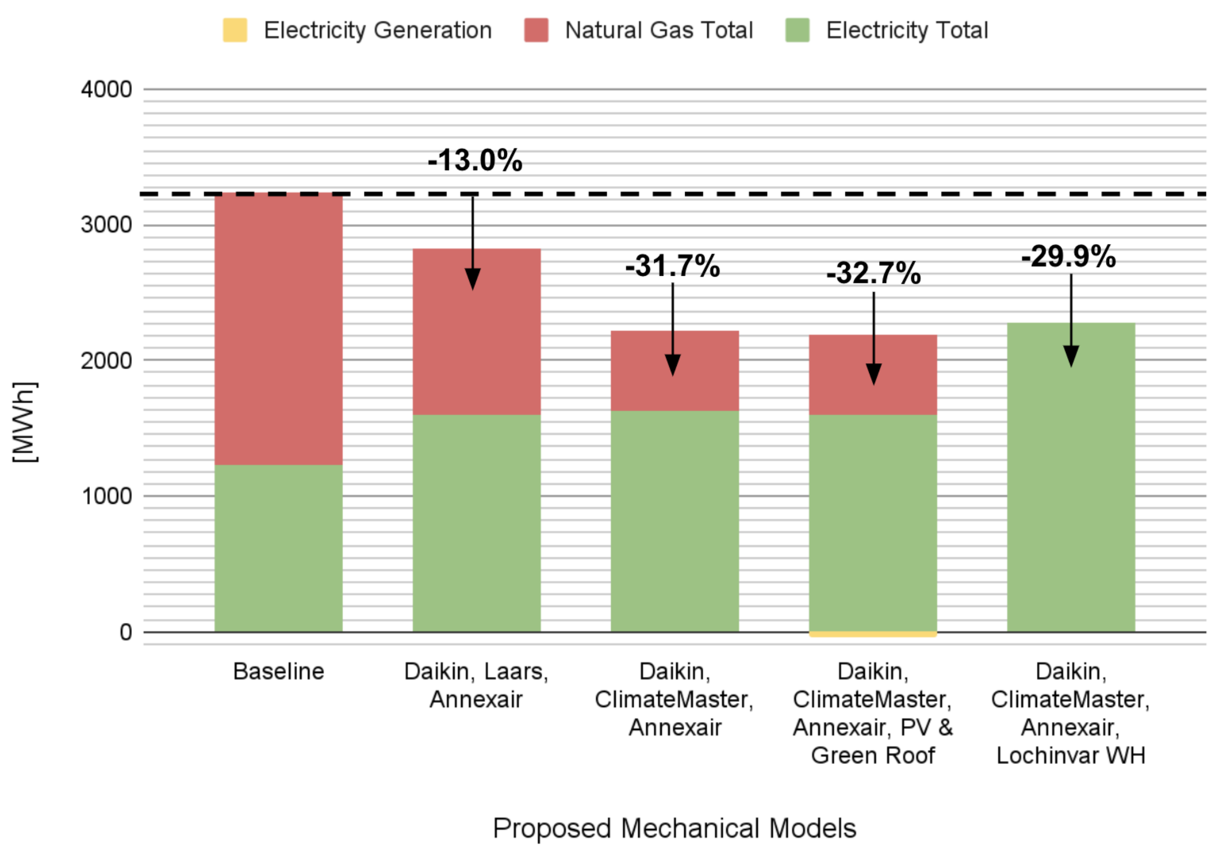


Figure 52

Comparison of Final Proposed Models in Unmet Setpoint Hours

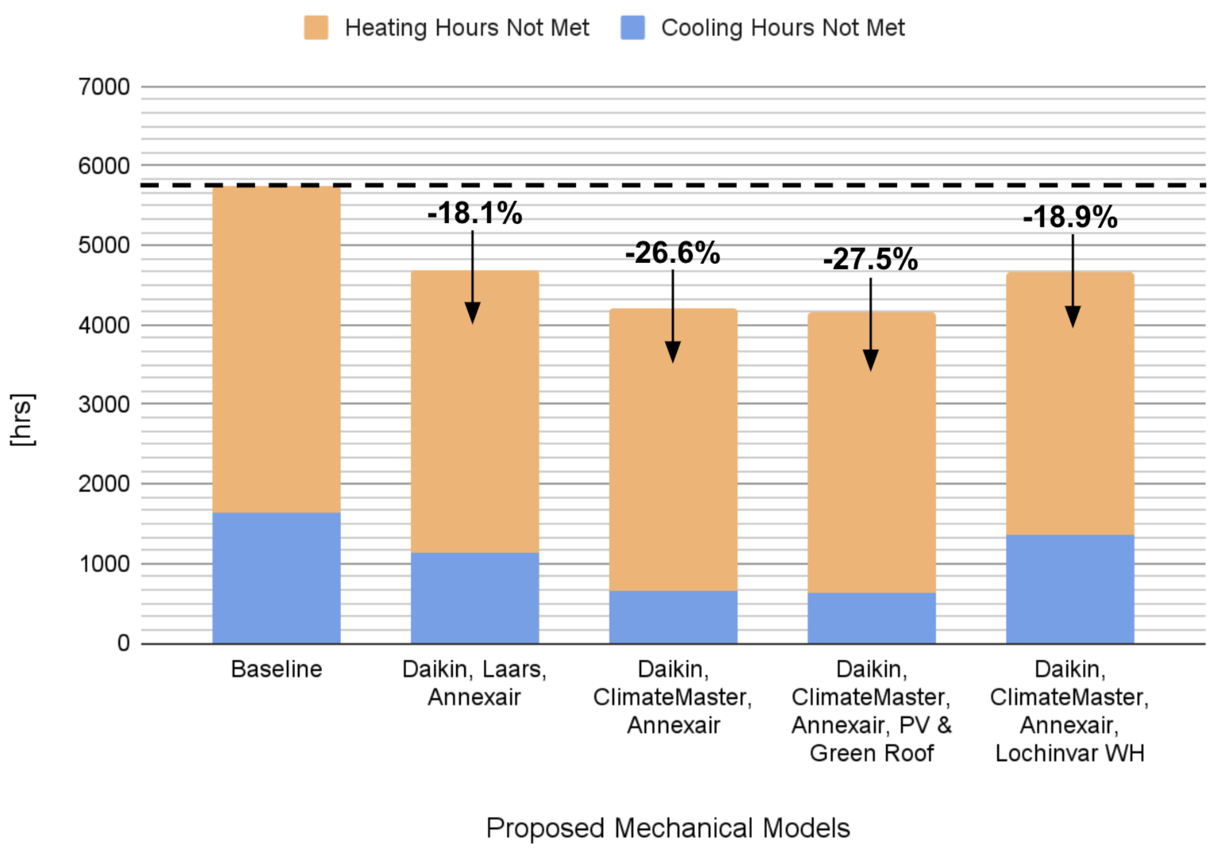
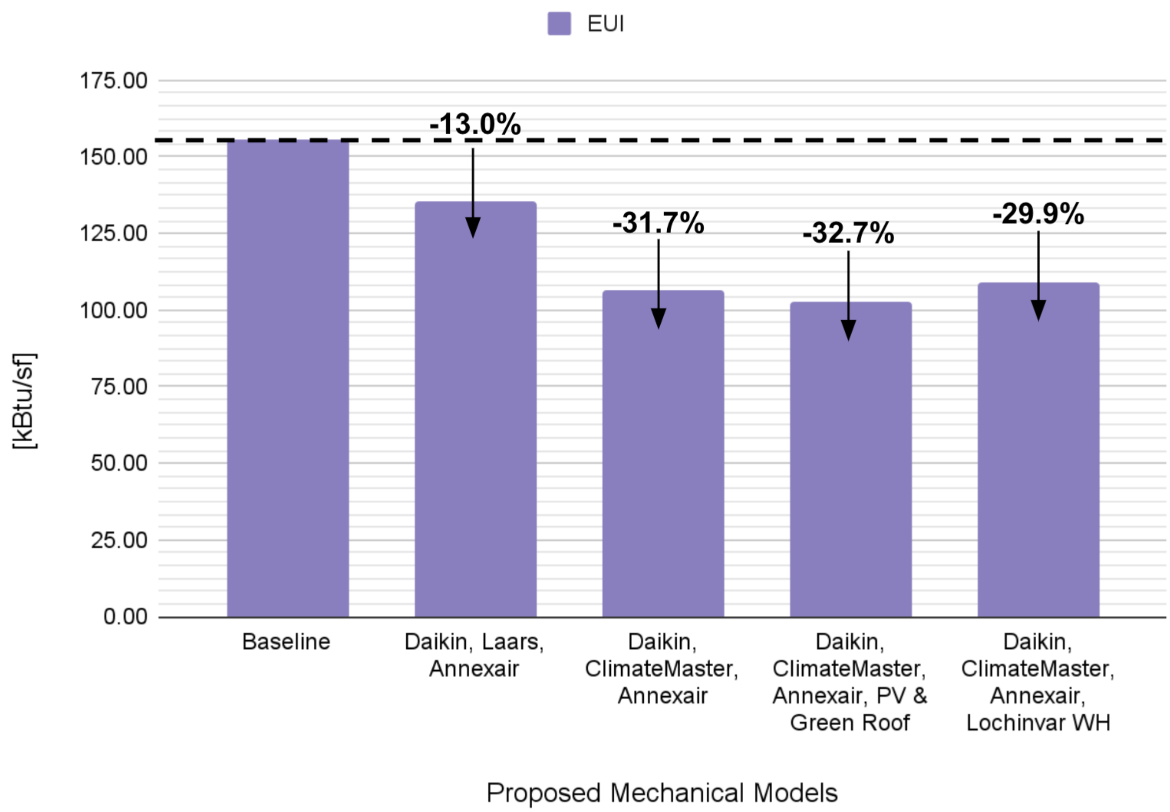


