SL1-SE16

Sustainable Campus Buildings:

A Case Study of Climate Control in Kaven Hall

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Abstract

This project analyzed the energy usage of Worcester Polytechnic Institute’s Kaven Hall, and examined various improvements that would efficiently provide a comfortable climate for learning. These improvements were ranked based on various factors, such as energy efficiency, comfort, and cost. The methods used to determine improvements were described in detail, so that a similar process could be applied to other buildings in need of indoor climate improvements.

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Glossary

R-value: A number that describes how well a particular construction material resists heat transfer. This value is measured with United States Customary units as $\frac{ft^2 * °F * Hr}{BTU}$ though R-values are often given without the unit. Higher R-Values indicate a material is more effective at insulating a building. Commercial buildings are required to have walls insulated to R-20 as per the International Energy Conservation Code [25].

U-value: The inverse of the R-value, and thus has a unit of $\frac{BTU}{ft^2 * °F * Hr}$. [34] This value is used in the United States to rate doors and windows, and represents the transfer of energy through conduction and radiation. The lower the U-value, the more insulating the material is, and the less energy transferred. [40]

BTU: Acronym for British Thermal Unit, that is defined as the amount of work necessary to raise the temperature of one pound of water one degree Fahrenheit. To put this into perspective, an average home in the United States required approximately 90 Million BTUs of heating in 2009 [41].

Therm: A unit of measure defined as 100,000 BTUs, often used for measuring fuel.

Emissivity: A ratio of a surface's effectiveness at emitting energy as thermal radiation compared to the thermal radiation emitted by an ideal black surface.

EER: The Energy Efficiency Ratio, is a ratio of the output cooling energy (BTU) to the input electrical energy in (Wh) used with window Air Conditioner units.

1 Introduction

Sustainability is defined broadly by the WPI Sustainability Report as encompassing human and ecological health, social justice, secure livelihoods, and a better world for all generations [38]. At WPI, sustainability is applied to teaching and learning, research, facilities operations, and community engagement. Starting in 2006, WPI has promoted energy efficient buildings on its campus through its campus sustainability initiative. In 2007, WPI's Board of Trustees passed a resolution that required all new buildings at WPI to meet Leadership in Energy and Environmental Design, (*LEED® green building program*) certifications. The first of the buildings on campus created with this in mind was the Bartlett Center. Since then, three more buildings have been built that are LEED®-certified and achieve different levels of this certification. The resolution requiring new buildings to meet LEED® certifications promotes sustainability at WPI by building an energy efficient campus. This project report will define sustainability more narrowly, as it relates to buildings: as a combination of livability and energy efficiency for the longevity of a building.

WPI has an ethical responsibility to promote sustainability on its campus through energy usage in buildings. Energy and fuel consumption in aging academic buildings as of April 2016 are very high when compared with the national average. Specifically, Kaven Hall has an energy use intensity (EUI) of 194 while the national EUI average for academic buildings is 130.7 [19]. The R.W. Kern Center is a "Living Building" built to promote sustainability and efficient energy use at Hampshire College in Amherst Massachusetts. This building was able to achieve an EUI of 12 by taking advantage of renewable energy, such as sunlight and rainfall. While Kaven Hall could not bring its energy use down to an EUI of 12, due to its dated design, a renovation of the building could reduce its EUI below the national average and decrease its energy use significantly.

The goal of this project was to determine ways to improve the current heating and cooling systems for outdated buildings on campus, with a focus on increasing building sustainability. The plan was to first analyze Kaven Hall by looking at the heating ventilation and air conditioning (HVAC) system in the building, and determine price estimates for a new HVAC system. The project group quickly determined that a new HVAC system design would be beyond the scope of an interactive qualifying project (IQP). A new HVAC system would be extremely costly as well, so the project team determined that the comfort and energy efficiency of Kaven Hall could be improved through smaller, lower cost solutions. These solutions were placed into a list of possible changes to Kaven Hall that would increase the energy efficiency of the building and create a more sustainable learning environment. With a list of recommended changes created, we detailed the procedure we used, so that a similar process could be applied to other buildings in need of climate improvements.

2 Background

2.1 Introduction

The purpose of this section is to provide background details on important topics needed to understand the focus of this report. The section starts with details about Kaven Hall, such as the physical properties and systems of the building, then briefly discusses the condition of heating ventilation and air conditioning (HVAC) in other buildings on campus. This chapter covers how HVAC systems work, what Leadership in Energy and Environmental Design (LEED®) certification is, and how LEED® certification is achieved. Finally, the chapter discusses Revit, and how it can be used to model the entirety of a building, down to energy usage and running costs.

2.2 Kaven Hall

Kaven Hall, shown in Figure 1 below, built in 1954, is currently one of the older buildings at WPI. The building is named after Moses Kaven, of the WPI Class of 1865, who was a frequent and generous donor to WPI. Kaven Hall is located on the northeast side of the main campus as seen on the map in Figure 2.

Figure 1: Kaven Hall in the winter [14]

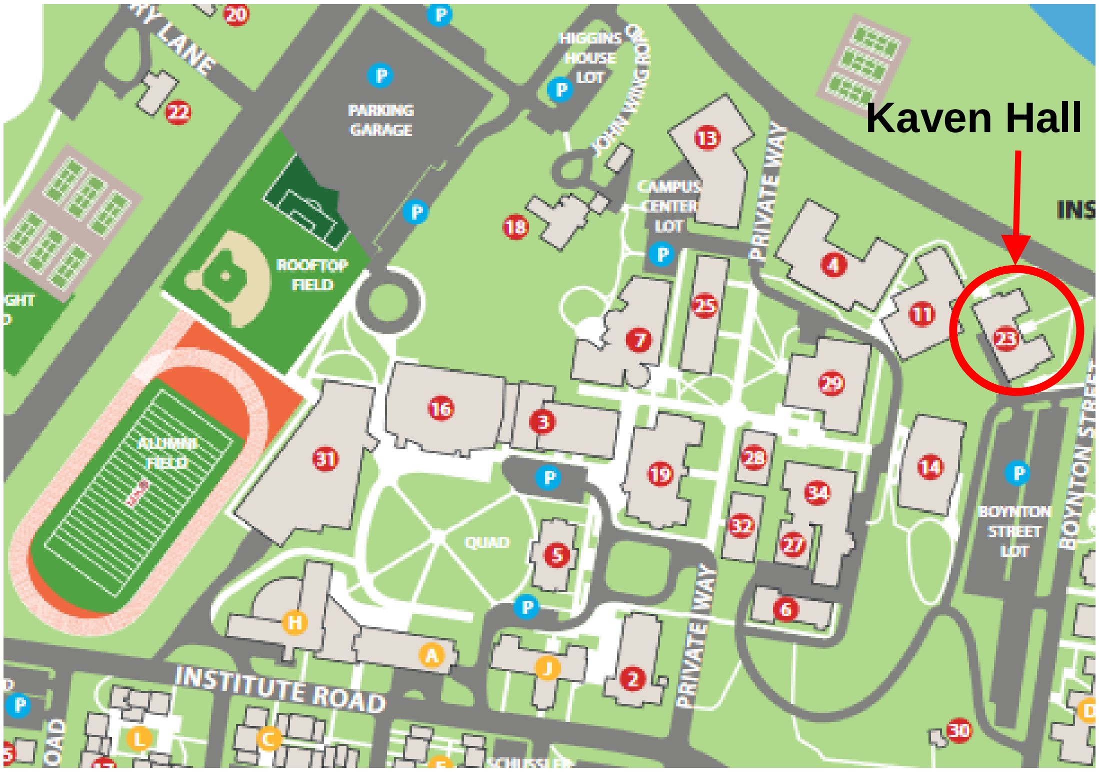


Figure 2: Map of WPI Campus with Kaven Hall marked [8]

Kaven Hall is an academic building that serves as the home of the Department of Civil and Environmental Engineering (CEE). Kaven Hall has three classrooms, KH115, KH116, and KH204 that are used by classes in various departments. One of these rooms, KH116 is one of the larger lecture halls on campus and is used by many large classes. The other two classrooms can hold approximately 30 people each and serve smaller classes in various departments throughout the school.

The basement of Kaven Hall doesn’t have any traditional classroom space, as it is home to 7 different labs that serve the CEE department. The labs located here include space for the Highway Infrastructure Program, a Structural Laboratory, Water Lab, Geotech Lab, Impact Lab, and the Environmental Engineering Lab. An office, as well as a number of mechanical rooms can also be found in the basement.

The first floor in Kaven Hall is occupied primarily by classrooms, and office spaces. KH115 and KH116 are both found on the first floor as indicated by the purple fill in Figure 3 below. The first floor contains 7 faculty offices, 2 TA offices, the Department office, and an office for the Department Secretary all indicated by yellow fill on the floor plan in Figure 3 below.

The second floor contains 12 faculty offices, as well as a large graduate student office. The second floor is also home to two computer labs. Kaven Hall 203 and KH 202 are available to all WPI students 24 hours a day 7 days a week. Additionally, the Architectural Engineering Lab can be found on the second floor of Kaven hall in KH207.

As of April 2016, the heating system in Kaven Hall utilizes many of the original heating and ventilation systems, including relying upon campus steam to provide heating. The steam is piped through radiators and unit ventilators located in every room. The radiators simply transfer heat from the steam to the air already in the room, while the unit ventilators can draw fresh air from outside the building and heat it before blowing the fresh air into the room.

The radiators and unit ventilators are both controlled with a pneumatic temperature control system. This system utilizes pressurized air lines to control the steam valves for each radiator. Air lines run from a central compressor to the thermostats in each room. The thermostats then adjust the output air pressure going to the valves for the radiators in the room to control the heat output.

Cooling systems were not a part of the original design specifications. Over the life of the building a number of different cooling systems have been added to the building. A Mitsubishi split air conditioning system has been added to KH116 to provide cooling. Other air conditioners have been installed outside that provide cooling for various labs in the building. Window air conditioners have been added to the other classrooms and many offices. An air handling unit that provides ventilation to parts of the building was also called for in the original blueprints for the building (See Appendix C).

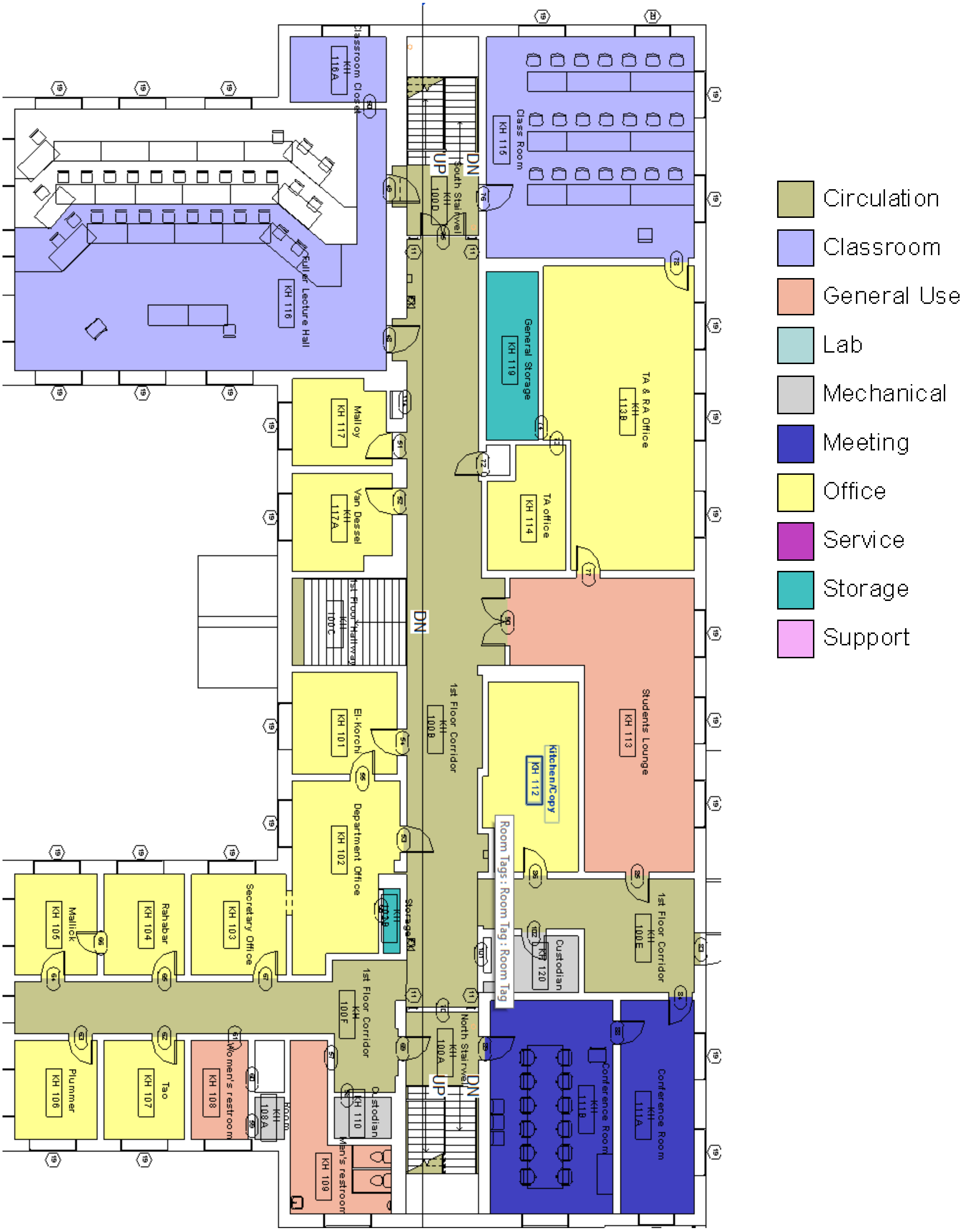


Figure 3: Floor plan of the first floor of Kaven Hall (Revit Model)

2.2.1 Chronology of Recent Renovations

The table below details all of the information the project team was able to find regarding recent renovations made to Kaven Hall.

Table 1: Renovations of Kaven Hall

Year	Renovation Details
1996	The CAD lab known as CECIL Lab was added to the building. CECIL Lab had an air conditioning system and “a temperature control” [31]. Fuller Lecture Hall 116 was also refurbished and given AC units. The first floor entrance was also refurbished, along with the first floor lounge area. [31]
1999	Kaven Hall room 204 was renovated, involving the installation of a new carpet and ceiling, as well as window treatment. [12] New equipment was added to the Environmental Infrastructure and Highway Infrastructure Program Laboratories was added.
2001	The basement was renovated, including the Highway Infrastructure and Program Laboratories. This seems to have had no effect on the heating and cooling of the building. [37]

2.3 HVAC Systems

HVAC is a commonly used acronym in the heating and cooling industry, which stands for “Heating, Ventilation, and Air Conditioning.” With an HVAC system, “warmed or cooled or dehumidified air flows through a series of tubes - called ducts - to be distributed to all the rooms,” of a building [10]. HVAC systems are usually the quietest and most convenient way to control the climate of a building. These systems account for 39% of the energy used in commercial buildings here in the United States [23]. The use of higher-performance HVAC systems alone can account for energy, emissions, and cost savings of up to 40% [23]. For higher savings, an entire building redesign would have to be done. For a building such as Kaven Hall, simply adding a new, higher-performance HVAC system would still result in the previously stated savings of up to 40%, while also improving the livability and comfort levels of the building.

Simple forced-air ducts are not the only form of HVAC system, however. Two important systems when considering the heating and cooling of academic buildings are the two-pipe and four-pipe systems. With a two-pipe system, only heating or cooling can be active for the entire building at any one time, which means less overhead than a four-pipe system. The drawback of a two-pipe system is that, because only heating or cooling can be active at any one time, the system can perform sub-optimally in the spring or fall months, when temperatures tend to swing back and forth. With a four-pipe system, any room can be heated or cooled at any time, at the cost of higher energy usage and higher initial construction costs [45].

2.4 LEED® Certification

The LEED® (Leadership in Energy and Environmental Design) system is a certification system for the energy efficiency of buildings. There are multiple levels of certification for new and old commercial and residential buildings. Buildings can either be designed with energy efficiency deserving of a LEED® certification, or be renovated in order to meet the criteria for certification. Buildings are scored "across several areas that address sustainability issues" [43], and according to this score, the buildings can receive different levels of LEED® certification, which are listed are in ascending order below:

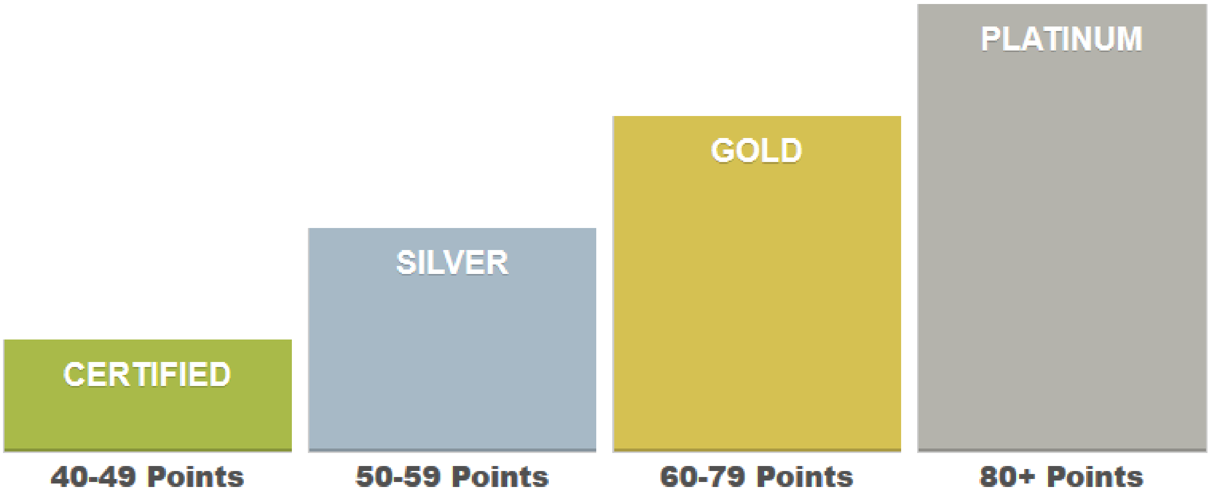


Figure 4: LEED certification levels by point requirements [43]

Though LEED started with one rating system, it has since created more specific rating systems for different types of buildings. The LEED® rating system for existing buildings is known as the LEED® O+M rating system, meaning "Building Operations and Maintenance" [43]. Each rating system is based on a number of different credits in multiple categories. The O+M rating system for example considers the following categories:

- Location and Transportation
- Sustainable Sites
- Water Efficiency
- Energy and Atmosphere
- Materials and Resources
- Indoor Environmental Quality
- Innovation
- Regional Priority

Within each category, there are a number of credits that can be achieved. Each credit requires that the project being certified meet specific criteria. The point ranges for each certification level can be seen in Figure 4.

Several previous projects have looked into making buildings on the WPI campus more energy efficient and sustainable. One project report, “Improving Comfort and Efficiency of WPI’s Ailing Buildings”, examined the heating and cooling systems of older buildings at WPI, such as the Stoddard residences, as well as comparing the older buildings’ energy usage to the newer Bartlett Center [34]. The project report provides an overview of how LEED® certification can be achieved for existing buildings, and then makes specific recommendations on how to improve heating efficiency of the Stoddard complex.

2.5 Revit Review

Revit is a computer aided design application that is used for designing buildings. According to the official website (autodesk.com/Revit), Revit was specifically built for Building Information Modeling, and includes features for architectural design, MEP and structural engineering, and construction [6]. Revit allows for modelling plumbing, HVAC, and electrical systems for planning purposes. This can be especially useful for laying out various ducts and piping and to ensure that structural walls are not intersected. Revit also includes numerous analysis tools, including structural analysis and energy analysis tools.

The energy analysis tools available within Revit make use of Autodesk’s Green Building Studio cloud application. Green Building Studio accepts a file that describes each room making up a building, and their location relative to each other. The energy analysis also requires the coordinates and angle of the building as it uses this information for choosing weather data, and solar radiation. Once GBS has all of the information necessary it utilizes the DOE-2 building energy analysis program to perform the energy calculations [23]. The DOE-2 model takes into account the outside weather, usage schedule, HVAC and lighting systems, as well as utility rates to simulate the energy usage of the building over a given time period. The model is considered accurate enough to qualify for usage in determining tax deductions by the IRS [41]. Green Building Studio is then able to return detailed information including fuel usage, electricity usage, and runtime for various HVAC components.

2.6 Summary

This chapter discussed the state of Kaven Hall, basic details of HVAC systems, and guidelines to acquire a LEED® certification. The chapter also gave an overview of Autodesk Revit and Green Building Studio, detailing how they can be utilized to provide an understanding of a buildings energy consumption.

3 Methods

3.1 Project Statement

This project looked at the state of the heating and cooling systems in Worcester Polytechnic Institute's Kaven Hall, and how these systems influenced the indoor climate of the building. We then created a plan for how various systems in the building could be improved to increase the stability of the temperatures throughout the building's academic spaces. This report documented the steps we took in order to establish a procedure that can be applied to other buildings in need of improvements to HVAC systems. The group performed a cursory analysis of modern HVAC systems, as well as an examination of smaller improvements that could be made, such as newer, more efficient door and window fixtures. The group utilized a Revit model of Kaven Hall in order to determine the relative effectiveness of these improvements. The group also looked at the general costs of implementing these smaller sustainable heating and cooling solutions, and determined which solutions would be the most viable to implement in Kaven Hall as well as on a campus-wide scale.

3.2 Temperature Data Logging

The team collected data about the temperature throughout Kaven Hall using three USB-501 Battery-Powered Remote Temperature Data Loggers, pictured in Figure 5. The data loggers must be configured to start collecting data using the "USB-500 & 600 Software" configuration application. The group configured the data loggers to take samples once every minute as this allowed for collecting data over eleven days, for a total of 16,382 samples [5]. The group then deployed the temperature sensors in classrooms on the first and second floors of Kaven hall, placing one in KH115, one in KH116, and one in KH203. We placed the data loggers under desks close to the middle of the classroom as this would represent the temperature many students experienced. We collected the data loggers after seven days, so that data was collected during the week when classes were in session as well as over a weekend when the building was not used as heavily. Once the data for those three rooms were logged and downloaded, the project group erased the data loggers and placed them in the labs found in the basement of Kaven Hall. This time all three loggers were placed in the concrete lab in various parts of the room to search for temperature differences throughout this one lab area.

Figure 5: Temperature Data Logger used in Kaven Hall

In order to place the temperature data loggers in the labs of Kaven Hall, the group got permission from Russ Lang, the lab supervisor. The temperature data loggers were left in the lab for a week to collect a similar dataset as before. After collecting the temperature sensors, the group downloaded the data using the “USB-500 & 600 Software” used to configure the data logger. In addition to the temperature data loggers that were placed in rooms inside Kaven Hall we were able to obtain outside temperature data from a weather station outside of a graduate student office on the second floor of Kaven Hall. We analyzed the data by graphing the inside temperature readings and outside temperature readings over the same time period.

3.3 Thermal Imaging

To determine how the windows and roof were performing in Kaven Hall, the project team utilized an infrared camera. This camera allowed the team to pinpoint parts of the windows that were letting cold air inside the building. The project team also used the camera at night to see parts of the roof that were letting out heat and any door seals that were letting heat out of the building.

Figure 6: FLIR I7 Camera [21]

The camera that the project team used was a FLIR I7 Camera, as shown above in Figure 6. This is a thermal camera, which, when aimed at a surface, displays the temperature of the surface. The temperature is represented in the image using a color scale, where the darker colors, blue or black, are the coldest parts of the image and the lighter colors, bright yellow and white, represent the hottest parts of the image.

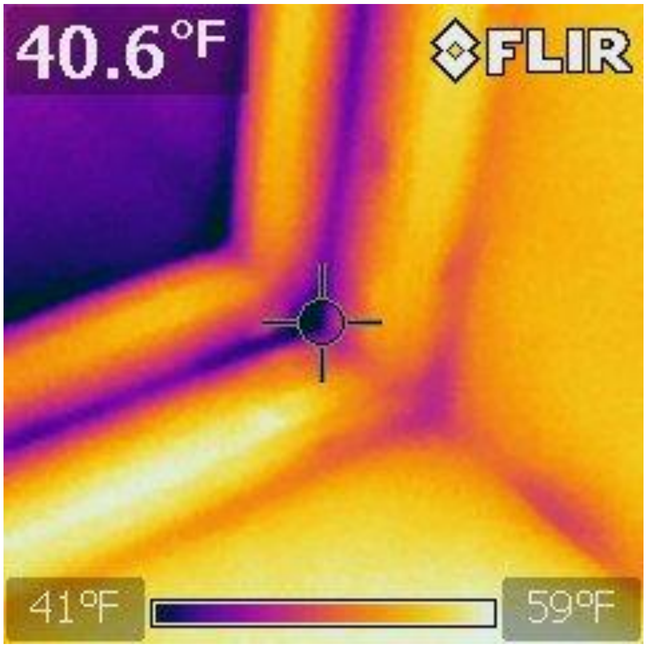


Figure 7: Example FLIR Picture of Window

Figure 7 is an example FLIR picture taken with the camera. As shown above, the color scale for this image varies between 41 and 59 degrees Fahrenheit in accordance to the colors in the given scale. In addition, the current temperature of the center of the picture is given in the top left corner. In this picture, the center is quite cold at 40.6 degrees Fahrenheit.

3.4 Revit Modeling

In order to find actual values to compare and rank improvements, the project team used a Revit model of Kaven Hall. With this model, the team was able to change the type of windows, doors, and other systems used, and compare the energy usage of the building before and after adding these improvements. While the numbers acquired were not guaranteed to be 100% accurate, these numbers did allow to team to get a relative sense of how much these improvements would help the building in terms of energy usage and running costs.

Through discussions with faculty in the Civil and Environmental Engineering (CEE) Department we found that Professor Guillermo Salazar, a CEE professor, was well versed in Revit as he taught classes on its usage. The project team contacted Professor Guillermo Salazar to see if he possessed a Revit model of Kaven Hall that could be used to do an energy analysis. Professor Salazar possessed an almost entirely complete model of Kaven Hall, and he gave it to the team for use on this project. After receiving the model, we visually inspected each side of the Revit model and compared it to pictures of the building. We also compared dimensions taken from the Revit model with dimensions in the original blueprints. The team found that the model was missing windows on the bottom floor. The group then visited Kaven Hall and measured the window openings for each basement window. While measuring window sizes we also measured the dimensions of the outside walls of Kaven Hall and confirmed that they matched the dimensions given in the original blueprints. We then utilized the information we gathered on window sizes along with the blueprints of the basement as seen in Appendix B to accurately place each window in the model.

Once we had verified the model's accuracy, we used Autodesk Green Building Studio (GBS) to perform an energy analysis. The group attempted to utilize the GBS integration in Revit, which automates the energy analysis process from one button in the interface. To get around this issue, the group was able to export the required energy model from within Revit as a gbXML file that contains detailed information on the building. We then uploaded the gbXML file through the actions menu, using the "Upload gbXML File (Creates a base run)" option as seen below in Figure 8.

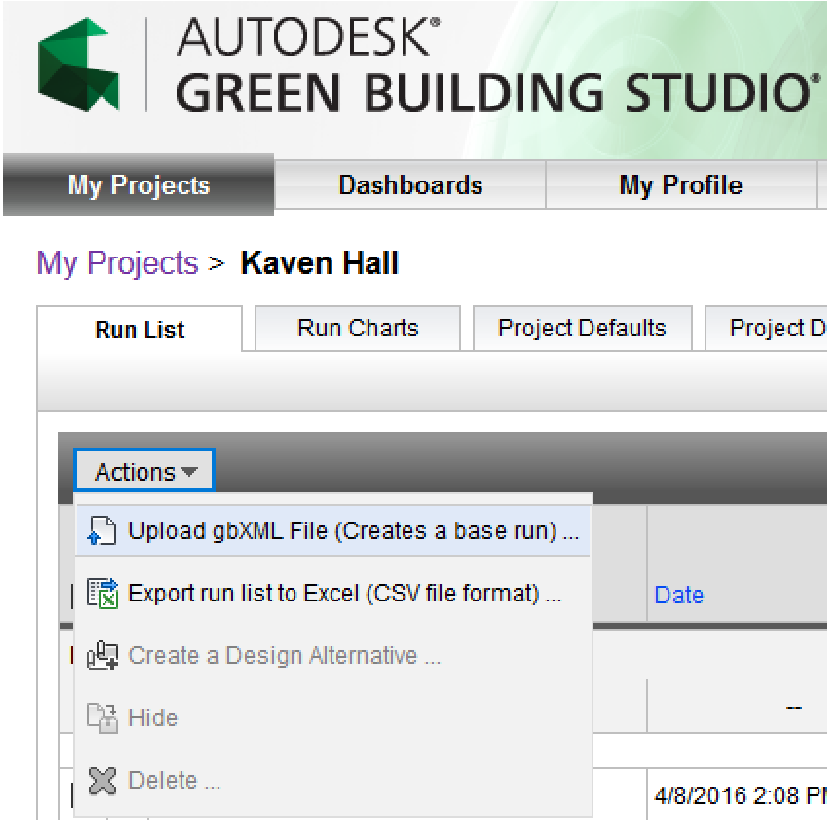


Figure 8: Upload gbXML file through the Green Building Studio web interface

After creating a base run in this manner GBS automatically creates a number of alternative runs that are queued to run. Each variation generally changes one setting in the model, such as the style of window, and then performs an energy analysis with the new parameters. As each alternative run looks at the effect of one parameter, the energy usage results can be utilized to compare individual changes to the building. The findings from this energy analysis were then used to help list and rank the potential improvements for Kaven Hall.

3.5 HVAC Requirements

In order to research the possibility of getting a new HVAC system installed in Kaven Hall, this study took into consideration the heating and cooling requirements of the building. The group analyzed the floorplan and dimensions of the building, and researched HVAC systems in order to determine what system would best suit the building, and if the building was even capable of being renovated to incorporate an HVAC system. This study had to take into consideration the general savings that a high-performance HVAC system can provide, and determine how long it would take for these savings to balance out the initial cost of renovations, installations, and maintenance for the system, as well as whether or not installing this system would be a viable option for the school.

To find information on the HVAC commissioning process, the group looked in the ASHRAE 2011 handbook [2]. This handbook contained the guidelines necessary for the project group to make a decision regarding whether or not we would be able to create a design for an HVAC system for Kaven Hall, which we ultimately decided against. The results of this research are described in greater detail in section 4.6 in the Results & Analysis section of this report.

3.6 Evaluating Improvements

Due to the time restraints inherent to large renovations, we looked into more immediate ways to improve the heating and cooling efficiency of the building. This included looking at the potential increases in sustainability due to changing the current door and window fixtures for more efficient ones, as well as looking at more efficient cooling methods than the currently implemented window units that were used for air conditioning. We looked at both the initial cost and the potential savings that these immediate measures could provide. This allowed us to rank the improvements based upon their impact on the building energy use. These improvements were also ranked according how much any related construction would affect the day-to-day activities of the occupants of Kaven Hall.

3.7 Summary

Members of the project team have studied Kaven Hall to understand its needs as a sustainable building. The group analyzed energy use and previous renovations of Kaven Hall in order to get a better understanding of the state of the building. The group has researched HVAC systems so that we can make an educated decision on which system will benefit the building and community the most. Members of the group have also used Revit to analyze the building and determine which small term fixes are going to be the most beneficial in terms of both energy efficiency and livability. Lastly, the group has researched the guidelines for the LEED®

certification of an existing building in order to see what it would take for a building such as Kaven Hall to be brought up to code.

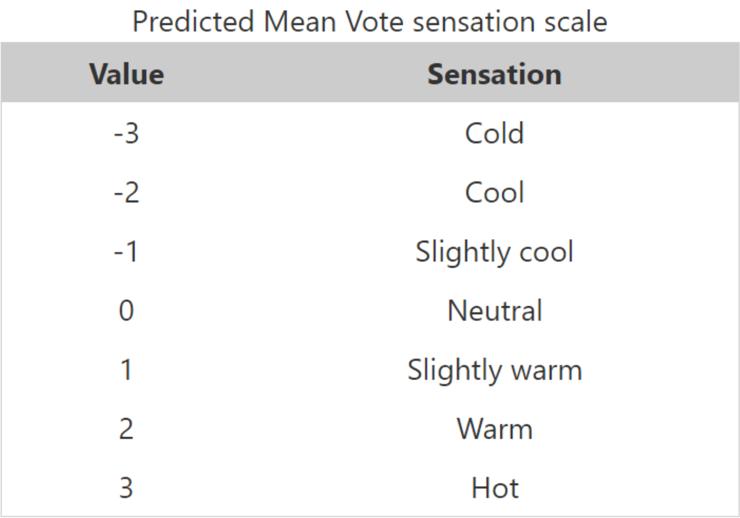
4 Results and Analysis

4.1 Introduction

This chapter details all of the results the project team gathered from research, interviews, and utilizing data gathering instruments. The section starts with data from the temperature data loggers, and then contains information found in Revit. The chapter contains information about HVAC sizing for Kaven Hall, data gathered from thermal imaging cameras, educational learning environments, and finally the project teams list and ranking of improvements that could be applied to Kaven Hall. Sections of this chapter may reference the appendix for further information and collected data.

4.2 Educational Learning Environments

Building climate plays an important role in the performance and health of its occupants. Using thermal comfort studies, the American Society for Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) has set standards for building climate that takes into account human thermoregulation in order to determine a suitable range of operation for any HVAC system [27]. Human thermoregulation calculations in the ASHRAE handbook take into account metabolic rate, clothing insulation, air temperature, air velocity, radiant temperature, and relative humidity. All of these variables have units, which are fairly well known and defined except for metabolic rate and clothing insulation. Human metabolic rate is measured as metabolic equivalents (MET) and one MET is defined as “the amount of oxygen consumed while sitting at rest and is equal to 3.5 ml O_2 per kg body weight x min” [26]. This concept is important because it has been used in estimates for thermoregulation, airflow rate and thermal load calculations. Clothing insulation units, Clo, represent insulation values added for each item of clothing. Clo values are similar to R-values (1 Clo = 0.88 R) that are used to describe insulation values in buildings. Generally accepted Clo values for various items of clothing are included in the ASHRAE handbook. These values are used throughout calculations and studies in order to define the set or average amount of clothing insulation worn by subjects play an important role. All of these variables in the performance and sensation of comfort for building occupants.