Figure 53

Comparison of Final Proposed Models in EUI



4.4.1. Associated Cost of Proposed Options

The team then calculated the associated cost for each of the proposed options. Many of the costs that were determined for each individual piece of equipment were estimates determined from wholesale or secondary retailers, not exact prices as calculated by the manufacturer. The price of installation and labor is included for some, but not all, of the equipment. The estimates for these proposed options are not meant to accurately represent the cost of these options, but to provide a general baseline of costs for any potential future pursuit of renovations. Table 6 summarizes the associated costs for all the variables, and Table 7 summarizes the costs for the proposed options. The cost savings were determined, as shown in Table 8, by estimating the cost of electricity to be $0.0738/kWh and the cost of natural gas to be $0.0638/kWh (Electricity Local, n.d.; Massachusetts DER, 2018).

Table 7

The Variables and Their Associated Costs

Associated Additional Variable Costs		
Proposed Variables	**Lower Total Cost**	**Upper Total Cost**
Daikin RTU	$231,000	
Annexair MAU	$18,000	
LAARS Boiler	$25,000	
ClimateMaster TMW600 Heat Pump	$200,000	$400,000
ClimateMaster TMW840 Heat Pump	$280,000	$560,000
Lochinvar Water Heater	$23,000	
PV Panels 10º	$74,000	
PV Panels 42º	$42,000	
Green Roof Option 1	$161,000	$261,000
Green Roof Option 2	$93,000	$150,000
Green Roof Option 3	$39,000	$63,000

Table 8

The Proposed Final Models and Their Associated Cost

Estimated Costs of Proposed Options			
Option	**Proposed Final Models**	**Lower Total Cost**	**Upper Total Cost**
1	Daikin RTU, Laars Boiler, and Annexair MAU	$273,000	
2	Daikin RTU, ClimateMaster Heat Pumps, and Annexair MAU	$448,000	$808,000
3	Daikin RTU, ClimateMaster Heat Pump, Annexair MAU, PV Panels, and Green Roof	$521,000	$881,400
4	Daikin RTU, ClimateMaster Heat Pump, Annexair MAU, and Lochinvar Water Heater	$471,000	$831,000

Table 9

The Proposed Final Models and Their Yearly Cost Savings

Option	Final Proposed Models	Electricity Costs	Natural Gas Costs	Total Yearly Savings
1	Daikin RTU, Laars Electric Boiler, and Annexair MAU	+$27,147.33	-$50,398.78	**-$23,251.45**
2	Daikin RTU, ClimateMaster Heat Pump, and Annexair MAU	+$30,194.90	-$91,629.70	**-$61,434.80**
3	Daikin RTU, ClimateMaster Heat Pump, Annexair MAU, PV Panels, and Green Roof	+$24,634.62	-$91,629.68	**-$66,995.06**
4	Daikin RTU, ClimateMaster Heat Pump, Annexair MAU, and Lochinvar Electric Water Heater	+$77,249.03	-$128,661.62	**-$51,412.59**

Note: All proposed models with heat pumps underwent a cost analysis for both the TMW840 and TMW600 options for ClimateMaster despite the TMW840 being used for the final model, as their initial single-variable simulated results were comparable.

5. Recommendations

The foremost recommendation is for the Campus Center to become LEED Existing Buildings: Operations + Maintenance v4.1 certified at the projected Silver level. WPI will need to verify any credits the CC is already able to achieve, such as the Integrated Pest Management credit, along with all of the prerequisites for each category that must be met for the building to be certified. As one of the most pivotal buildings in campus life, certifying the CC would exemplify WPI's commitment to sustainability and how WPI puts thought into both their new and existing buildings.

Since none of the proposed options were determined to improve the baseline LEED score of the existing building, the final proposed models were evaluated based on the two major concerns that often come with retrofits: cost and energy usage reduction. The team recommends that the WPI Administration investigates two of the four final models. The team primarily recommends the administration to pursue Option 2, which involves the following changes:

- Replace the existing RTU with a model that includes an energy recovery wheel.
- Replace the current kitchen MAU with a model that includes a cooling coil.
- Remove the building from the steam loop by installing a ground source heat pump.

Interest in the installation of a geothermal heat pump was expressed by members of the Facilities Office as they envisioned the CC becoming the first WPI campus building on the path to electrification. The CC would further represent WPI's dedication to sustainability and willingness to make the necessary significant changes to address climate change. The CC could also serve as a case study for WPI to retrofit other campus buildings to become less dependent on natural gas. Although this option has a relatively high potential total cost, it yields the second most energy savings, significantly reduces natural gas usage, and has an innumerable positive impact on the school's reputation.