Predicted Mean Vote sensation scale

Value	Sensation
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
1	Slightly warm
2	Warm
3	Hot

Figure 9: Thermal Sensation Scale [24]

ASHRAE Standard 55 defines a thermal sensation scale used to gauge occupant comfort. This thermal sensation scale is continuous and runs from -3 to +3 with given integer values map to their sensations as shown in Figure 9. It’s recommended that a suitable range for occupants be between -0.5 and 0.5 on the thermal sensation scale while maintaining a total percent of people dissatisfied (PPD) with the climate below 10% [24]. The ASHRAE handbook does not try to give an answer in terms of temperature; instead, it gives thermoregulation calculations on how estimations should be derived and defers to studies in order to demonstrate effects of the climate variables of comfort, sensation, and performance. However, what they do explain demonstrates that building climate in offices and schools should be constant and set to optimize occupant performance.

Building climate has been studied extensively in order to optimize three factors: comfort, occupant performance, and monetary cost. One method of tracking these three factors is through building occupant complaint submission due to discomfort and Sick Building Syndrome (SBS) symptoms. The EPA describes SBS as a “catch-all” term for any reason an occupant may have for submitting a complaint about medical or bodily discomfort due to prolonged exposure in a building. Some symptoms of SBS include common complaints such as the following provided by the EPA [22]:

- irritation of the eyes, nose and throat
- headache
- stuffy nose
- mental fatigue
- lethargy
- skin irritation

These symptoms are obvious signs of discomfort, cause occupants to perform at below optimal levels, and increase the running cost of an HVAC system due to unscheduled maintenance triggered by occupant complaints [44]. Upon measuring SBS symptoms in the range of 19-24°C, it was found that the proportion of subjects reporting headache and fatigue increased from 10% at 20-21°C to over 60% at 24°C [28]. One study looked at occupant complaints from 690 commercial buildings and found that 96.5% of those complaints were at both ends of the comfort spectrum, below 21°C and above 24°C [20]. Another study by Pepler and Warner looked specifically at temperature as it applied to comfort and performance. They found that the temperature at which subjects were most comfortable (27°C) was also the temperature at which they exerted least effort and performed the least amount of work. Conversely at the temperature when subjects performed best (20°C) most felt uncomfortably cold [33]. Implementation of HVAC inside of Kaven Hall causes the temperature to rise steadily throughout the day leading to temperatures in the “red zone” (temperatures above 23-24°C), where a greater percentage of students may experience SBS symptoms and begin to exert less effort in compensation for the temperatures above the comfort zone for optimal performance.

Temperature and air flow have been the main focus of studies looking at performance of students in the classroom. Room temperature can effect students’ level of alertness and motivation while both temperature and air flow rate have a direct effect on student health and the prevalence of SBS symptoms. Ventilation rate in a room is directly correlated to the amount of airborne particles and the concentration of carbon dioxide (CO_2), directly measured in parts per million [32]. Studies run on school children in late summer looked at temperature and air flow rate independently of each other. The purpose of the study was to gauge students’ performance in classrooms with moderately raised temperatures and various outdoor airflow rates. Airflow rates were set using estimates of children’s metabolic rate in order to determine the amount of airflow needed to displace their carbon dioxide production. Split air units were used to keep the temperature at around 20°C. Natural summer heating of the building was used to keep the classroom at the lower reference temperature, which they expected to be around 25°C. However, due to opening of windows and doors at rates higher than predicted, the average temperature in the room at the higher temperature averaged around 23.6°C. Despite this moderate difference in temperatures, the study still found statistically significant improvements in student performance between the two room conditions. Performance was measured by giving students eight different tasks in mathematics, logical reasoning, and reading. Experimenters gathered data on student completion time and error rate for each task.

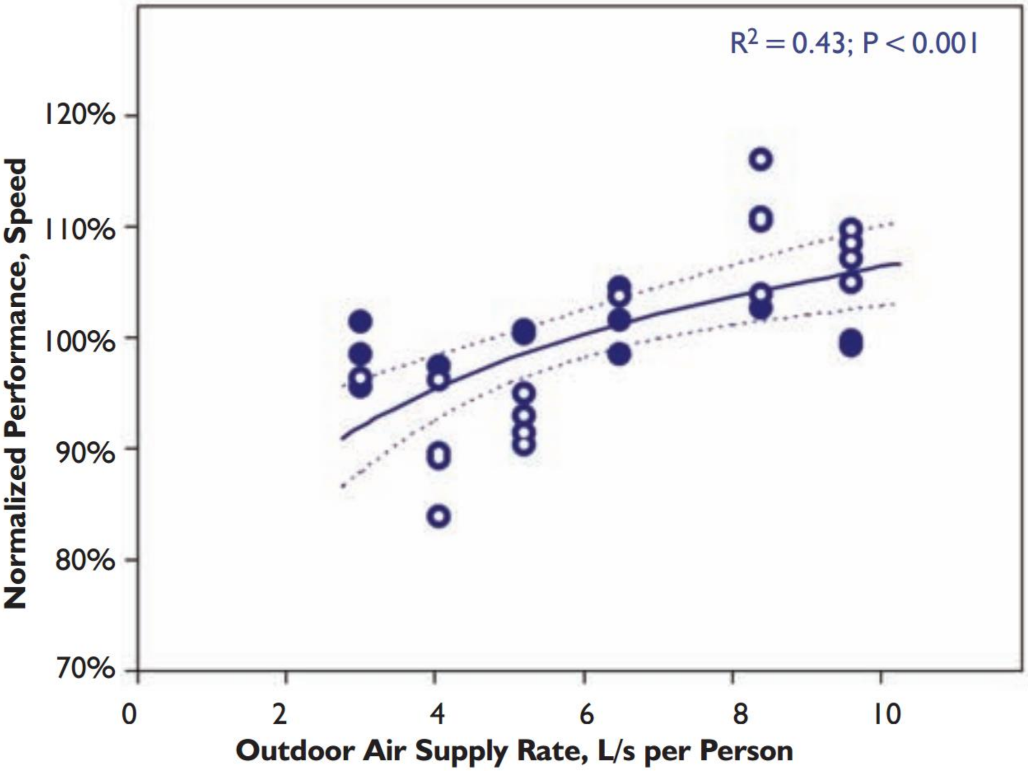


Figure 10: Performance of schoolwork as a function of outdoor air supply rate [17]

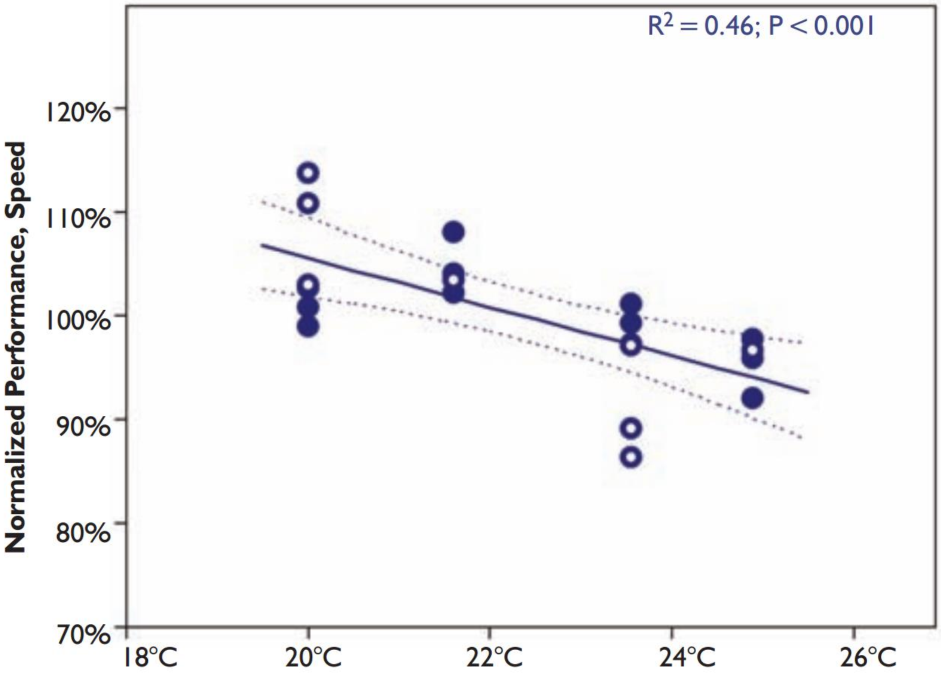


Figure 11: Performance of schoolwork as a function of classroom temperature [17]

Figures 10 and 11, from a report on the effects of HVAC on student performance, show student performance as a function of outdoor air supply rate and temperature respectively. The y-axis on both graphs shows the performance of students in terms of speed, where 100% is their average performance rate. This means that at any point below 100%, students are performing below average and any point above 100% students are performing above average. Therefore Figure 10, shows that student performance increases with increasing outdoor air supply rate and Figure *11* shows that student performance increases with decreasing classroom temperature. No significant changes in performance in terms of error rate were found. These results suggest that doubling a low outdoor air supply rate (below 5 L/s per person) would improve the performance of schoolwork in terms of speed by about 8% and student speed performance increases by about 2% for every reduction in degree Celsius in the range of 20°C to 26°C [29]. Therefore, decreasing classroom temperatures and increasing outdoor air supply rate is correlated to speed improvements in student performance. Furthermore, when surveying students in one of the experiments, it was found students exhibited a lower rate of SBS symptoms at the lower temperature. In the same experiment it was found that "children's thermal sensation decreased from slightly too warm to neutral" [32]. In the study, a panel of adults was used to survey the condition of each room. It was found that they reported the room air quality to be significantly fresher and more acceptable at the lower air temperature and found the similar results in rooms with higher outdoor air supply rates [32]. Overall findings in this study suggests that lower room temperatures and higher outdoor air supply rates helps improve student performance in terms of speed by decreasing the prevalence of SBS symptoms and increasing student attentiveness. These findings are relevant to college classrooms and should be used as part of a guideline for the derivation of an optimal building climate.

However, the previous study looked at schoolchildren, 11 to 12-year olds who are estimated to have a higher average metabolic rate in the classroom due to increased amounts of activity both between and during lessons [32]. The study assumed that the metabolic rate of children was about 1.7 MET due to the higher activity rate mentioned and because the production rate of CO_2 by children in the experiments was found to be similar to what is produced by adults [32]. 1.7 met is 40% higher than the metabolic rate for adults is offices but about the same as that of students working a laboratory (1.6 MET) [32] [30].

Maintaining a building condition that maximizes the percentage of people satisfied with the climate will optimize the performance of workers and show a return on investment not typically included in the price of an HVAC system. Unsolicited office building complaints from occupants can cause unscheduled maintenance actions depending on the policies of the facility authorities [35]. Should these complaints not be minimized, the building may be performing below optimal levels and even missing days due to SBS symptoms. A 2006 study aimed to quantify the cost of performance increases and maintenance cost decreases from the installation of HVAC systems by gathering data on 24 relevant studies on the effects of HVAC systems on office work. They state that “potential health and productivity benefits are not yet generally considered in conventional economic calculations pertaining to building operation and design”, which is, today, more relevant to renovations on older buildings such as Kaven Hall [35]. The study compiled performance data on office workers from 24 studies and normalized the data, adding weights for precision, data set size and relevance to real world work. In the studies observed the ventilation rate, was constant.

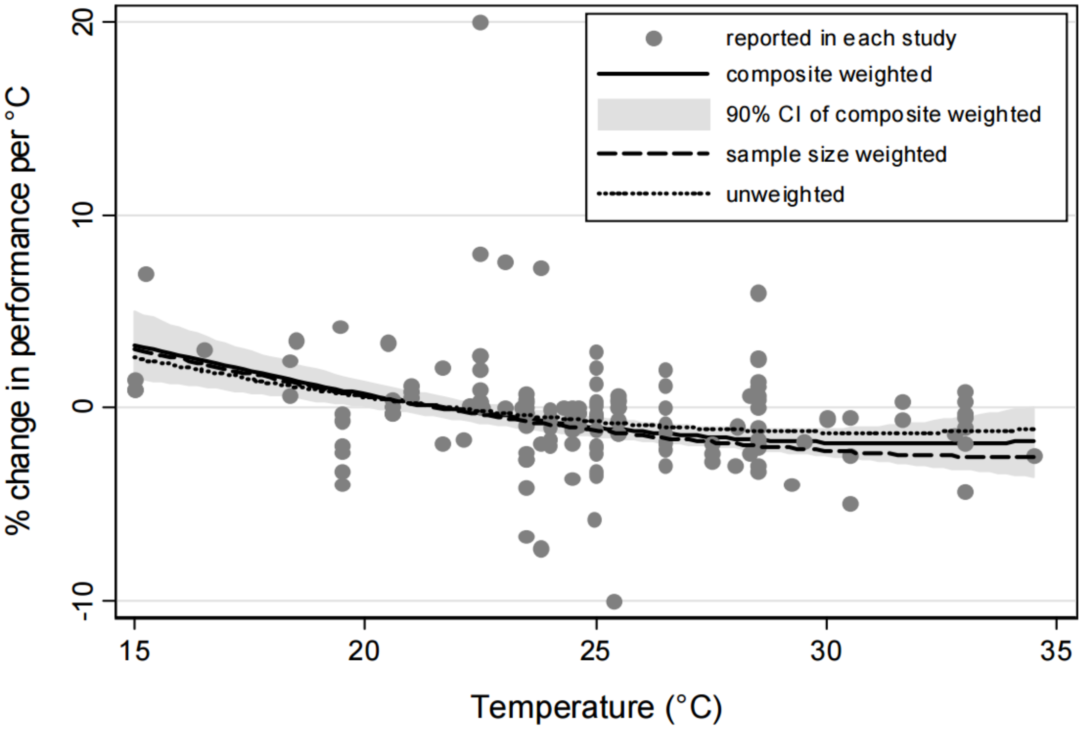


Figure 12: Percentage Change in Performance vs Temperature [35]

Figure 12 is a graphical summary of the results, showing raw data points from each study and the various weighted and unweighted regression lines. This figure shows the percentage change in performance as a function of temperature. Positive y-values are interpreted as positive percent changes in performance and negative values represent a negative percent change in performance per degree Celsius. The confidence interval (grey shaded section) shows a positive change in performance per degree Celsius up to 20°C. This means that up to 21°C, an increase in temperature is associated with a statistically significant improvement in performance and above 24°C increases in temperature are associated with a statistically significant decrease in performance. In other words, performance of workers in these studies increase with temperature up to 21-22°C and decreases with temperatures above 23-24°C [35].

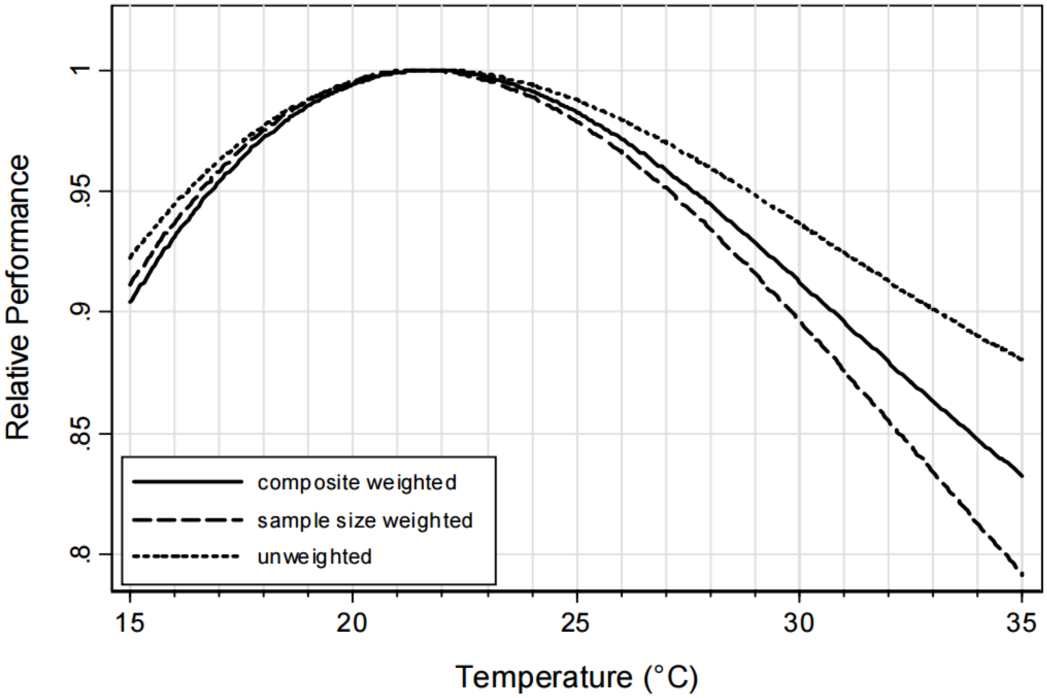


Figure 13: Normalized Performance vs Temperature [35]

From this data, the researchers conducting this study derived a graph of the percent deviation of worker performance, relative to the optimal, per degree Celsius, shown in Figure 13. This figure shows a peak work performance at 21.75°C. Deviations from optimal on both sides of that point show a certain percent decrease in performance relative to the peak performance. “For example, at the temperature of 30°C the performance is only 91.1% of the maximum at 21.75°C, i.e. the reduction in performance is 8.9%” [35]. Overall, this means that, for the studies observed in this report, workers’ performance peak at 21.75°C but no statistically significant performance differences in the range of 20-23°C.

Realistically, one can imagine any facility will be looking to optimize their worker performance alongside the operating cost of their HVAC system. One factor that may impact the setting of a climate controlled building is the seasonal change of occupant temperature preference. It has been found that the indoor temperature of occupant comfort varies with average outdoor temperature. One study analyzed at this effect took gathered data from an ASHRAE database on thermal comfort studies. First off a comfort model was created using thermal load calculations to render a lab-based Predicted Mean Vote (PMV) model. A PMV index is a function that predicts the mean comfort response of a large group of people by taking into account metabolic rate and thermal loads of building occupants. From this the Predicted Percentage Dissatisfied (PPD) index can be derived in order to create an indoor comfort model.

To test the results of the model 21,000 sets of raw data from 160 different office buildings had to be normalized before aggregating it for analysis. This was accomplished by applying “standardized data processing techniques, such as methods for calculating clo and various comfort indices, were then applied consistently across the entire database” [13].

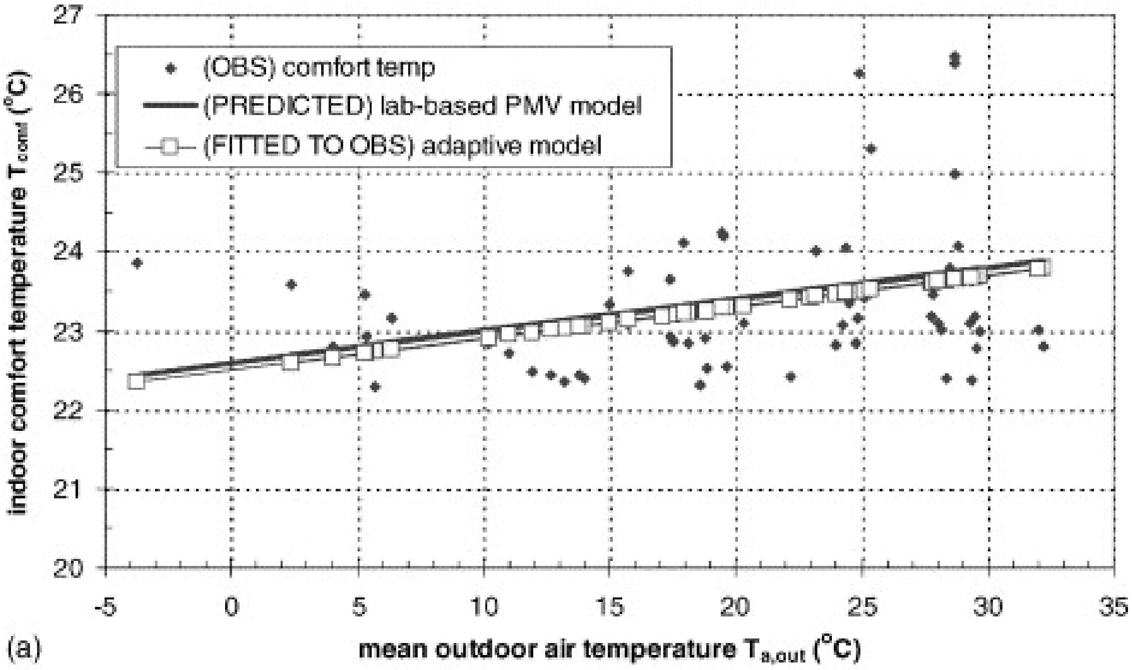


Figure 14: Indoor Comfort Temperature vs Mean Outdoor Temperature [13]

Figure 14 shows the resulting regression line fitted to the observations matching up to the predicted comfort model. This shows that the comfort of building occupants changes as a function of average outdoor temperature. In other words, when it’s colder outside people feel comfortable with a cooler indoor temperature and when it’s hotter outside people feel more comfortable with warmer indoor temperatures. Although this is only a comfort model, which has been established to be separate and different from a performance model, it can be used as a baseline for including economic concerns in the setting of an indoor climate for an academic building. It would not be unreasonable to assume that an indoor temperature optimal for occupant performance follows a similar path when mapped to average outdoor temperature.

As of spring 2016, Kaven Hall is using an unstable mix of heating and cooling systems. The main heating used throughout the building are steam radiators. It has been observed by members of the WPI community, including this project team and the facilities staff, that these radiators are regularly unstable for various reasons, which leads to rooms overheating. This means occupants must open windows in order to cool the room back to a comfortable level. Opening windows has the adverse effect of creating a thermal gradient in the room, which leaves students closer to the windows colder than those near the window for the duration of their opening. That means the room is uncomfortable for the time the temperature rises above around 75°F until the time the window is opened and for the duration they are open until the temperature levels off. For a 50-minute class period, just 10 minutes of uncomfortable or unstable temperature in a room means that 20% of the day's class is non-optimal for learning. The impact of uncomfortable building climates on its occupants continues to be studied by organizations such as ASHRAE.

4.3 Temperature Logger Data

The following charts are temperature logs, measured in degrees Fahrenheit, of three rooms in Kaven Hall. The first two rooms are Kaven Hall 115 and 116, which are both commonly used classrooms on the first floor. The last room is Kaven Hall 203, which is a computer lab on the second floor. To record the data, the project team placed temperature data loggers in the center each room taped under desks. We verified that the thermostats for the steam radiators located in each room were set to 72 degrees Fahrenheit.

After analyzing both the graphs of the outdoor temperatures and inside temperatures, the team determined that there seemed to be a correlation between higher outside temperatures and high temperatures inside Kaven Hall, which is what we expected to find. On March 31st and April 1st, the temperatures outside tended to be above 60 degrees Fahrenheit, almost reaching 70 degrees Fahrenheit at one point. On those days, the rooms in Kaven Hall reached temperatures upwards of 80 degrees Fahrenheit. This was far too warm and could be attributed to several potential factors. The first of these is the heating system still actively heating the rooms. In several rooms, the project team could feel heat coming out of the radiators. The second factor is faulty steam valves on the radiators. The steam system may have been off, however, if a radiator steam valve had malfunctioned, it would continue to heat the room at full power. Lastly, the control systems themselves could be broken or opposing each other. The climate control systems within Kaven Hall are not connected, which means that both systems could be on, trying to both heat and cool the building at the same time. Figures 15 through 18 compare the outside temperatures with the temperatures collected inside various rooms in Kaven Hall, while Figures 19 and 20 detail average temperatures in Kaven Hall on a school day.

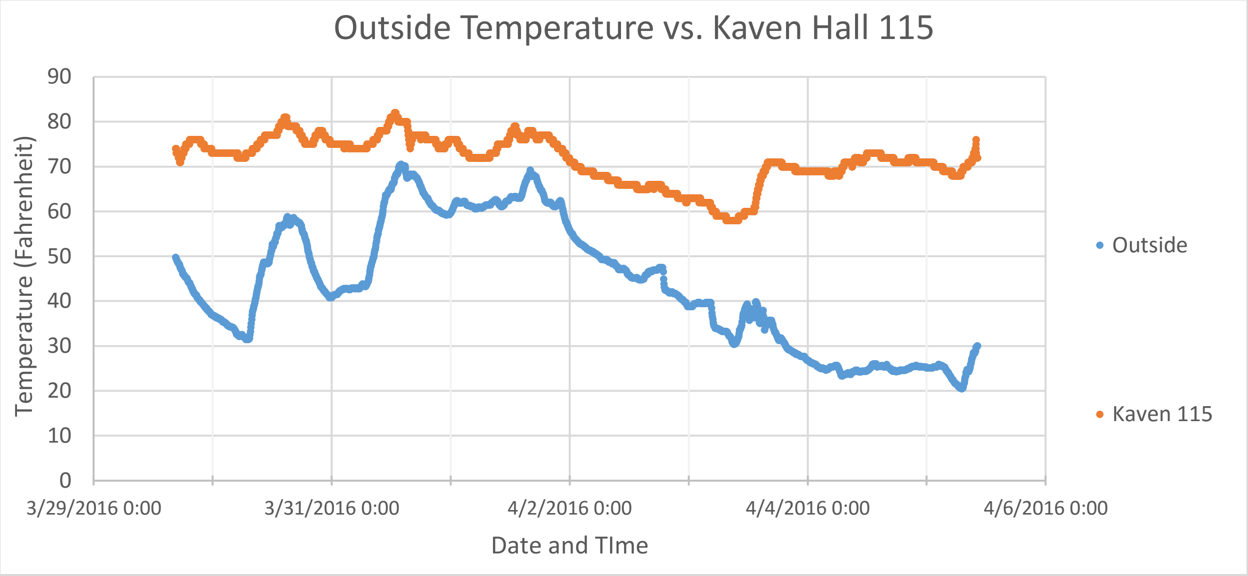


Figure 15: Comparison Outside Temperature vs KH115

Figure 15 details a comparison graph between the outside temperatures and the inside temperatures of Kaven Hall room 115. As the outside temperatures increase and decrease, the temperatures inside also rise and fall in a similar fashion. The inside climate does not rise and fall as severely as the outside, due to the heating and cooling systems in place. Inside, the room is getting much too warm even though the temperature was set to 72 degrees Fahrenheit, reaching 83 degrees on two different school days. On the weekend, the room dropped to 57 degrees Fahrenheit, which could possibly be attributed to an open window.

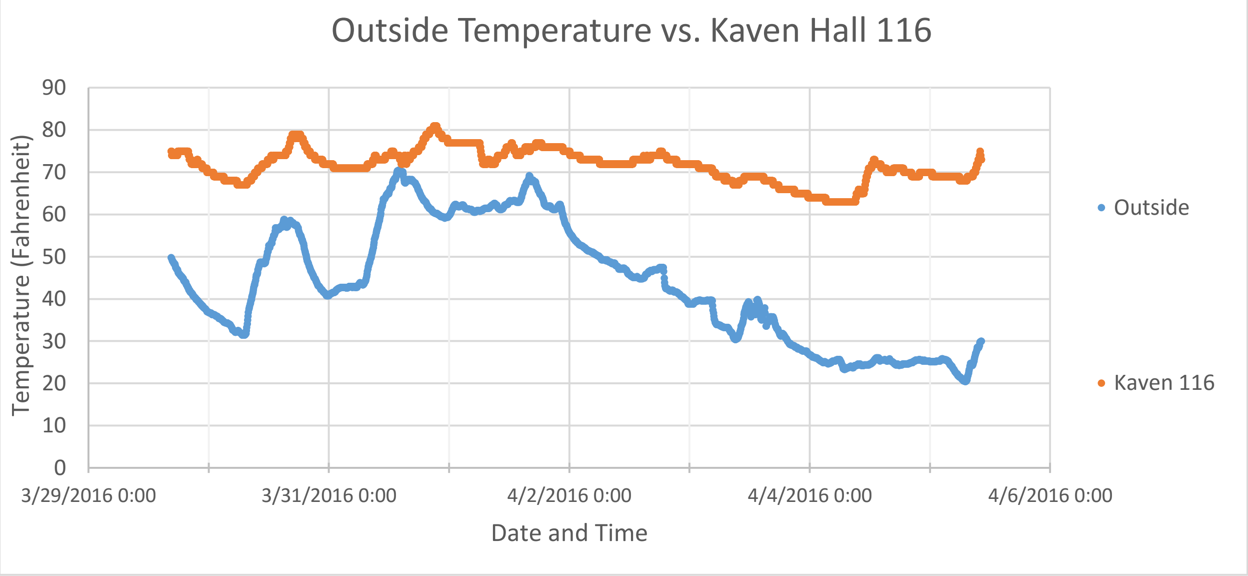


Figure 16: Comparison Outside Temperature vs. KH116

Figure 16 compares the outside temperatures and the inside temperatures of Kaven Hall room 116. There are several times when the inside temperature correlates to the outside temperature. This first is when the temperature outside decreases, the temperature inside Kaven 116 also decreases. The second is between March 30th and April 2nd and this section shows similar rising and falling between the inside and outside temperatures. The room reached temperatures between 67 and 81 degrees Fahrenheit, depending on the time of day. During class times, the temperature seemed to be between 71 and 73 degrees Fahrenheit. The temperature rose as the early evening and night came. The system overheats the room at night when it is not being utilized. The weekend temperatures were between 63 and 70 degrees Fahrenheit, which are reasonable temperatures for those times.

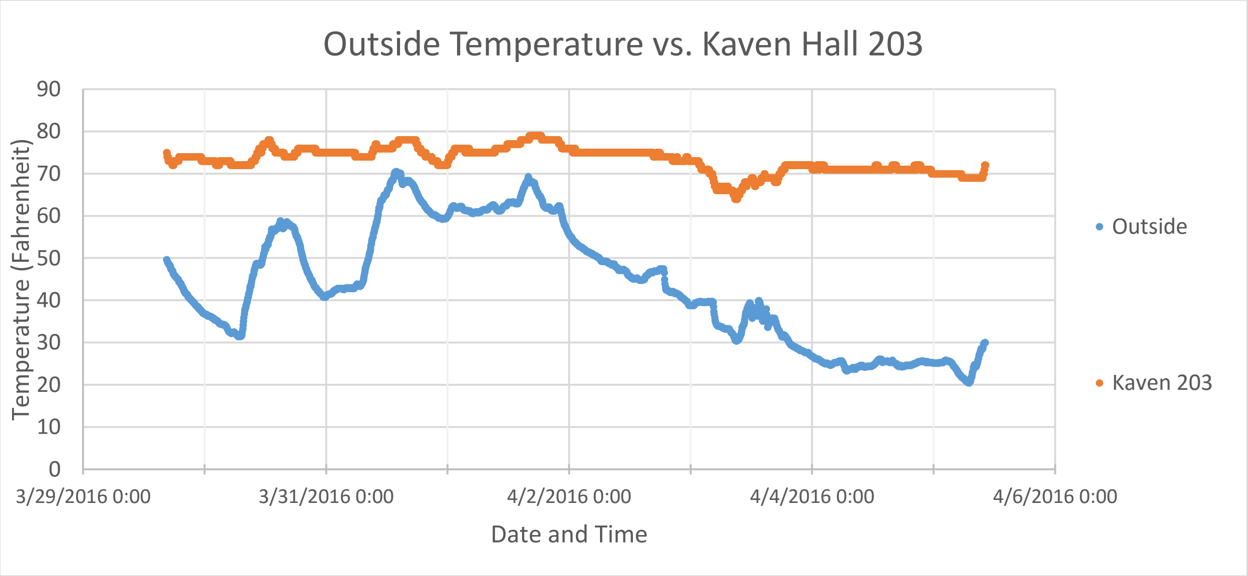


Figure 17: Comparison Outside Temperature vs KH203

Figure 17 details a comparison graph between the outside temperatures and the inside temperatures of Kaven Hall room 203. This graph shows little correlation between the two temperatures. This may be attributed to the room being a computer lab and having a more controlled heating and cooling system. The room varied in temperature, but tended to remain above 72 degrees Fahrenheit. During the day, the room would reach temperatures upwards of 78 to 80 degrees Fahrenheit, which is far too warm for students. On the weekend, the temperature dipped down 64 degrees, though this has less of an impact as the room is not often utilized over the weekend.

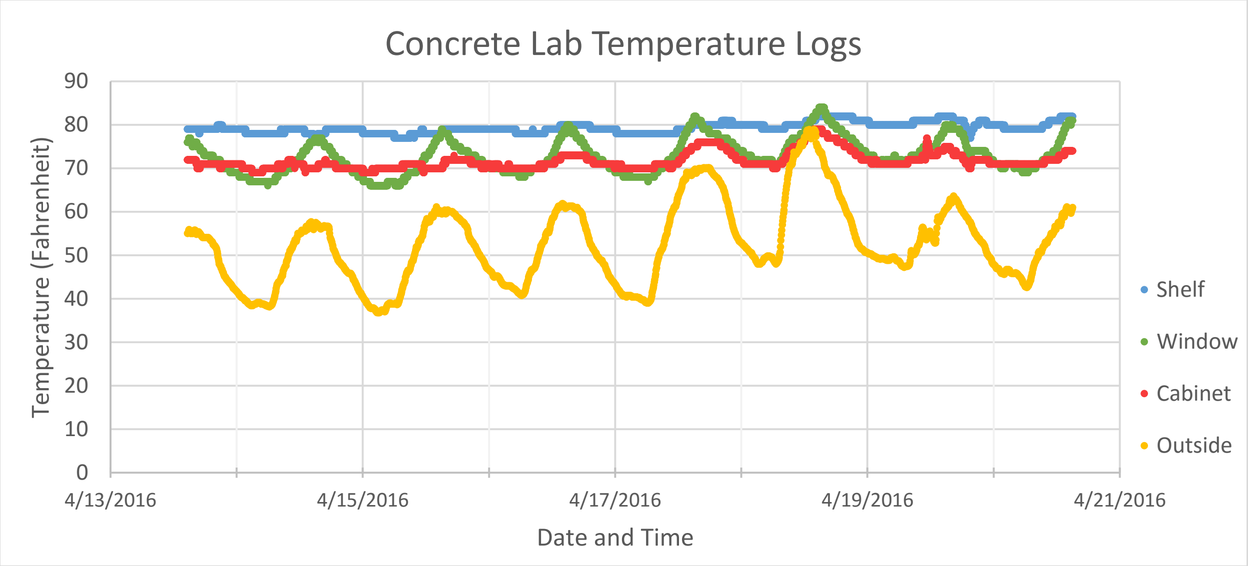


Figure 18: Comparison Outside Temperature vs Concrete Lab

Figure 18 details the three temperature data loggers that were placed in the Concrete Lab of Kaven Hall, located in the basement. The logger that was located on the shelf was the most consistent temperature of the three loggers and tended to stay between 78 and 82 degrees Fahrenheit. This is exceptionally warm, however it is consistent and could possibly be adjusting with the control system. The second logger was placed near a window within the Concrete Lab. This logger was consistent with the large temperature gradient that occurred everyday around the same time. The gradient followed the same fashion as the outside temperature, reaching a peak around 4pm each day, possibly indicating an inefficient window. The last logger was placed on a cabinet inside the Concrete Lab near the garage door that opens periodically. This logger consistently had a temperature gradient that was smaller than the second logger, however could also be attributed to inefficient windows, the garage door, or an inefficient temperature control in that area.