The alternative recommendation would be Option 1, which has the lowest cost, but the least energy savings. It would involve replacing the following equipment, which all have either reached the ends of their useful lives or do not currently meet thermal comfort thresholds:

- Replace the existing RTU with a model that includes an energy recovery wheel.
- Replace the current kitchen MAU with a model that includes a cooling coil.
- Replace the summer boilers with high efficiency electric boilers.

If WPI wants to pursue LEED Gold or Platinum certification for the CC, additional points can be obtained by investigating underutilized categories. Some credits that could be relevant to explore are Heat Island Reduction and Rainwater Management in the Sustainable Sites category (1 pt each), Water Performance in the Water Efficiency category (8 pts), Enhanced Refrigerant Management in the Energy and Atmosphere category (1 pt), Purchasing in the Materials and Resources category (4 pts), Green Cleaning in the Indoor Environmental Quality category (1 pt), and IEQ Performance in the IEQ category (13 pts).

The Heat Island Reduction credit can be gained by increasing roof reflectance, installing roof vegetation, or implementing non-roof measures, such as PV panels. Additional framing members to increase structural capacity would be necessary if WPI chooses to mount a rooftop PV panel system. The Rainwater Management credit would involve the implementation of low-impact development practices to reserve and reuse 25% of onsite water found on impermeable surfaces during storms. The remaining Water Performance credit(s) can be achieved by reducing the annual water consumption. This can include implementing motion-activated sinks and dual-flush toilets, and utilizing collected non-potable water for flushing. The Enhanced Refrigerant Management credit would involve either transitioning to low-impact refrigerants or no refrigerants or calculating the impact of the existing refrigerants. The Purchasing credit(s) can be achieved by tracking up to four different purchases and their associated environmental impacts, including ongoing consumables, building materials, electronic equipment, and food and beverage. The Green Cleaning credit would be achieved by accomplishing one of four provided options, including a custodial effectiveness assessment, improving entryway systems, updating the powered janitorial equipment, or changing the cleaning products and materials to meet specified green standards. Finally, the remaining IEQ credit(s) can be acquired by conducting an indoor air quality evaluation. This involves an investigation of interior CO_2 and total volatile organic compound (TVOC) levels.

6. Limitations

Many simplifications were made to facilitate this project, namely in the DesignBuilder program. The program presented many challenges when calibrating the model to accurately reflect the conditions of the existing building. Certain concessions were made to simplify the model and to allow for continued progression of the project so as not to be slowed by incongruities between model and reality. One example of this is the reduction of zones and, subsequently, the combining of occupancy schedules. The time to simulate the energy usage of the CC for one month took approximately three hours with the zoning as shown in *Webctrl*. The team was able to simplify the number of zones from 152 to 102 by combining zones with the same mechanical equipment in proximity to one another, reducing simulation time for one month to 15 minutes. To be conservative, combined zones with differing occupancy schedules used the higher occupied schedule. The reduction of zones allowed for a faster process of collecting and analyzing results, but it reduced the accuracy of the building's interior organization and HVAC delivery system.

Another simplification is the impact of the kitchen equipment on the heating and cooling loads in the DesignBuilder model. All the variable simulations and half of the proposed model simulations were already completed when the potential heating and cooling effects were brought to the team's attention. To incorporate the radiant and latent fractions of the kitchen equipment would require the team to resimulate every month. At approximately 15 minutes per month per simulation, this inclusion would take approximately 30 hours of simulation time. The team chose to omit this consideration from the project due to the limited time available.

7. Further Research

There are a number of aspects to this project that were left unexplored or undeveloped due to the original scope and time constraints. Below, the team discusses some areas that are available for further research and some initial thoughts. These areas may be important to examine further if the WPI Administration moves forward with certifying the CC under the LEED certification program, and if they want to address current thermal comfort issues.

Figure 54, Figure 55, Figure 56, and Figure 57 compare the simulated hourly indoor air temperature data for specific zones that either met or did not meet most of the occupied setpoint hours for thermal comfort in the months of January and July. Figure 58 and Figure 59 show the location of the specified zones in the floor plans.

Figure 54

Indoor Air Temperature Compared to Heating Setpoint and Setback for Odeum

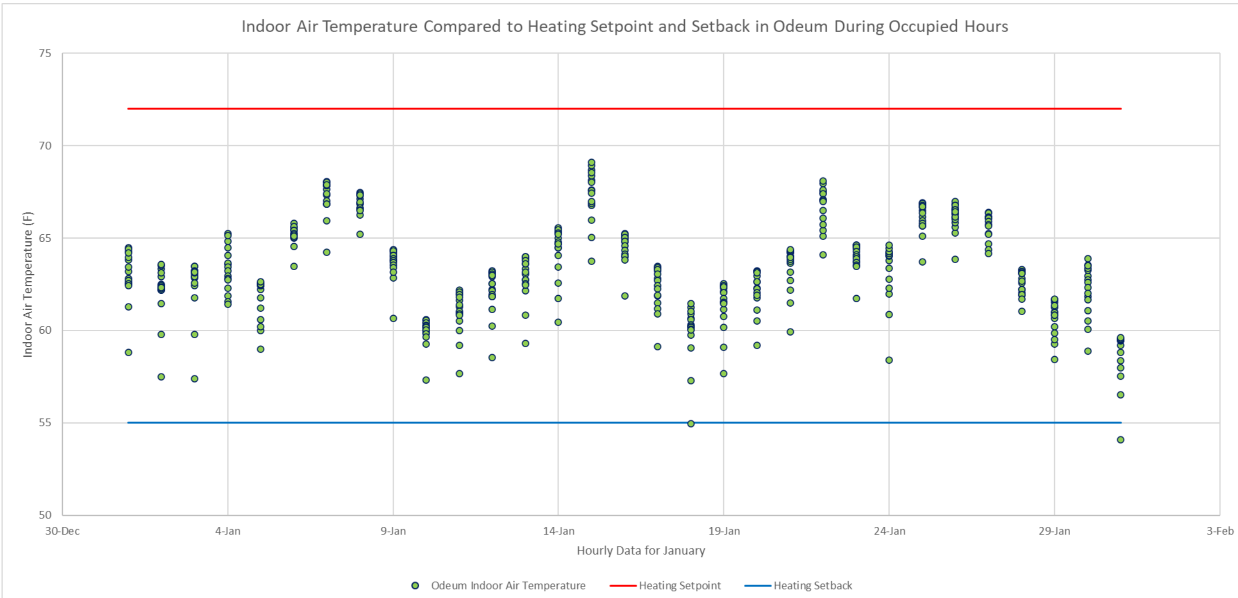


Figure 55

Indoor Air Temperature Compared to Heating Setpoint and Setback for Room Audio 339