Before applying the findings of building climate research to Kaven hall data needed to be collected in order to assess the building's status in terms of temperature. Kaven Hall is a mix of classrooms, computer laboratories, materials laboratories, offices, and meeting/work spaces. It was decided to focus on classrooms and labs as those are the non-optional learning areas where students are given lessons and examinations. Analysis of Kaven Hall's temperature data was split by room type. Starting with classrooms, one temperature logger was placed in three separate rooms: Kaven Hall 115, 116, and 203. Those loggers were left to collect temperatures for one week. Weekends and nights were excluded from the analysis since undergraduate students do not have classes scheduled in those classrooms during those periods. Each day at WPI the undergraduate schedule is split into nine 50-minute class periods starting at 8:00AM and ending at 4:50PM. Lessons and exams end promptly at the 50th minute of the period to allow students time to reach their next class should they have one. This means that the important temperature sections to examine are those 50-minute periods. The temperature for each 50-minute period was averaged, and then these values were averaged over the school days we collected data. This resulted in 9 data points, with one for each class period. These temperatures alone meant nothing without a baseline acceptable temperature. Research suggests that for students in a classroom, an acceptable temperature range for optimal work performance is 70-73.4°F or about 71.15°F (see section 4.2). A temperature line of 71.15°F was added to the table for comparison. The compiled data resulted in the graph shown in Figure 19.

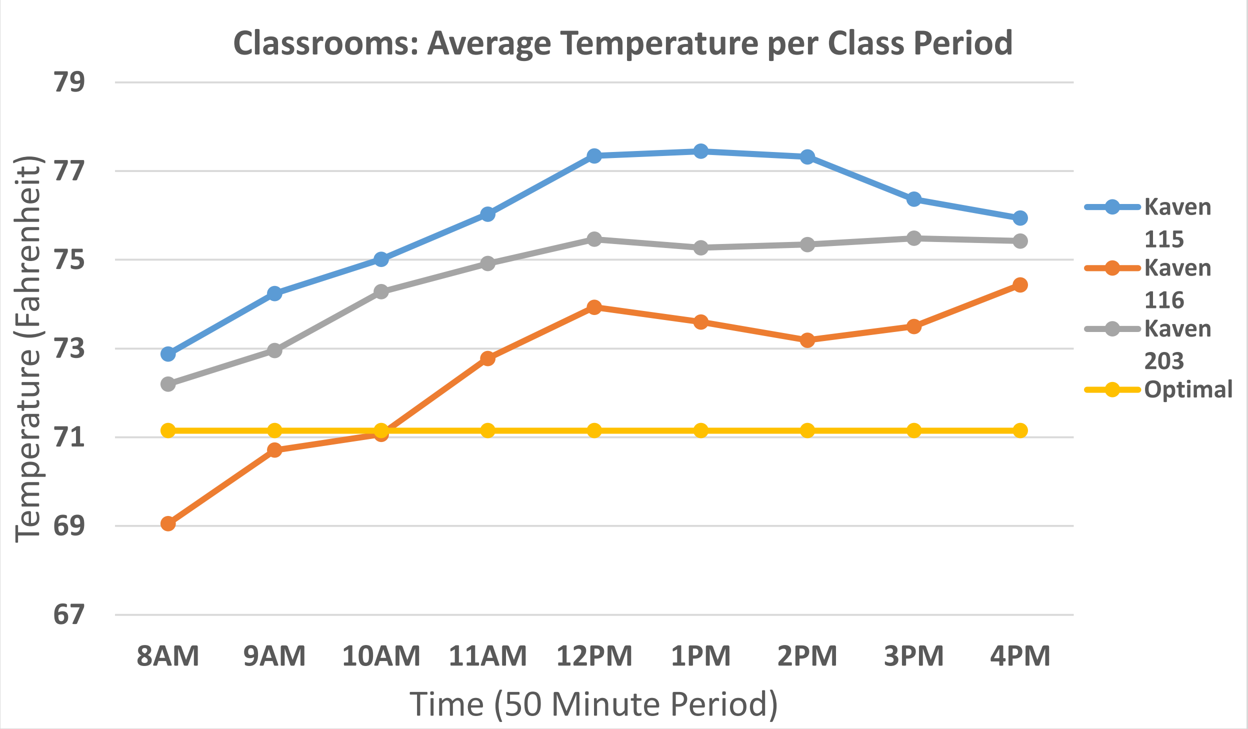


Figure 19: Average Temperatures in Kaven Hall's Classrooms

Figure 19 shows that there is a general trend for temperature in each classroom to rise throughout the day. A visual analysis shows that there are only one or two periods in the morning where the temperature in any of the three classrooms is within two degrees Fahrenheit of the set optimal temperature. Any change of more than three degrees Fahrenheit from the optimal may result in a statistically significant deviation from optimal performance [2]. Another notable fact is that the temperature averages are mostly above the optimal, where Sick Building Syndrome (SBS) Symptoms tend to be more prevalent [5]. The same methods described above were used to compile a graph of the temperatures in Kaven Hall's Concrete Lab. However, students in the lab are rarely sitting or at rest, instead they are physically engaged in their work. This higher level of activity means their metabolic rate is higher (~1.6 MET) and thus requires a lower working temperature of about 68°F [14].

Figure 20 shows the temperatures at three points within the Concrete Lab. Average temperatures in the concrete lab never cross or even come within 3°F of the optimal line. There are some interesting trends to point out in this graph. For example, the window is consistently a high 79°F+ while the shelf, right across the room from the window, tends to approach that temperature by the end of the day. The cabinet, located in a separate room on the lab, on average maintains a constant lower 72°F despite being nearest an outside door. An in-depth, room-by-room analysis of Kaven Hall might look at each classroom's temperature and activity level over a longer period in order to begin examining possible changes to improve that micro-environment. In the end a holistic analysis may be conducted to determine if any changes can be made to Kaven Hall as a whole (i.e. HVAC upgrades, windows upgrades etc.). However, the purpose of the experiment was to create an argument as to the necessity for more in-depth analyses to be conducted so Kaven Hall may begin to improve.

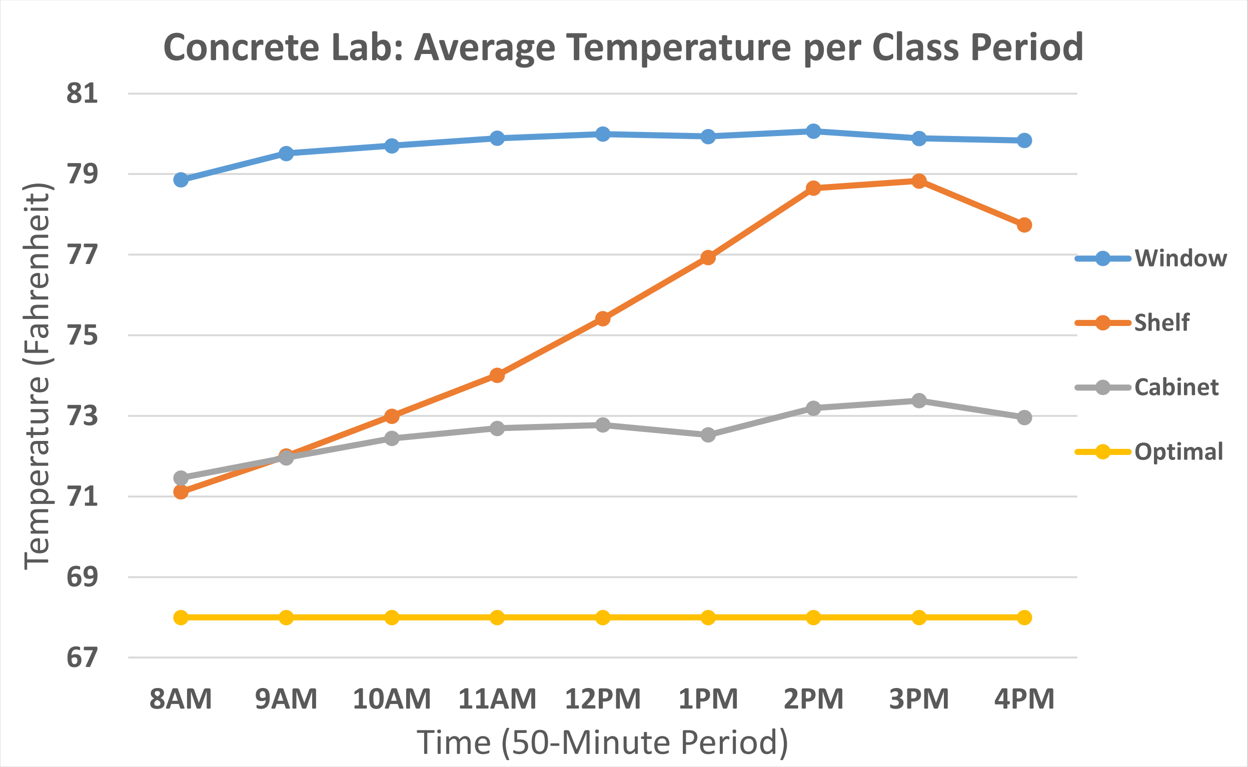


Figure 20: Average Temperatures in Kaven Hall's Concrete Lab

The data presented in this section show that three rooms in Kaven Hall and the concrete lab overheat during the day. When the temperature outside is warmer, the inside temperature tends to be warmer. The temperature gradient near the window and near the garage door on top of the cabinet consistently have large changes in temperature every day. The temperature gradients and overheating show that Kaven Hall is unable to create a consistent and adequate learning environment.

4.4 Thermal Imaging Data

Figures 21 through 24 contain infrared pictures that were taken on various dates at Kaven Hall to analyze heat loss in the building as well as normal pictures to compare the thermal images too. A description follows each figure, with each description explaining the issues with the building that its figure highlights. Thermal pictures were also taken around the Campus Center to compare newer systems to the older fixtures in Kaven Hall.

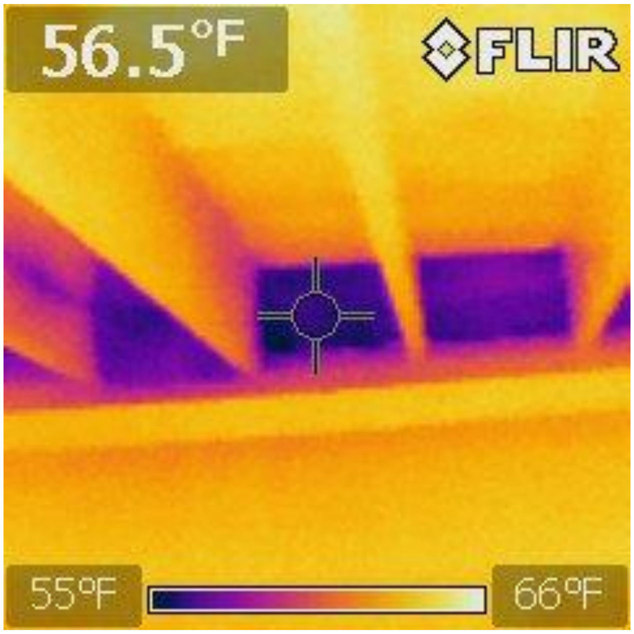


Figure 21: Attic of Kaven Hall Brick Edge (Thermal)

Figure 22: Attic of Kaven Hall Brick Edge

Figure 21 details the thermal energy of the ceiling in the Kaven Hall attic. This image shows the edge where the exterior brick meets the ceiling specifically. In this building the ceiling has no insulation, though the 16” thick concrete floor provides some insulation from the rest of the building. The image shows the ceiling being warm at a temperature around 63 degrees Fahrenheit. There is a difference of about 10 degrees Fahrenheit between the brick edge and the ceiling, which indicates the exterior brick walls have a lower insulation value than the ceiling. In addition, there were several holes in the brick wall that would allow for airflow. These holes and the lack of insulating value provided by the brick allows for heat to escape from the attic. Figure 22 shows a similar area to where the thermal picture was taken.

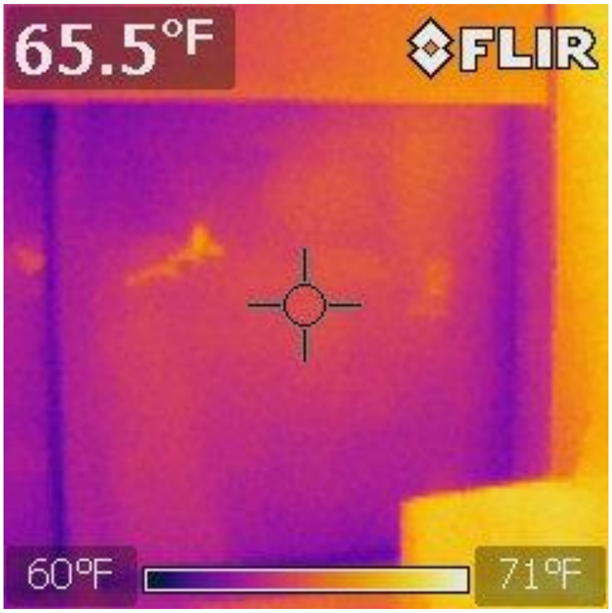


Figure 23: Inside Campus Center Window

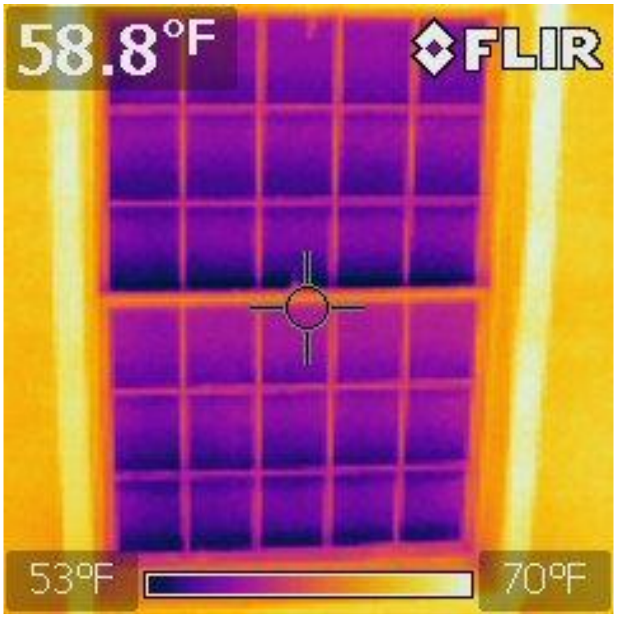


Figure 24: Inside Kaven Hall Window

Figure 23 shows a window in the Campus Center. The windows in this building leak only a little amount of heat around the edges and the windowpane itself. Figure 24 shows a window in Kaven Hall. This older style of window is markedly less efficient at containing thermal energy than its newer counterpart in the Campus Center. The single panes of glass all are leaking a significant amount of heat, and the edges all have a cold draft from the outside. Newer windows like those shown in Figure 23 leak hardly any heat through the panes and significantly less through the edges of the window itself. This comparison was also made for doors of both the Campus Center and Kaven Hall. This can be found in Appendix E, along with other thermal pictures of Kaven hall which detail the attic, roof, and other various sections throughout the building.

4.5 Revit Results

After receiving the Revit model of Kaven Hall, we looked over it to ensure that it contained all of the detail we would find necessary for doing an energy analysis. We were specifically looking for the sizing and placement of windows, and doors, as well as the overall geometry of the building. The Revit model we received was an accurate representation of the interior of the building as well as all windows on the first and second floors of Kaven Hall, but was missing all of the windows on the basement floor, as seen in Figure 25.

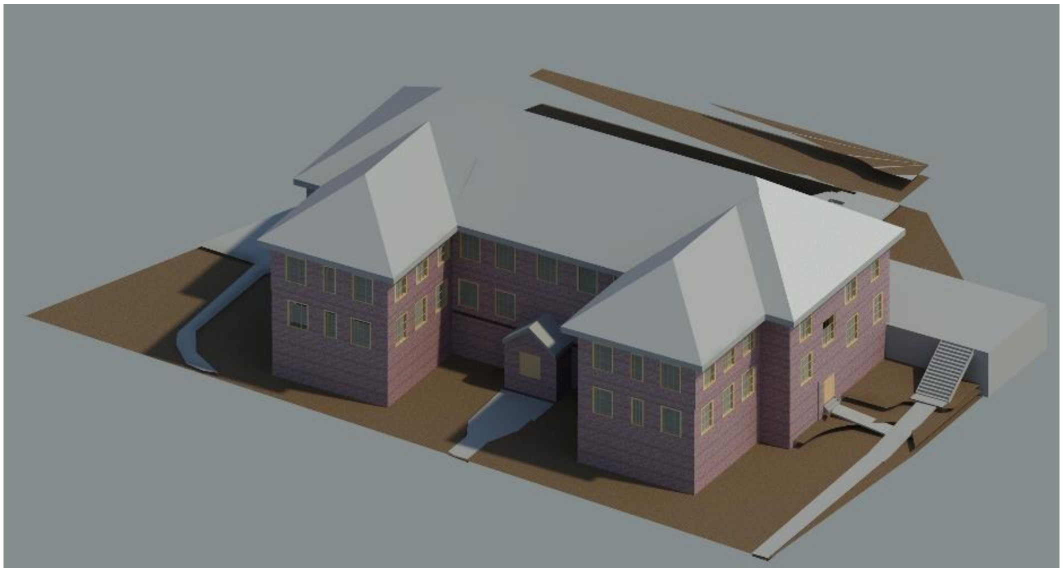


Figure 25: Render of the Revit Model as received

As windows play an important role in energy simulations, the group decided to add the missing windows to the model. We used the original construction blueprints, as well as measurements of the windows (taken on site) to update the model. The group added a total of 36 windows located on the basement floor of Kaven Hall to the model as seen in Figure 26. With the windows added to the model, we were ready to perform an energy analysis.

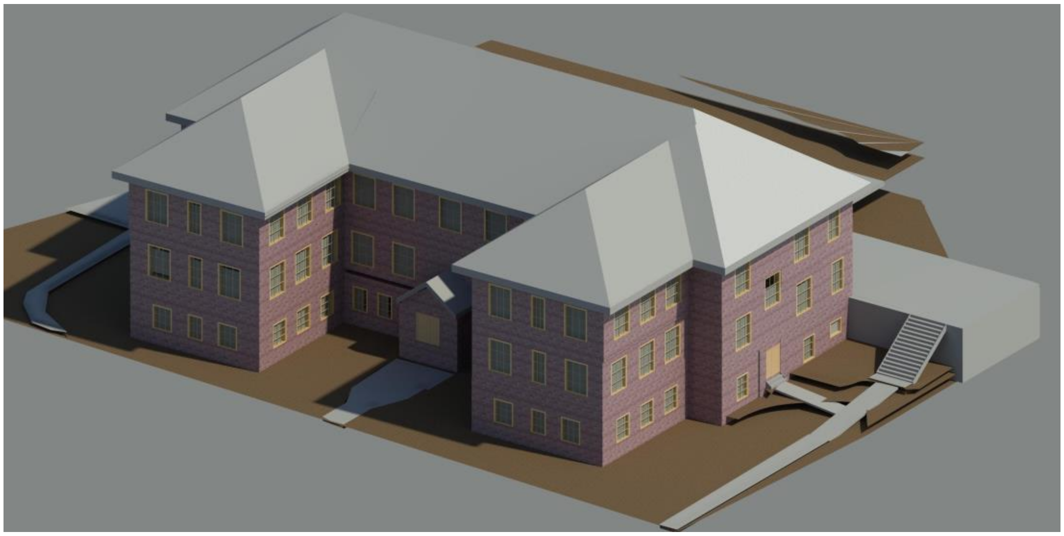


Figure 26: Render of Kaven Hall after windows were added to the Revit model

The 36 windows joined the 80 windows already in the model for a total of 116 windows that are in Kaven Hall. The windows on the building are a variety of different sizes, ranging from 3’ 9” wide to 7’ wide, and between 3’ 9” tall to 7’ tall. The windows and their respective sizes can be seen in Table 2.

Table 2: Window size and quantity in Kaven Hall

Number of windows	Width (inches)	Height (inches)
1	52	45
2	52	70
7	60	70
8	52	84
13	60	84
24	45	70
55	84	84

The project team then created an energy model from the structural model of Kaven Hall, which can be seen in Figure 27. At this point, we ran into an issue with the integration between Revit and Green Building Studio (GBS) where Revit cannot confirm that a student Autodesk account has a subscription to Green Building Studio. This seems to be a common issue that has not been fully worked out with Autodesk’s databases. We were able to work around this issue by exporting the energy model to a gbXML file that could be imported in GBS.

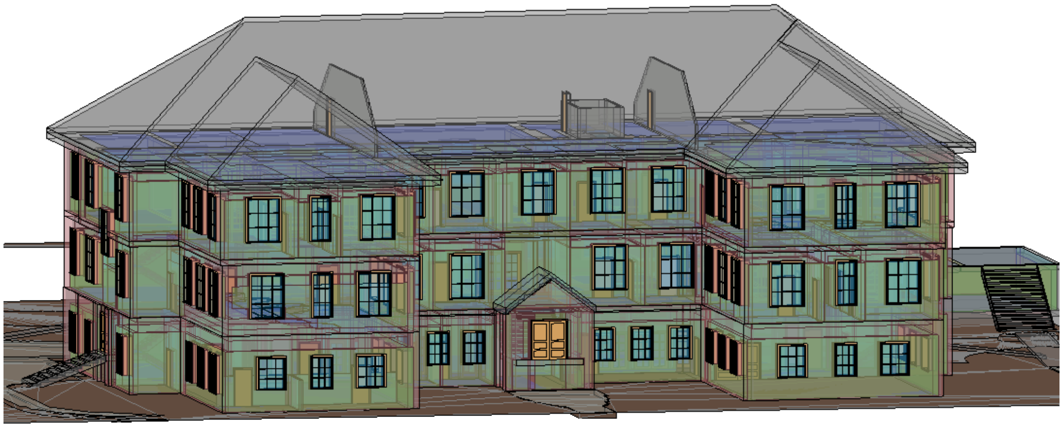


Figure 27: Energy Model created in Revit from the structure

Before running the energy analysis, the group specified a number of settings for the model to more accurately resemble the current state of Kaven Hall. We were careful to specify the usage of Single Pane windows based on the information gathered in Section 4.4 Thermal Imaging Data. It was also important that we accurately set the type of heating and cooling utilized by the building, as this would have a large effect on the amount of electricity and fuel used by the building. Green Building Studio does not provide the ability to specify the heating and cooling per room, but most rooms in the building are heated with campus steam through radiators. Additionally, the building is cooled almost exclusively with window A/C units. We found that the most accurate option utilized an Energy Efficiency Ratio (EER) value of 9.5. This value was calculated from the currently installed AC units in Kaven hall. While not all AC units were installed in the building at the time of our walk through, we believe that the two models listed in Table 3 are representative of the AC units installed in Kaven Hall.

Table 3: Air Conditioning Models Used In Kaven Hall

AC Model	**Voltage**	**Amperage**	**Watts**	**BTU**	**EER (calculated)**	**EER (Rated)**
KM18L30-A	230	8	1840	17600	9.57	10
AHM18DPT1	230	8.1	1860	18350	9.87	10.7

As performing hand calculations for the thermal load of the building is outside of the scope of this project, we have chosen not to verify the accuracy of the results of the simulation. The results are thus being used for comparing the relative benefits of different improvements that could be made to the building.

The base Energy Analysis run estimated that Kaven Hall uses 462,757 KWhs of electricity and 51,751 Therms of fuel annually as seen in Table 4. The base run with the estimated electricity and fuel usage can be found along with the difference from the base run for some of the important alternative runs. This estimate assumes that the walls have an R-value of 20. While we were able to verify the absence of insulation in the attic of Kaven Hall, we could not verify the composition of the walls to determine their R-value. As we were also unable to verify the electricity and fuel consumption, the difference in energy usage from the base run is more useful in our analysis.

Table 4: Energy Usage of Base Run Compared to Alternative Runs

Title	Annual Electricity Cost ($)	Annual Fuel Cost ($)	Annual Electricity Use (KWh)	Annual Fuel Use (Therms)	EUI
Kaven Hall	62935	19666	462757	51751	193.84
Kaven Hall Double Low Emissivity Window	-2019	-1652	-14842	-4348	-13.93
Kaven Hall Triple Low Emissivity Window	-3758	-1906	-27635	-5015	-17.10
Kaven Hall Quad Low Emissivity Window	-3600	-2146	-26469	-5648	-18.80
Kaven Hall High Eff. Heat Pump	+33084	-18154	+243264	-47775	-113.29
Kaven Hall Infiltration 3.5 Air Changes per Hour	+9647	+8111	+70937	+21346	+68.21

More detailed results from the base run and all alternative runs can be found in Appendix D. These results compare annual electricity cost, fuel cost, electricity usage, fuel usage, and EUI (Energy Usage Intensity) for each alternative run to the base run. The annual electricity usage, fuel usage, and EUI are colored on a scale from red to green based on the magnitude of the difference from baseline, e.g. the largest reduction will be the greenest, the base run will be halfway between green and red, and the largest increase will be the most red. Each column is colored based on this scale, while the table is only sorted by EUI.

The group looked at replacing the windows in Kaven Hall as a major source of energy efficiency improvement. There were a number of different window options available, that were analyzed in the GBS energy analysis, including single, double, triple and quad paned windows. Each additional pane of glass reduced the EUI of the building as the higher insulation value decreases the amount of heating and cooling necessary. We are unsure of the exact reason that quad paned windows utilized more electricity than triple paned windows, but believe the higher insulating value limits natural cooling available in early spring and late fall resulting in higher cooling load during these times. The energy usage improvements can be seen in Table 4 which gives a clear view of the diminishing returns found in more efficient windows.

Green Building Studio also produces an EUI value for each run that is performed. This value serves as a good means of comparing each improvement as it takes into account both fuel usage and electricity consumption. Green Building Studio estimates an EUI of 193.8 for the base run, while the Energy Star notes a U.S. National Median EUI for Colleges of 130.7. While the EUI of the base run is only 63 higher than the national median, an alternative run that assumes the building allows 3.5 Air Changes per Hour (ACH), produce EUIs that are up to 68 higher than the base run. With such a large air flow into and out of the building, heating and cooling systems will have to work harder throughout the year to maintain temperatures in the building. This increases the gap to 131, which represents significantly worse building efficiency. The largest improvement to energy usage would be found by replacing the heating with a High Efficiency Heat Pump, based on the GBS simulation, such a change would bring the EUI down to 80. This and other improvements can be seen in Appendix D by looking at the entries with a negative EUI, and will be located below the Base Run in Appendix D.

4.6 HVAC Findings

HVAC commissioning for existing buildings was discovered to be a very in-depth process. It includes creating a commissioning team to do a site survey and draft up a plan for the HVAC system, as well as hiring a balancing agency and a contractor for the actual implementation of the system.

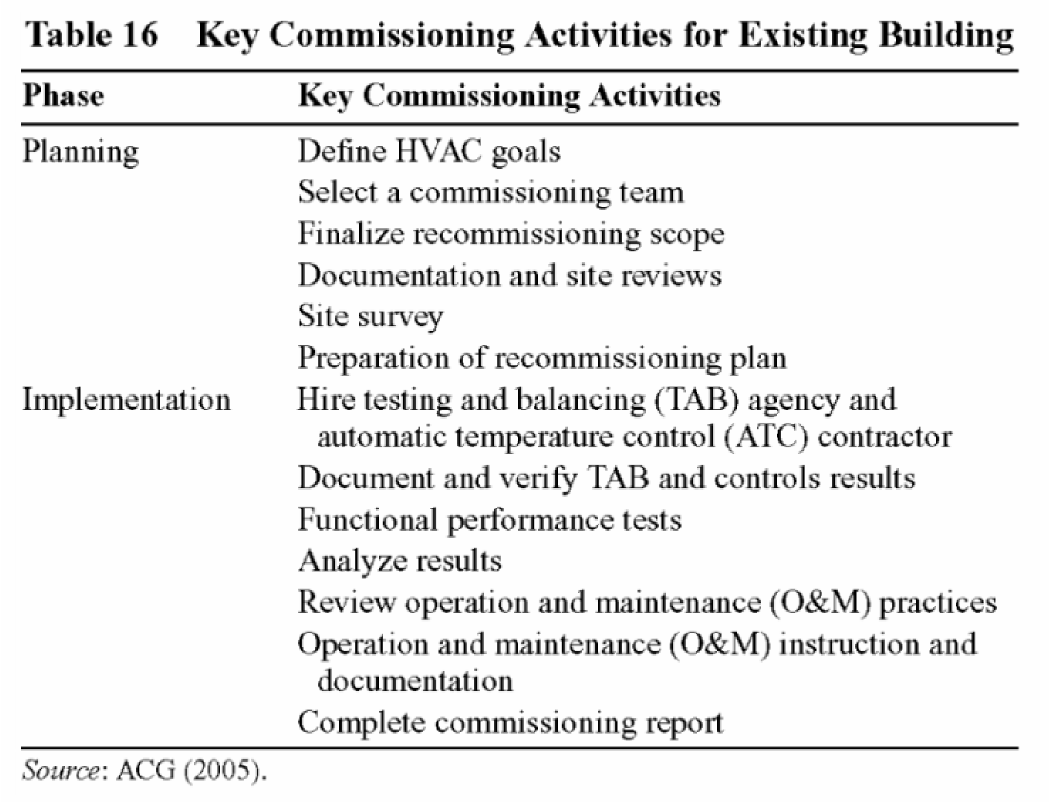


Table 16 Key Commissioning Activities for Existing Building

Phase	Key Commissioning Activities
Planning	Define HVAC goals
	Select a commissioning team
	Finalize recommissioning scope
	Documentation and site reviews
	Site survey
	Preparation of recommissioning plan
Implementation	Hire testing and balancing (TAB) agency and automatic temperature control (ATC) contractor
	Document and verify TAB and controls results
	Functional performance tests
	Analyze results
	Review operation and maintenance (O&M) practices
	Operation and maintenance (O&M) instruction and documentation
	Complete commissioning report

Source: ACG (2005).

Figure 28: Goals to plan a new HVAC system [2]

Pictured above is a table from the ASHRAE Handbook which details the various actions required to commission an HVAC system for an existing building [2]. The ASHRAE Handbook cites the 2005 ACG commissioning guideline here, but the Handbook has condensed the data available in the ACG commissioning guideline into an easy-to-view table. From the information available here, the team determined that it would be impossible to come up with our own plan for an HVAC system, as this is something that is normally done by a commissioning team, and was outside the scope of our project.

4.7 Evaluating Changes to Kaven

The following sub-sections contain details on the various changes that the group looked at for increasing the energy sustainability and the indoor climate of Kaven Hall. The group examined several different types of windows and doors that could be used to replace the current ones in Kaven Hall. The group also looked at solar shading solutions for the windows of the building, as well as the feasibility of reviewing and replacing broken or malfunctioning steam valves in the building on a regular basis. All pricing data in this section is based off of pricing data found directly in the 2016 RS Means Assembly Cost Data and Mechanical Cost Data books.

4.7.1 High-Performance Windows

High-performance or energy efficient windows are the most obvious change to be made to a building like Kaven Hall to increase the building's ability to support a stable indoor climate for users. High-performance windows are windows with a Low-E, or Low Emissivity, rating, meaning that they allow relatively little heat to radiate through them when compared to windows without a Low-E rating. Table 5 contains pricing estimates for a few different types of windows, as well as the yearly savings provided by each type of window, in terms of fuel and electricity usage, measured in Therms and KWh, respectively. These values are specific to Kaven Hall, and were determined using the energy analysis done on the Revit model of the building.

Table 5: Window Pricing and Estimated Savings

Window Type	Cost to Install	Yearly Savings (Therms)	Yearly Savings (KWh)	Payback Period
Single Pane	0 (current)	0 (current)	0 (current)	N/A
Double Pane	$99,760 – $149,640	4347	14842	40 Years
Triple Pane	$139,664 - $209,496	5015	27624	36 Years
Quad Pane	~$564,300	5647	26486	96 Years

In Table 5, the "Cost to Install" is the price from RS Means, including installation and material prices, multiplied by the number of windows in Kaven Hall. Because Kaven Hall has multiple windows of different sizes, an average size was chosen for the windows, namely eight feet by four feet. Windows smaller than this would be marginally cheaper, and windows larger would cost marginally more, but this size gives a good idea of a realistic value to replace these windows. It is worth noting that while this does include installation costs, RS Means cites these costs for new constructions, not renovations. From comparing pricing data found on remodeling.hw.net with data found in RS means, we have determined that prices for window renovation projects can be at least 50% higher than new construction prices for the same windows [31]. Because of this, we have added a range of 50% initial price to the price for windows in this graph, as it could cost markedly more to install these windows in a preexisting building as opposed to a new construction. This will at least capture the low end of renovation prices, and serve to make these numbers more realistic in scope.

The "Cost to Install" for triple and quad-pane windows in the above table is an estimate, based upon the price for double-pane windows. Triple-pane windows generally cost 15% - 40% more than the equivalent double pane windows from the same company [39]. The cost for quad-pane windows is around $150 per square foot [29], so the high-value for quad-pane windows in the table is just $150 multiplied by the amount of square feet of windows in Kaven Hall. The cost to install for all of these windows is the same; the only difference is the material cost.