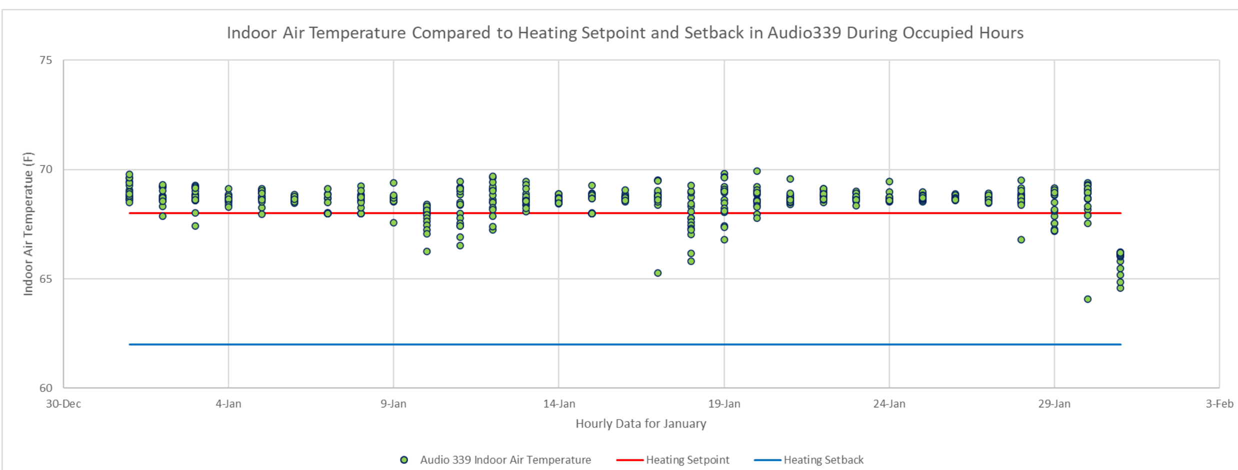


Figure 56

Indoor Air Temperature Compared to Cooling Setpoint and Setback for Odeum

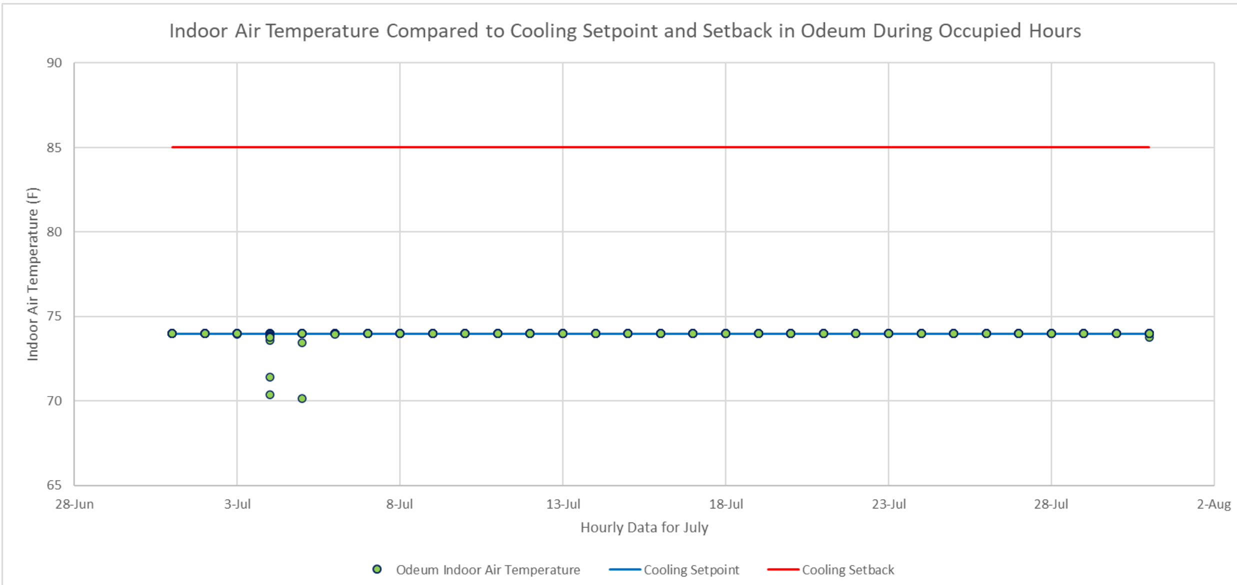


Figure 57

Indoor Air Temperature Compared to Cooling Setpoint and Setback for Lounge 203

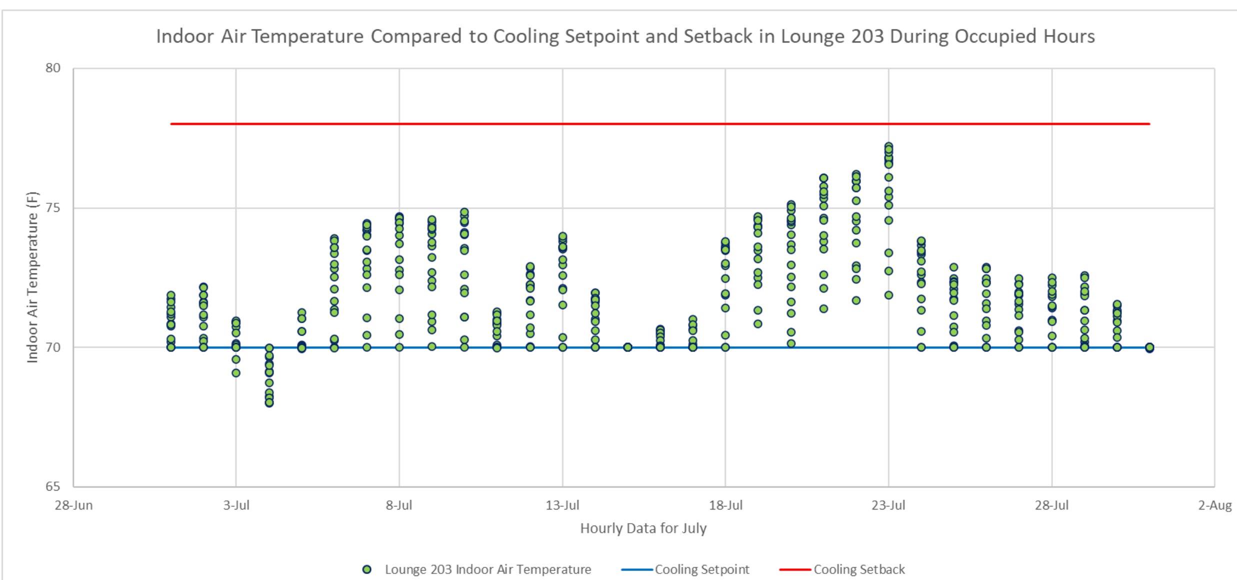


Figure 58

Locations of Room Audio 339 and the Odeum on the Third Floor of the CC

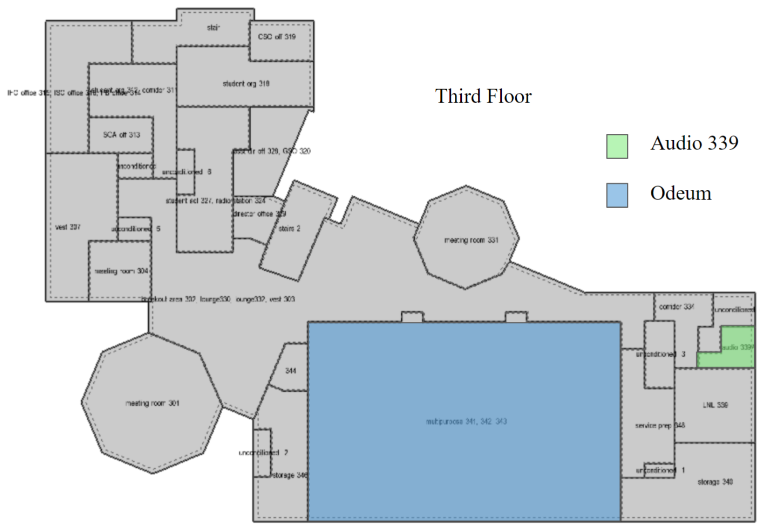
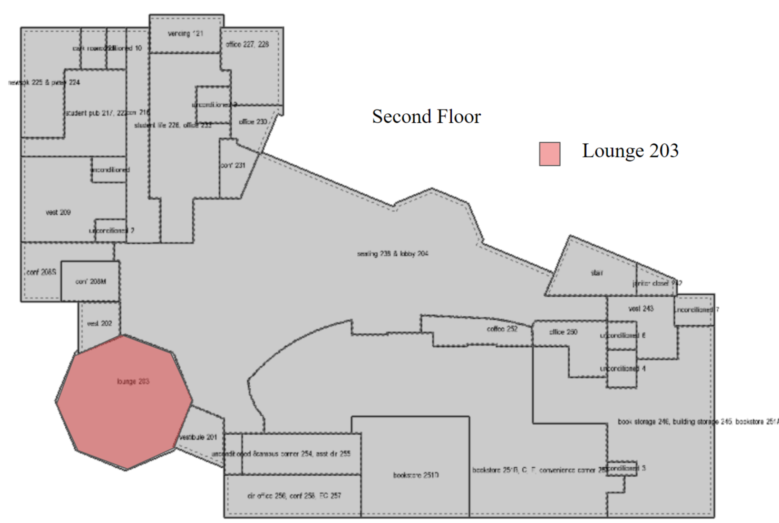


Figure 59

Location of Lounge 203 on the Second Floor of the CC



The high number of unmet heating and cooling setpoint hours as depicted in previous figures may be attributed to a few factors. 51 of the total 66 conditioned zones experienced varying amounts of unmet setpoint hours, and 30 of these zones have 100 or more unmet hours per month during heating, cooling, or both. Many of these highly affected zones were previously multiple separate zones that were combined to decrease simulation time. Furthermore, when looking at the real-time performance of zones in *Webctrl* at any given point, many zones are not within the ideal setpoint temperature range. This could mean that the existing set-up of the HVAC delivery system is not effective at maintaining thermal comfort, or the setpoint and setback temperature range for many zones could be too narrow. There could also be errors in the team's replication of the HVAC system in *DesignBuilder* which could not be properly deduced and fixed within the project's timeframe. Exploring avenues for reducing these unmet hours by either altering the existing heating and cooling delivery system or introducing supplemental heating and cooling equipment in affected zones was outside of the scope of this project. Although this high number of unmet setpoint hours for thermal comfort was not anticipated at the beginning of the project, it needs to be addressed prior to any implementation of renovations. Occupant comfort cannot be sacrificed for increased energy savings; a building can be incredibly efficient, but if it is uninhabitable, then there is no point to the building's existence.

8. Conclusion

As WPI continues its goal to increase on-campus sustainability, a focus on the operations and management of existing buildings can further promote these interests. Prioritizing existing building retrofits through LEED EBOM certification can increase the number of high-performance buildings on campus. Additionally, supporting existing buildings rather than demolishing and replacing them with new construction can reduce WPI's overall environmental impact.

The primary objective was to develop a LEED EBOM certification plan for the CC through quantitative analysis. The team investigated the existing building and its current mechanical and structural systems, creating a benchmark to compare the impacts of proposed changes to the building's energy efficiency and environmental impacts, and developed the current LEED scorecard. The secondary objective of this project was to demonstrate the feasibility of achieving LEED EBOM certification for the CC to the WPI Administration. This was accomplished by developing a sustainability proposal consisting of a variety of packages, with their associated budgets, that could achieve different levels of LEED certification. These objectives were created under the assumption that the CC would not initially be able to achieve any LEED certification.