The fuel usage and electricity usage in Table 5 are directly from the Revit model of Kaven Hall that the project group used. These values are the difference between the usage numbers from a base energy analysis run of the building as it currently is, and a run with the specified window type incorporated into the building. More information on this process can be found in section 4.5 Revit Results.

4.7.2 Energy-Efficient Doors

Most modern doors, made of steel and fiberglass, have R-values around R-5 or R-6. “For example, a 1-1/2 inch (3.81 cm) thick door without a window offers more than five times the insulating value of a solid wood door of the same size” [16]. What this means is if the wooden doors on Kaven Hall were to be replaced, users of the building would see a substantial increase in the insulation provided by the doors, ensuring more even temperatures in the stairwells near the doors. As for the glass windows on the doors, these would adhere to similar standards as the windows outlined in the previous section, 4.7.2, ensuring even temperatures year-round.

Table 6 shows the various prices that the project group was able to estimate for replacing the current doors in Kaven Hall. The cost listed is the cost for replacing all five main doors of Kaven Hall.

Table 6: Doors

Door	Cost
Narrow Stile	$22,375
Wide Stile	$27,850
Full Vision	$28,975
Non-Standard	$30,150

Narrow Stile doors are doors in which a large glass window, almost the size of the entire door, is surrounded by a thin frame. In the table above, all of the doors are glass and aluminum, so in a Narrow Stile door, the frame would be aluminum. These are the cheapest model of door, and can be efficient if the glass is a Low-E glass and double or triple-paned, but the price estimate in RS Means doesn’t specify which type of glass is used for its doors, so we have assumed standard glass.

Figure 29: Narrow, Medium, and Wide Stile Doors [9]

Wide Stile doors are similar to Narrow Stile doors, but, as the name would suggest, with a wide frame rather than a narrow frame. These doors are slightly more efficient than Narrow Stile doors, because of the reduced square footage of the window area, but the choice is more an aesthetic one for building designers. Figure 29 shows the difference between Narrow and Wide Stile doors. Medium Stile doors are also shown, but pricing data for this style was not in RS Means, and so it has been excluded from our list of potential door styles.

Full Vision doors are doors with a metal body, but a large glass window. These are more efficient still than Wide Stile doors, because, again, of the reduced window area.

Non-Standard doors are not a specific model, because, as their name would imply, they are non-standard. These are specialty doors which can be built to the requirements of the existing doorframe, and the specifications of the contractor. We have assigned them the highest efficiency rating of the doors in the table, because they have the capability of being built to the most efficient specifications.

Green Building Studio, which the project team used to run energy analyses on the Revit model of Kaven Hall, has no way to change types of doors. This meant that the team was unable to do energy comparisons in Green Building Studio, which is why we have provided a more qualitative run-down of the relative efficiencies of the above types of doors. It is important to note that the efficiency of these doors is not as important as the design of the entranceways of the building when considering factors such as heat loss due to constant use of the doors.

The exterior doors located on Kaven Hall's stairwells cannot support a vestibule-style two-door design, in which there is one exterior door, a gap of a few feet, and then an interior door. This style is often used to limit the amount of heat lost in entranceways that see heavy traffic, such as Kaven Hall's doors during class transition times. An air curtain solution would be much more feasible for the doors that connect to the building's stairwells. A study also found that air curtains can be up to 10% more efficient than traditional two-door vestibules, and that air curtains are also far cheaper and less labor intensive to install [1]. Some of the newer buildings on campus already utilize air curtains, such as Faraday Hall. While we don't have the energy usage data for these buildings before and after installing air curtains, we feel that this is a solution that could be further explored for implementation in Kaven Hall.

4.7.3 Solar Shading for Windows

With a Solar Shading solution for Kaven Hall, drapes or shades would be used to control the amount of light that is let into the building [42]. This can decrease the amount of heat due to sunlight in various rooms, allowing the users of the rooms to have some measure of control over how much light and heat their room receives on any given day. Many of the rooms in Kaven already have some measure of solar shading available, but as the group saw during our on-site visits, many of these fixtures are quite dated, and users of the rooms could benefit from having them updated. One of these fixtures can be seen in Figure 30. As shown, the shade is almost transparent, letting most of the outdoor light into the room.

Figure 30: Solar Shade in Kaven Hall

Table 7 shows the various types of solar shading that the project group considered for Kaven Hall. The table shows the type of solar shading and the initial price. The group was not able to estimate the yearly savings due to solar shading for either of these options, as solar shading is not an option that can be added in the Revit energy analysis.

Table 7: Solar Shading

Solar Shading	Initial Cost
Mylar, Triple layer, Heat-Reflective	$36,842
Mylar, Single Layer, Non-Reflective	$16,515
Vinyl, Heavyweight, 6 ga.	$11,248
Vinyl, Lightweight, 4 ga.	$5,868

Mylar shading is typically better at blocking heat and light than vinyl shading. Among the Mylar shadings listed in Table 7, triple layer, heat-reflective shading is better at shielding a room for the sun than single layer, non-reflective shading. The large price differences in these solutions reflect this difference.

Solar shading is not as important as efficient windows in terms of saving energy [15], but for a building like Kaven Hall, an improvement like this is more of a quality-of-life improvement for faculty and students of the building. Solar shading can keep the heat and light of the summer months out of the classrooms, and while this has a relatively small impact on energy bills, compared to a change like high-efficiency Low-E windows, solar shading can improve the perception of the occupants of a room regarding the indoor climate.

4.7.4 Steam Valve Replacement

Steam valves are a critical component of a steam-heated building such as Kaven Hall. While the valves are cheap to replace, they tend to have a fairly high failure rate, and when they do fail, any rooms that were reliant on them for heating will be overheated.

According to Bill Spratt of the WPI Facilities Department, the overheating issues experienced by students and faculty in Kaven Hall could be due to a faulty steam valve [36]. Reviewing the steam valves in Kaven and replacing any faulty ones would be an effective solution to the current overheating problems that the building is experiencing, as long as a faulty steam valve were the cause of these problems. If nothing else, a review of the current steam valves that found no faulty valves would allow the WPI Facilities Department to focus on the other areas for improving the heating and cooling systems in Kaven Hall.

In terms of finding replacement steam valves, the team was able to locate pricing information within RS Means, but these prices are only for steam valves (steam traps) with specific pipe sizes. The prices for steam traps in RS Means ranged from around $500 all the way up to $6450, depending on the pipe size and the specific type of steam trap. Without the appropriate information from the WPI Facilities Department, namely current steam valve types and pipe sizes, we are unable to come up with suitable suggestions for replacement steam valves.

4.7.5 New Control System

There are currently multiple control systems for Kaven Hall, which control the various heating and cooling units independently [36]. This means that the current systems can be working against each other to achieve the desired temperature, wasting energy and resulting in an inefficient system. The current system is designed to control the steam radiators, through the usage of thermostats in each room. This system is unable to control the window mounted Air Conditioners, as well as auxiliary heating or cooling that may have been added to each room. Additionally, the current system is unable to change the temperature set point at night, or over the weekend when fewer students are expected to be utilizing the building. All of these features would assist in reducing the energy consumption of the building as well as providing a more comfortable climate for students.

As the current climate control system does not provide a way to determine when the system is on or off for each part of the building, as well as the lack of energy usage information for Kaven Hall, it is difficult to quantify the impact a new control system would have. A replacement control system would be designed to provide centralized control over both heating and cooling throughout Kaven Hall. This would allow for less strict temperature regulation overnight, and on the weekend when the building is not being used extensively. This replacement system would face a number of difficulties in controlling the many disparate climate control systems in place in Kaven Hall currently. A better solution would be to remove these disparate heating and cooling systems, and install a centralized HVAC system that could heat and cool the building without fighting against itself.

4.8 Summary

The results and analysis chapter provides the data that was collected while researching possible changes that could be made to Kaven Hall. The data allowed the project team to understand where Kaven Hall was failing as an academic center, the condition of the current climate control system, and possible changes that could be made to Kaven Hall. The data collected allowed the project team to provide recommendations that would help with energy efficiency and creating a sustainable learning environment.

5 Recommendations

5.1 Recommended Improvement Plan

Based on the project group's findings regarding the various proposed changes to Kaven Hall, the group has determined which item in each category would best suit the building. The categories in which the team was able to locate a suitable improvement are as follows: windows, doors, solar shading, steam valves, and a centralized HVAC system. The following sub-sections will each discuss what we saw as the best-fit solution for each of these categories, based on our findings from the Revit model of Kaven Hall, as well as our online research into these areas. These upgrades will help the building to earn points towards an eventual LEED Certification rating. While on their own, these upgrades do not provide a quantifiable amount of points, they all contribute towards the thermal comfort of the building, which is an Environmental Quality credit in the LEED rating system [43].

As an academic institution, WPI is, and should be committed to maximizing the academic excellence of its students. This commitment should extend towards optimizing the climate of their buildings for student performance. Any paid academic institution has an ethical responsibility to provide a suitable environment for its students to work in. Social sustainability encompasses the social responsibility of improving one's community environment through concepts such as livability and engagement. At WPI this means constantly improving the learning environment and engaging students so they may do the same. Along the same line, there is an environmental responsibility to the community at large. Lastly, there is an economic incentive driving those environmental and social responsibilities. These recommendations for improvements will provide a guideline for structural developments that will help WPI improve its social, economic and environmental sustainability.

5.1.1 Windows

The proposed change for the windows in Kaven would be to replace the original-construction single-pane windows with triple-pane windows made of MSG Low-E glass, with non-metal improved frames [18]. This type of window is rated to keep indoor temperatures at a neutral level both in summer and in winter, with a U-factor of less than or equal to 0.22 [18]. This corresponds to an R-value of about 4.55, which is 3.55 better than the estimated R-value of the current windows in Kaven, estimated to be around 1.

Figure 31: Cutaway of a high-performance window, triple glaze [3]

These newer windows, seen in Figure 31, would have improved performance during every season; both in terms of energy and in comfort, with significantly improved performance in keeping the building heated [18]. For users of the building, this would greatly increase comfort levels during the winter months, where the building is currently reaching excesses of 61 degrees Fahrenheit (Figure 16).

According to Bill Spratt of the WPI Facilities Department, a previous project looked at the cost of replacing the windows for Kaven Hall in this manner, and determined that it would cost somewhere in the ballpark of $900,000. Our estimates place the price closer to half of that, around $560,000 for quad-pane windows, and $210,000 for triple-pane windows, but these estimates are based on prices for new constructions, not renovations, so it is entirely possible that the price could be closer to $900,000 for new windows to be installed during renovations.

5.1.2 Doors

As Kaven Hall currently stands, the doors are not the weakest part of the building in terms of energy efficiency. If the building's windows were replaced with high-efficiency windows, however, the doors would stand out in stark contrast as being very energy-inefficient. Our short-term recommendation for the doors of Kaven Hall is simply to replace the weather-stripping and to make sure that the doors have a tight seal.

Our long-term recommendation for Kaven Hall's doors is to replace them with high-efficiency aluminum-and-glass doors. In Table 6 of section 4.7.2 Energy-Efficient Doors, this type of door is the "Non-Standard Door". This type of door could be built to specification, so it could have relatively low window area, resulting in a higher R-value, and better heating and cooling efficiency for the building as a whole. As with the current doors, the weather-stripping and seals would have to be checked and replaced periodically, but these new doors would be better insulating than the current doors.

5.1.3 Solar Shading

Our recommendation for a Solar Shading solution for Kaven Hall is actually twofold: one for a building where high-efficiency windows have already been installed, and one for the current windows in Kaven Hall.

If the windows in Kaven Hall were replaced with the high-efficiency windows listed above, our recommendation for the building would be a heavyweight vinyl shade (6 ga.). This type of shade is both affordable and effective, and aesthetically would fit in with the appearance of the building more than a Mylar shade. The shades do not have to be heavy-duty in terms of blocking heat and light, because the windows of the building would already be blocking a large portion of the heat that would normally come through.

If the windows in Kaven Hall were kept in their current state, we would recommend a single-layer Mylar shade. This type of shade would help the building to contain heat in the winter, and would block light well in the summer, although with the current system the rooms could get quite stuffy with these shades installed. This is far less optimal than replacing the windows and using a vinyl shade, but it would still be an improvement over the current system.

5.1.4 Steam Valves

Through our research into the heating systems of Kaven Hall we found that the steam valves used to control the radiators in the building can fail, leading to radiators unnecessarily heating a room. While replacing all steam valves would not save significant amounts of energy, it is important that broken steam valves be replaced quickly to avoid overheating the building. Due to this, we recommend that steam valves be inspected regularly and replaced if they are found to be broken. Due to time constraints we were unable to gather specific information on what steam valves are currently in use in Kaven Hall, and we are unable to recommend a specific replacement. Such valves could be replaced with equivalent models

5.1.5 HVAC

Designing a specific HVAC system for an academic building is a task that is unfortunately beyond the scope of an Interactive Qualifying Project. The commissioning of an HVAC system is done by a commissioning team, hired by an HVAC company for an individual project: the renovation or construction of a building to incorporate an HVAC system.

Despite this, we believe that a central air HVAC system is singularly important when talking about bringing Kaven Hall up to modern livability standards. It is unacceptable for a building at a cutting edge engineering university such as WPI to have an indoor climate that is too hot for students to effectively work, especially when this is a problem that can be solved by a single renovation project. While the older design of Kaven Hall is not conducive to incorporating an HVAC system, and any plan for renovating the building to include central air would be quite complex, we believe that this is the only way for Kaven Hall to truly be brought up to modern standards, and to provide a comfortable and academically stimulating learning environment.

5.2 Application to Additional Campus Buildings

There are three main procedures that we suggest be followed when planning renovations to a building. The first step is to collect temperature data from the building being considered. Then, taking thermal images of the building can help to pinpoint specific areas that need improvement. Finally, creating and using a Revit model of the building is important for comparing renovations.

Collecting temperature information from the heavily used spaces inside of a building is important to planning out future renovations. This data assists in determining what systems need improvement, with overly cool temperatures in the winter requiring improvements to the heating systems, and overly warm temperatures in the summer indicate that improvements to cooling systems are necessary. The temperature data will also indicate any changes in temperature throughout the day. Such temperature gradients have been found to decrease occupant comfort, and have a negative impact on performance.

Thermal images of windows, doors, and roofs are essential to determine failing insulation components of a building. Collecting pictures of windows can show where heat is being lost such as around the edges of the window or through the glass panes. Door pictures can show faulty seals. Lastly, roof pictures can show where insulation is lacking or nonexistent. Overall, thermal pictures can show the key locations of a building that are leaking heat and wasting thermal energy.

Building Information Modeling serves an important role in planning renovations to existing buildings. Having an accurate 3D model of the building under consideration provides a number of advantages, including the ability to perform an energy analysis, as well as provide a visualization of proposed renovations. This report discusses the group’s usage of Revit for creating a model of Kaven Hall, and using the model to perform an energy analysis. This energy analysis provided an understanding of the building’s current energy needs for climate control as well as energy used to light the building, and power various equipment inside the building. Various improvements, such as more insulating windows, can be tested through the usage of Green Building Studio.

5.3 Conclusion

The recommendations that were provided in this chapter would improve the energy use of Kaven Hall and improve the learning environments in the building. The methods used in this study of Kaven Hall can be utilized to analyze other campus buildings to help increase the comfort of learning environments and reduce energy usage across the WPI campus. A project plan for renovating Kaven Hall could utilize data from this project as an outline of tasks to be considered for a renovation. Such a plan could take into account LEED certification, and attempt to update the building for LEED certification in the future. Lastly, the topics studied in this report could be extended and researched further to determine the comfort levels of the WPI community and apply those findings in renovations of other academic buildings.