After evaluating the potential for LEED EBOM status for the CC, it was determined that the current building can achieve LEED Silver certification. Through discussions with members of the Facilities Office, surveys of occupant satisfaction, and simulations of the current mechanical and enclosure systems, possible changes were identified that could reinforce WPI's sustainability goals, increase occupant comfort, and reduce energy usage. However, the final proposed models did not increase the achievable LEED certification score and level, so recommendations were made on the basis of cost and energy savings. The team's primary recommendation for WPI includes replacing the RTUs and MAU, and implementing a ground source heat pump. These changes simulated a total energy reduction of 31.7% from the baseline and have an estimated cost range of $448,000 to $808,000. The team's secondary recommendation also includes the replacement of the RTUs and MAU, as well as the replacement of the summer boilers. These changes simulated a total energy reduction of 13% from the baseline and had an estimated cost of $273,000. If WPI chooses the primary recommendation, the CC would be the Institute's first large-scale retrofit and have the least dependence on natural gas, which could serve as a case study for the other campus buildings. Furthermore, the WPI administration could evaluate the additional relevant credits that were not investigated in depth, such as IEQ Performance and Water Performance, to reach a higher LEED certification level.

References

Agdas, D., Frost, K., Masters, F.J., & Srinivasan, R.S. (2015). Energy use assessment of educational buildings: Toward a campus-wide sustainable energy policy. *Sustainable Cities and Society.* 17. 15-21. http://ggi.dcp.ufl.edu/_library/reference/Agdas%20Srinivasan%20et%20al%20SCSociety.pdf

van Alstyne, J.P., Boyd, J.M., Grogan, W.R., Heventhal, C.R., Jr., Moruzzi, R.L., & Shipman. C.W. (1970). The future of two towers part IV: A plan. *Worcester Polytechnic Institute.* https://www.wpi.edu/sites/default/files/docs/Academic-Resources/Gordon-Library/Future_of_Two_Towers_Part4.pdf

American Institute of Steel Construction (AISC). (2017). AISC Steel Construction Manual, 15th edition.

American Society of Civil Engineers. (2017). Minimum design loads and associated criteria for buildings and other structures: ASCE/SEI 7-16.

Amiri, A., Ottelin, J. and Sorvari, J., 2019. Are LEED-certified buildings energy-efficient in practice?. Sustainability, 11(6), p.1672.

Awadh, O. (2017). Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *Journal of Building Engineering*, *11*, 25-29.

Bardhan, S. (2011). Assessment of water resource consumption in building construction in India. *Ecosystems and Sustainable Development VIII*, *144*, 93-102. https://doi.org/10.2495/ECO110081

Boehm, R.F., Mandala, S., & Sadineni, S.B. (2011). Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews. 15*(8). 3617-3631. https://doi.org/10.1016/j.rser.2011.07.014

Commonwealth of Massachusetts. (2017). *Massachusetts State Building Code (MSBC) 780 CMR: State board of building regulations and standards.* https://www.mass.gov/doc/780-cmr-state-board-of-building-regulations-and-standards-massachusetts-amendments-to-the-0/download

Cowan, K. (2020, May 7). Top ten green building certifications. *Measurabl.* https://www.measurabl.com/top-ten-building-certifications/

De Rooij, D. (n.d.). Solar panel angle: How to calculate solar panel tilt angle? *Sinovoltaics.* https://sinovoltaics.com/learning-center/system-design/solar-panel-angle-tilt-calculation/

Delucchi, M.A. & Jacobson, M.Z. (2016). Meeting the world's energy needs entirely with wind, water, and solar power. *Bulletin of the Atomic Scientists, 69*(4). https://doi.org/10.1177/0096340213494115

DHCD Massachusetts. (2014). Solar photovoltaic systems. *In Design and Construction Guidelines and Standards*. https://www.mass.gov/doc/070700solarphotovoltaicsystemspdf/download#:~:text=Ballasted%20PV%20systems%20should%20typically,to%20the%20roof%20or%20tilted

Diehl, A. (2020). Determining module inter-row spacing. *CED Greentech.* https://www.cedgreentech.com/article/determining-module-inter-row-spacing

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, *123*, 243-260.

Electricity Local. (n.d.). Worcester Electricity Rates. https://www.electricitylocal.com/states/massachusetts/worcester/#ref

Energy Star. (n.d.). Commercial buildings. https://www.energystar.gov/buildings?s=mega

Fakhar, A., Pishghadam, K., Samali, B., & Vakiloroaya, V. (2014). A review of different strategies for HVAC energy savings. *Energy Conversion and Management.* 77. 738-754. https://doi.org/10.1016/j.enconman.2013.10.023

Global Alliance for Buildings and Construction. (2019). *2019 Global Status Report for Buildings and Construction.* https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

Global Alliance for Buildings and Construction. (2020). *The Global Status Report for Buildings and Construction.* https://globalabc.org/news/launched-2020-global-status-report-buildings-and-constructio n

Green Building Initiative. (n.d.). *Green Globe certification: How to certify.* https://thegbi.org/green-globes-certification/how-to-certify/

Howell, J., Mayer, A., & Wentz, E. (2021). *Developing a net-zero framework for the WPI campus.* https://digital.wpi.edu/pdfviewer/tq57nt795

International Living Future Institute. (n.d.). *Living Building Challenge 4.0 Basics.* https://living-future.org/lbc/basics4-0/

International Well Building Institute. (n.d.). WELL v2. https://www.wellcertified.com/certification/v2/

The Intergovernmental Panel on Climate Change. (2019). *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land* *management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* https://www.ipcc.ch/sr15/

Karyotakis, K., Tsagarakis, K.P., & Zografakis, N. (2012). Implementation conditions for energy saving technologies and practices in office buildings: Part 1. Lighting. *Renewable and Sustainable Energy Reviews*. 16(6). 4165-4174. https://doi.org/10.1016/j.rser.2012.03.005

Massachusetts Department of Environmental Protection. (n.d.). *Green Roofs*. Massachusetts Clean Water Toolkit. https://megamanual.geosyntec.com/npsmanual/greenroofs.aspx

Massachusetts DER. (2018). *Massachusetts household heating costs: Forecast of energy prices for heating fuels during 2021/22 winter heating season.* https://www.mass.gov/info-details/massachusetts-household-heating-costs

Murakami Y., Terano M., Obayashi F., & Honma M. (2007). Development of cooperative building controller for energy saving and comfortable environment. *Human Interface and the Management of Information. Interacting in Information Environments.* https://doi.org/10.1007/978-3-540-73354-6_118

Passive House Institute U.S. (n.d.). Passive House principles. https://www.phius.org/what-is-passive-building/passive-house-principles

Quick Electricity. (n.d.). *How Commercial Solar Panels Differ From Residential.* https://quickelectricity.com/solar-energy-texas/commercial-solar-panels/#:~:text=The%20concept%20of%20%E2%80%9Cresidential%20solar,which%20makes%20them%2020%25%20taller

Ried, R.C. (2008). Using LEED as a resource for campus sustainability planning: A white paper.

Soulti, E. (2016, January 31). The value of green building certifications. *Sense and Sustainability.*

https://www.senseandsustainability.net/2016/01/31/the-value-of-green-building-certifications/

University of Oregon. (2015). Sun path chart program. *University of Oregon, Solar Radiation Monitoring Laboratory.* http://solardat.uoregon.edu/SunChartProgram.php

U.S. Green Building Council. (n.d.a). *LEED rating system selection guide.* USGBC. https://www.usgbc.org/leed-tools/rating-system-selection-guidance

U.S. Green Building Council. (n.d.b). *LEED v4.1.* USGBC. https://www.usgbc.org/leed/v41

Vierra, S. (2019, August 5). Green building standards and certification systems. *Whole Building Design Guide.* https://www.wbdg.org/resources/green-building-standards-and-certification-systems

World Green Building Council. (2017). *New report: the building and construction sector can reach net zero carbon emissions by 2050.* WGBC. https://www.worldgbc.org/news-media/WorldGBC-embodied-carbon-report-published#_ftn1

World Green Building Council. (n.d). *Bringing Embodied Carbon Upfront.* WGBC. https://www.worldgbc.org/news-media/WorldGBC-embodied-carbon-report-published#_ftn1

Worcester Polytechnic Institute. (n.d.a). *Campus operations.* https://www.wpi.edu/offices/sustainability/campus-operations

Worcester Polytechnic Institute. (n.d.b). *Rubin Campus Center.* https://www.wpi.edu/about/locations/rubin-campus-center

Worcester Polytechnic Institute. (n.d.c). *The WPI campus.* https://web.wpi.edu/academics/library/history/techbible/campus.html

Worcester Polytechnic Institute. (2020a). *Sustainability report 2019-2020.* https://www.wpi.edu/sites/default/files/inline-image/Offices/Sustainability/Sustainability%20Report%202019-2020_FinalDraft_Post.pdf

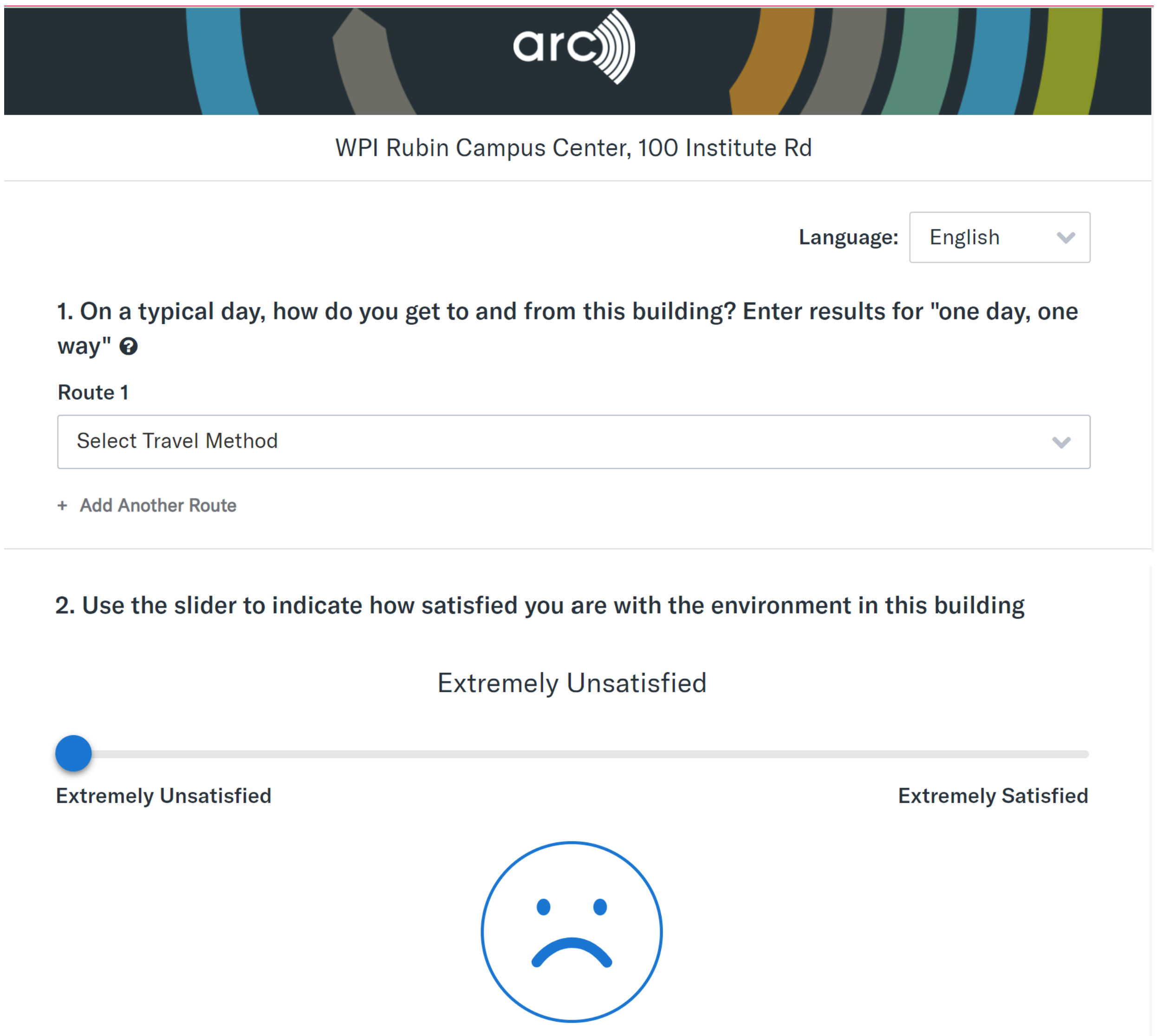
Worcester Polytechnic Institute. (2020b). *WPI's sustainability plan: 2020-2025.* https://www.wpi.edu/sites/default/files/2021/01/08/Sustainability_Plan_2020-2025_Post1.1.pdf

Yale. (2020, October 19). Yale experts explain green building certifications. https://sustainability.yale.edu/explainers/yale-experts-explain-green-building-certifications

Appendices

Appendix A: Transportation and Human Experience Survey Questions

Note: The slider ranges from extremely unsatisfied, very unsatisfied, unsatisfied, neither satisfied nor unsatisfied, satisfied, very satisfied, to extremely satisfied. Question 3 appears when either range of unsatisfied or satisfied is selected.



3. We're sorry to hear that. Please select the options below that significantly reduce your satisfaction:

- [ ] Dirty
- [ ] Cold
- [ ] Drafty
- [ ] Smelly
- [ ] Dark
- [ ] Bright
- [ ] Stuffy
- [ ] Glare
- [ ] Views to Outdoors
- [ ] Acoustics
- [ ] Privacy
- [ ] Sound
- [ ] Hot
- [ ] Humid

2. Use the slider to indicate how satisfied you are with the environment in this building

Neither satisfied nor unsatisfied

Extremely Unsatisfied **Extremely Satisfied**

2. Use the slider to indicate how satisfied you are with the environment in this building

Extremely Satisfied

Extremely Unsatisfied — Extremely Satisfied

3. We're glad to hear that. Please select the options below that significantly enhance your satisfaction:

- [ ] Thermal Comfort
- [ ] Sound
- [ ] Air Quality
- [ ] Cleanliness
- [ ] Light
- [ ] Privacy
- [ ] Views to Outdoors
- [ ] Daylight

Comments (Optional)

Location - eg. Lobby, 2nd Floor East, 50th Floor - Suite 500

Name (Optional)

Which type of occupant are you?

Regular Occupant

Appendix B: Full-time IEQ Survey Questions

Background

- How many years have you worked in this building?

- Less than 1 year
    - 1-2 years
    - 3-5 years
    - 5-10 years
    - More than 10 years
- In a typical week, how many hours do you spend in your workspace?
    - 10 or less hours
    - 11-30 hours
    - More than 30 hours
- How would you describe the work that you do?
    - Administrative support
    - Food service
    - Student organization
    - Retail
    - Facilities
    - Mail services
    - Other
        - FR

Personal Workspace Location

- On which floor is your workspace located? (Check all that apply)
    - Check box
        - Ground floor
        - 1st Floor
        - 2nd Floor
- Where do you work? (Please list office/room number as applicable.)
    - FRQ
- Are you near (i.e., within 15 feet)...
    - An exterior wall
        - Yes
        - No
    - A window
        - Yes
        - No

Thermal Comfort

- Which of the following do you personally adjust or control in your workspace? (Check all that apply)
    - Window blinds or shades
    - Operable window

    - Thermostat
    - Portable heater
    - Permanent heater
    - Room air-conditioning unit
    - Portable fan
    - Ceiling fan
    - Adjustable air vent in wall or ceiling
    - Adjustable floor air vent (diffuser)
    - Door to interior space
    - Door to exterior space
    - None of the above
    - Other
- How satisfied are you with the temperature of your workspace?
    - Very satisfied, Satisfied, Somewhat satisfied, Neither satisfied nor dissatisfied, Somewhat dissatisfied, Dissatisfied, Very dissatisfied
- Overall, does your thermal comfort in your workspace enhance or interfere with your ability to get your job done?
    - Significantly enhances, Enhances, Somewhat enhances, Neither enhances nor interferes, Somewhat interferes, Interferes, Significantly interferes
- You have said that you are dissatisfied with the temperature in your workspace. Which of the following contribute to your dissatisfaction?
    - In warm/hot weather, the temperature in my workspace is: (Check all that apply)
        - Often too hot
        - Often too cold
    - In cool/cold weather, the temperature in my workspace is: (Check all that apply)
        - Often too hot
        - Often too cold
    - How would you best describe the source of this discomfort? (Check all that apply)
        - Humidity too high (damp)
        - Humidity too low (dry)
        - Air movement too high
        - Air movement too low
        - Incoming sun
        - Hot/ cold floor surfaces
        - Hot/ cold ceiling surfaces
        - Hot/ cold wall surfaces
        - Hot/ cold window surfaces
        - Heat from office equipment
        - Drafts from windows
        - Drafts from vents

        - Drafts falling from the ceiling
        - My area is hotter than other areas
        - My area is colder than other areas
        - Thermostat is inaccessible
        - Thermostat is adjusted by other people
        - Heating/ cooling system does not respond quickly enough to the thermostat
        - Clothing policy is not flexible
        - Other
            - FRQ
    - Please describe any other issues related to being too hot or too cold in your workspace.
        - FRQ

Air Quality

- How satisfied are you with the air quality in your workspace? (i.e., stuffy/ stale air, cleanliness, odors)
    - Very satisfied, Satisfied, Somewhat satisfied, Neither satisfied nor dissatisfied, Somewhat dissatisfied, Dissatisfied, Very dissatisfied
- Overall, does the air quality in your workspace enhance or interfere with your ability to get your job done?
    - Significantly enhances, Enhances, Somewhat enhances, Neither enhances nor interferes, Somewhat interferes, Interferes, Significantly interferes
- You have said that you are dissatisfied with the air quality in your workspace. Please rate the level of each of the following problems.
    - Not a problem, Minor problem, A problem, Major problem
        - Air is stuffy/ stale
        - Air is not clean
        - Air smells bad (odors)
- If there is an odor problem, which of the following contribute to the problem? (Check all that apply)
    - Tobacco smoke
    - Photocopiers
    - Printers
    - Food
    - Carpet or furniture
    - Other people
    - Perfume
    - Cleaning products
    - Outdoor scents (car exhaust, smog)

        - Other
            - FRQ
- Please describe any other issues related to the air quality in your workspace that are important to you.
    - FRQ

Lighting

- Which of the following controls do you have over the lighting in your workspace? (Check all that apply)
    - Light switch
    - Light dimmer
    - Window blinds or shades
    - Desk (task) light
    - None of the above
    - Other
        - FRQ
- How satisfied are you with…
    - The amount of light in your workspace
    - The visual comfort of the lighting (e.g., glare, reflections, contrast)
        - Very satisfied, Satisfied, Somewhat satisfied, Neither satisfied nor dissatisfied, Somewhat dissatisfied, Dissatisfied, Very dissatisfied
- Overall, does the lighting quality enhance or interfere with your ability to get your job done?
    - Significantly enhances, Enhances, Somewhat enhances, Neither enhances nor interferes, Somewhat interferes, Interferes, Significantly interferes
- You have said that you are dissatisfied with the lighting in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)
    - Too dark
    - Too bright
    - Not enough daylight
    - Too much daylight
    - Not enough electric lighting
    - Too much electric lighting
    - Electric lighting flickers
    - Electric lighting is an undesirable color
    - No task lighting
    - Reflections in the computer screen
    - Shadows on the workspace
    - Other
        - FRQ
- Please describe any other issues related to lighting that are important to you

- ○ FRQ

General Comments

- All things considered, how satisfied are you with your personal workspace?
    - Very satisfied, Satisfied, Somewhat satisfied, Neither satisfied nor dissatisfied, Somewhat dissatisfied, Dissatisfied, Very dissatisfied
- Please estimate how you perceive your productivity has increased or decreased by the environmental conditions in the building (e.g., thermal, air quality, lighting)
    - Increased 20%, Increased 10%, Increased 5%, Neither increased nor decreased, Decreased 5%, Decreased 10%, Decreased 20%
- How satisfied are you with the building overall?
    - Very satisfied, Satisfied, Somewhat satisfied, Neither satisfied nor dissatisfied, Somewhat dissatisfied, Dissatisfied, Very dissatisfied
- Any additional comments or recommendations about your personal workspace or building overall? (e.g., thermal comfort, air quality, and lighting)
    - FRQ

Appendix C: Example Threshold Calculations for High Roof Girders and Columns

Comparison

High Roof/Odeum Example Girder Structural Analysis

Input	Scheme b14 Lower Capacity		Unit
Beam Size	W36X135		
Beam Weight	135		lbs
Girder L	16.9		ft
Beam Length	56		ft
DL Membrane Roof	66.9		psf
LL	35		psf
LL Δ max	1		in
LL + DL Δ max	0.8		in
Load Combinations			
1.4D	1311		lb/ft
1.2D + 1.6L	1908		lb/ft
Output	Scheme 1		Unit
Wu	1908		lb/ft
Mu	67.9		ft-kips
Zx	18.1		in^3
	Select: W12X16		
New wu	1927.1		lb/ft
New Mu	68.6		ft-kips
New Zx	18.3		in^3
	Select: W12X16		
Deflection	LL	LL + DL	Unit
Δ max (in)	1.0	0.84	in
Ix (in^4)	103	103	in^4
Δactual (in)	0.36	1.05	in
Imin (in^4)	37.2	128.2	in^4
	Select: W12X19		
New wu	1930.7		lb/ft
New Mu	68.7		ft-kips
New Zx	18.3		in^3
	Select:W12X16		

Input	Scheme b14 Upper Capacity		Unit
Wu	53623.045		lb/ft
Mu	1908.750		ft-kips
Zx	509		in^3
Start	W36X135		
Deflection	LL	LL + DL	Unit
Δ max (in)	1.0	0.8	in
Ix (in^4)	7800	7800	in^4
Δactual (in)	0.005	0.014	in
Imin (in^4)	37.2	128.2	in^4
SELECT	W12X19		
New wu	53645.8		lb/ft
New Mu	1909.6		ft-kips
New Zx	509.2		in^3
	Select:W36X135		

High Roof/Odeum Example Column Structural Analysis

Input	Scheme cI Lower Capacity	Units	Input	Scheme c1 Upper Capacity		Units
K	1		Trib Area Roof	684.25		ft^2
Size	W12x40		Floor DL	45		psf
Lb	14	ft	Roof DL	12.6		psf
φc	0.9		Floor LL	100		psf
ry	1.94	in	Roof LL	20		psf
rx	5.1216	in	Roof SL	35		psf
Fy	50	ksi	Exterior Facade DL	54.3		psf
E	29000	ksi	Load Combinations			
Ag	11.7	in^2	1.4D	297	297	kips
Output			1.2D + 1.6 (Lr or S o	293	293	kips
Lc/r	86.6		1.2D + 1.6L + .5 (Lr	267	267	kips
4.71√E/Fy	113.4		Input			units
	≤, use E3-2		K	1		
Fe	38.2		Size	W12x87		
Fcr	28.9		Lb	14		ft
φcPn	304.3		φc	0.9		
φcPn ≥ Pu	√ Select W12X40		ry	3.07		in
			rx	5.3725		in
			Fy	50		ksi
			E	29000		ksi
			Ag	25.6		in^2
			Output			
			Lc/r	54.7		
			4.71√E/Fy	113.4		
				≤, use E3-2		
			Fe	95.6		
			Fcr	40.2		
			φcPn	925.5		
			φcPn ≥ Pu	√ Select W12X87		