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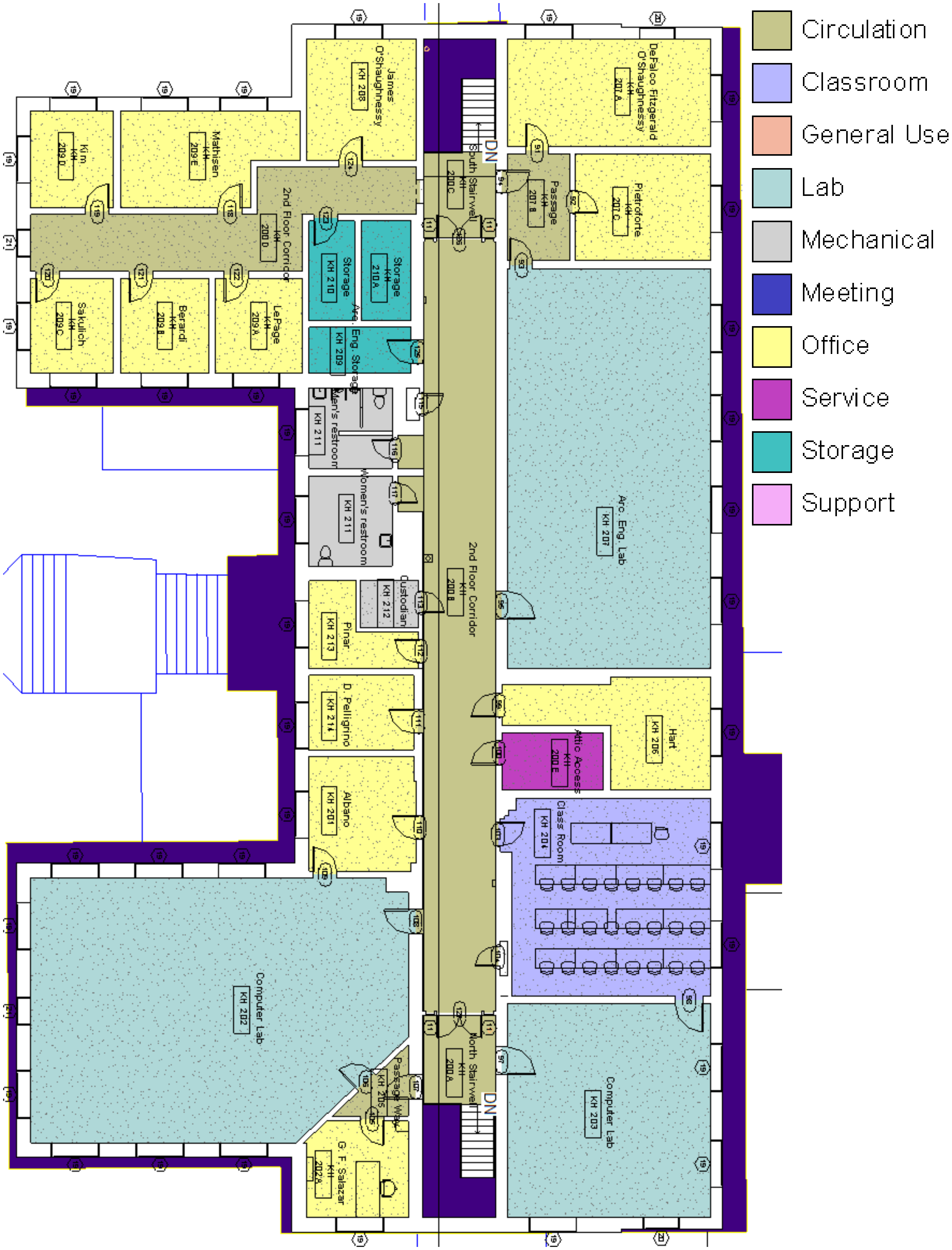
Appendices

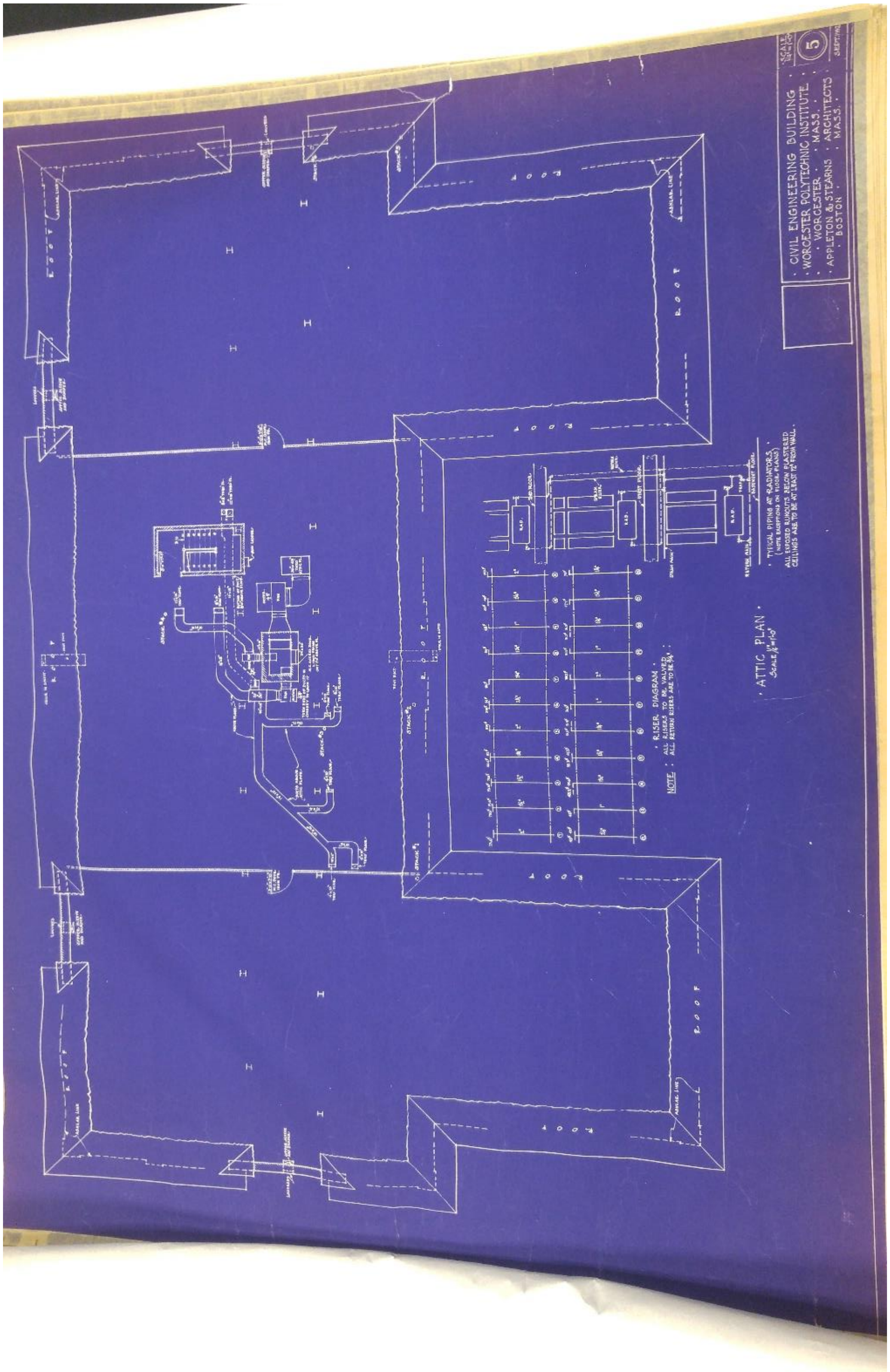
Appendix A

Floor plan of the basement of Kaven Hall

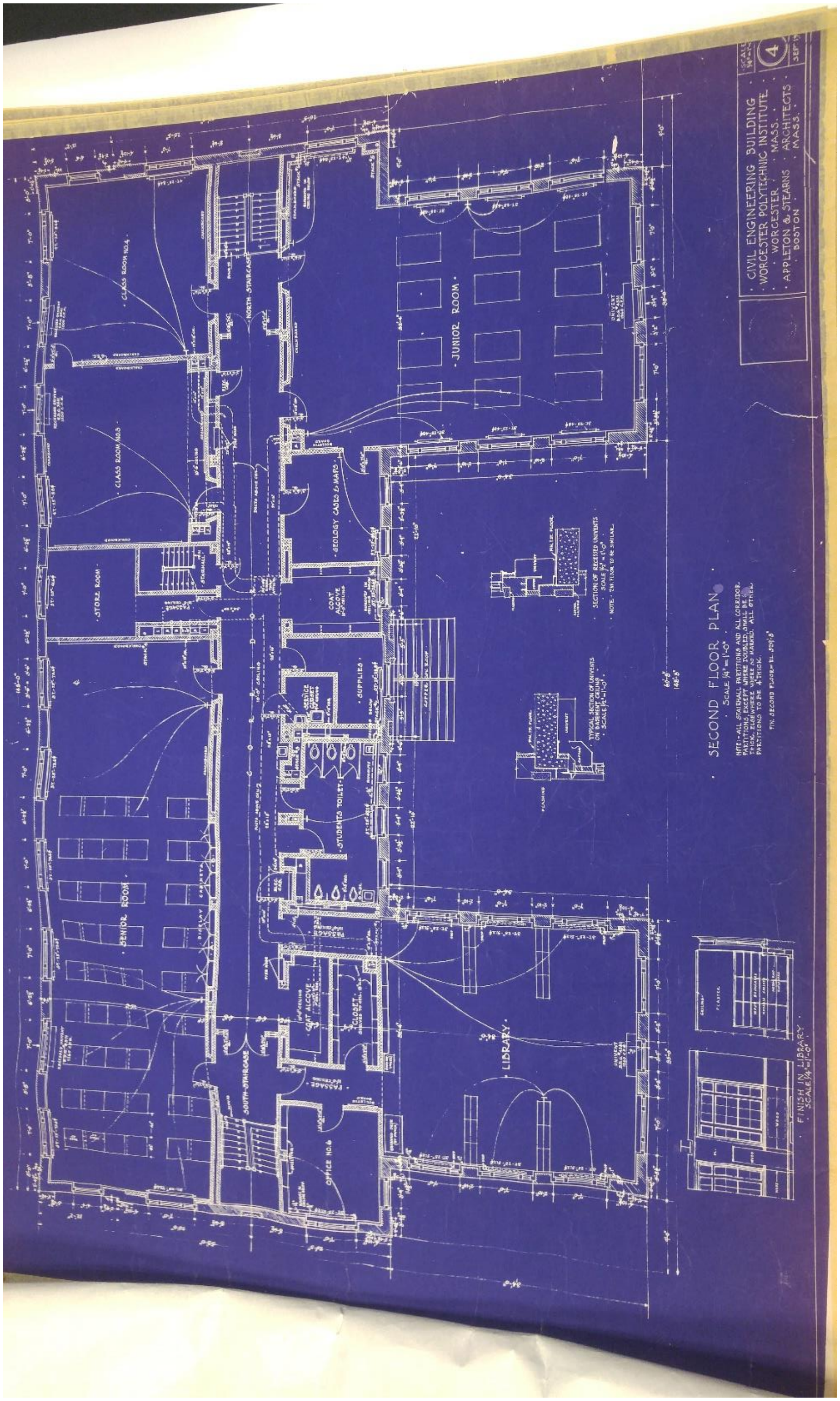


Floor Plan of the second floor of Kaven Hall

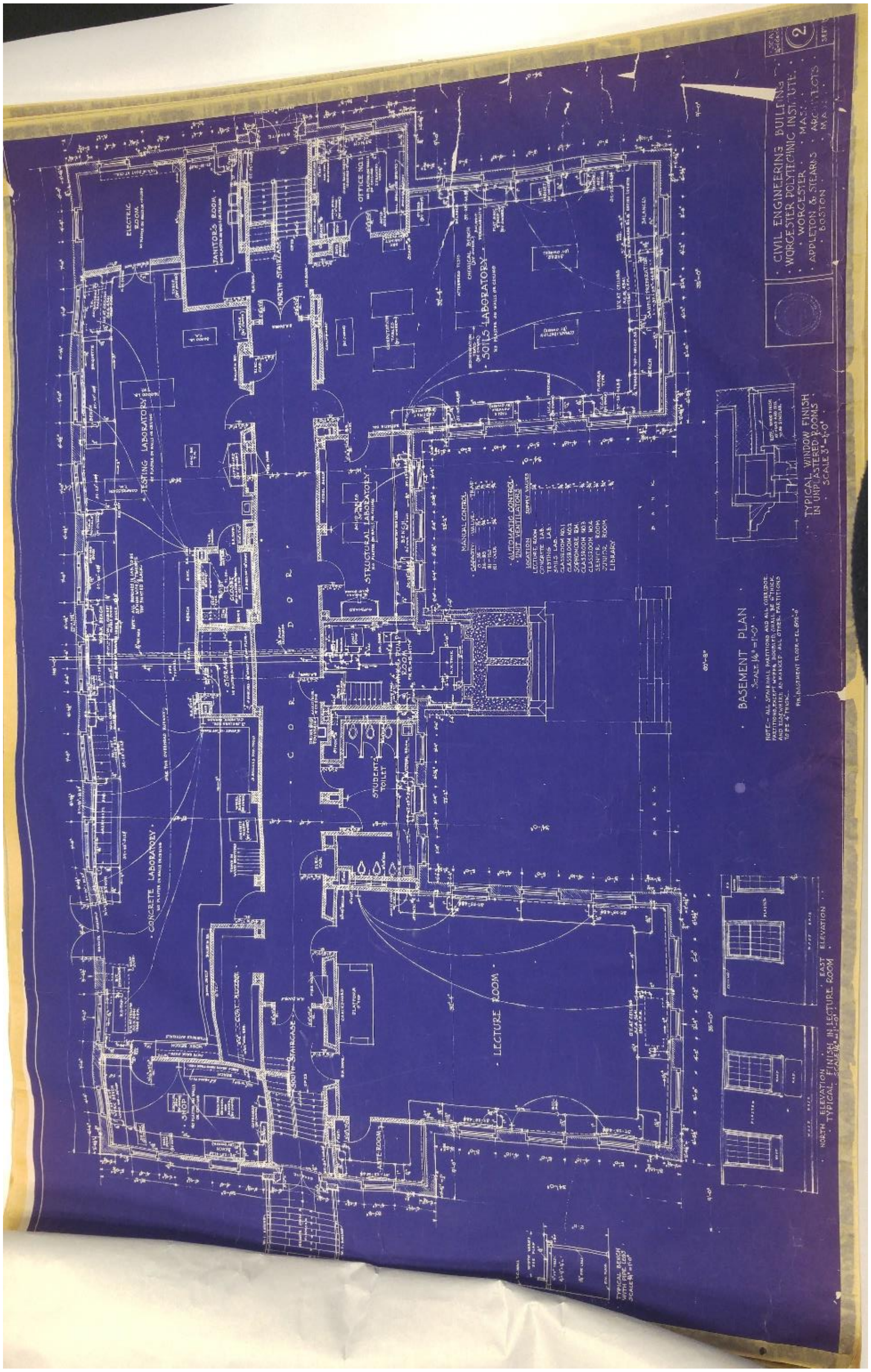
Appendix B



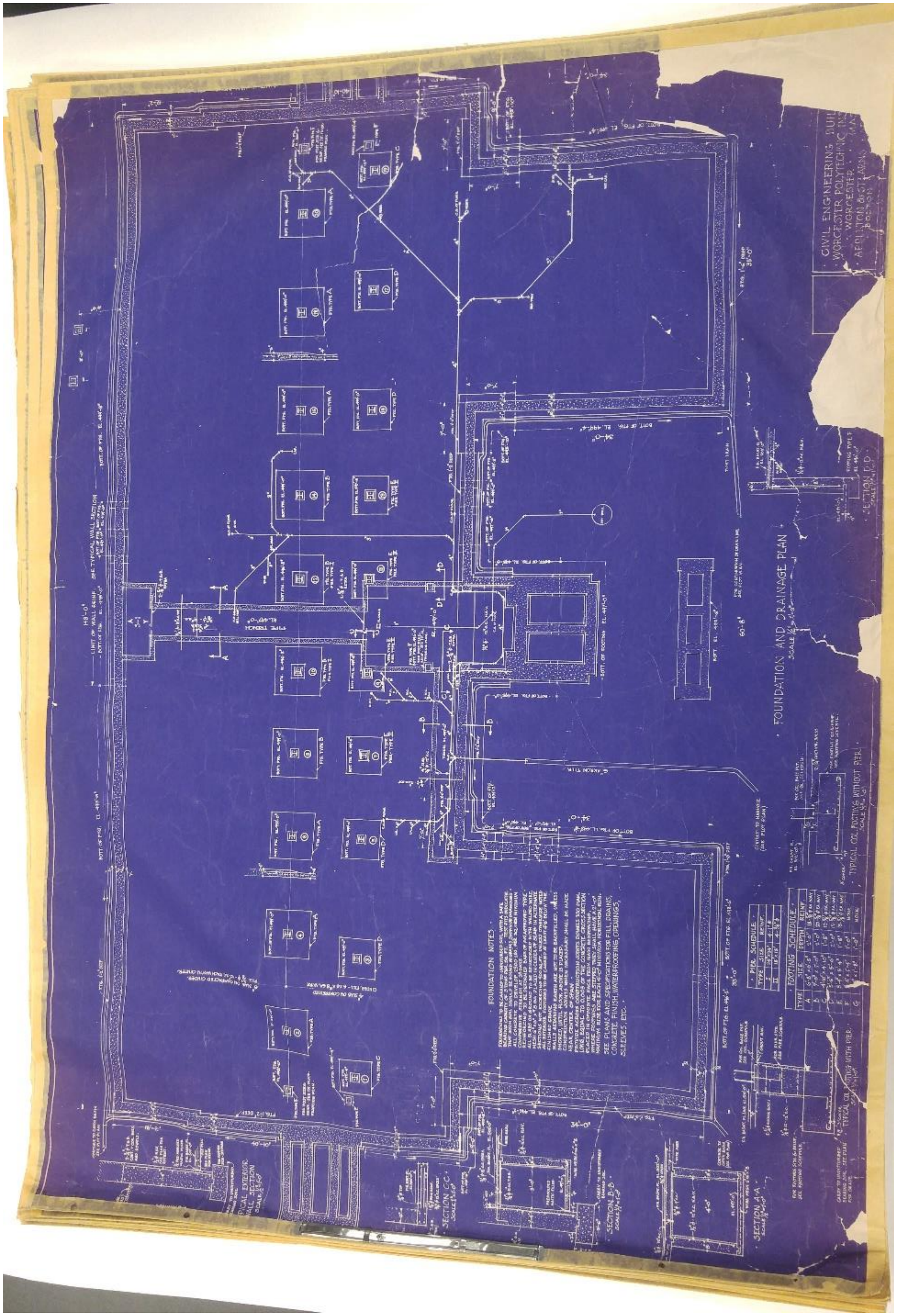
Attic Kaven Hall Original Blueprint Circa 1952 (WPI Archives)



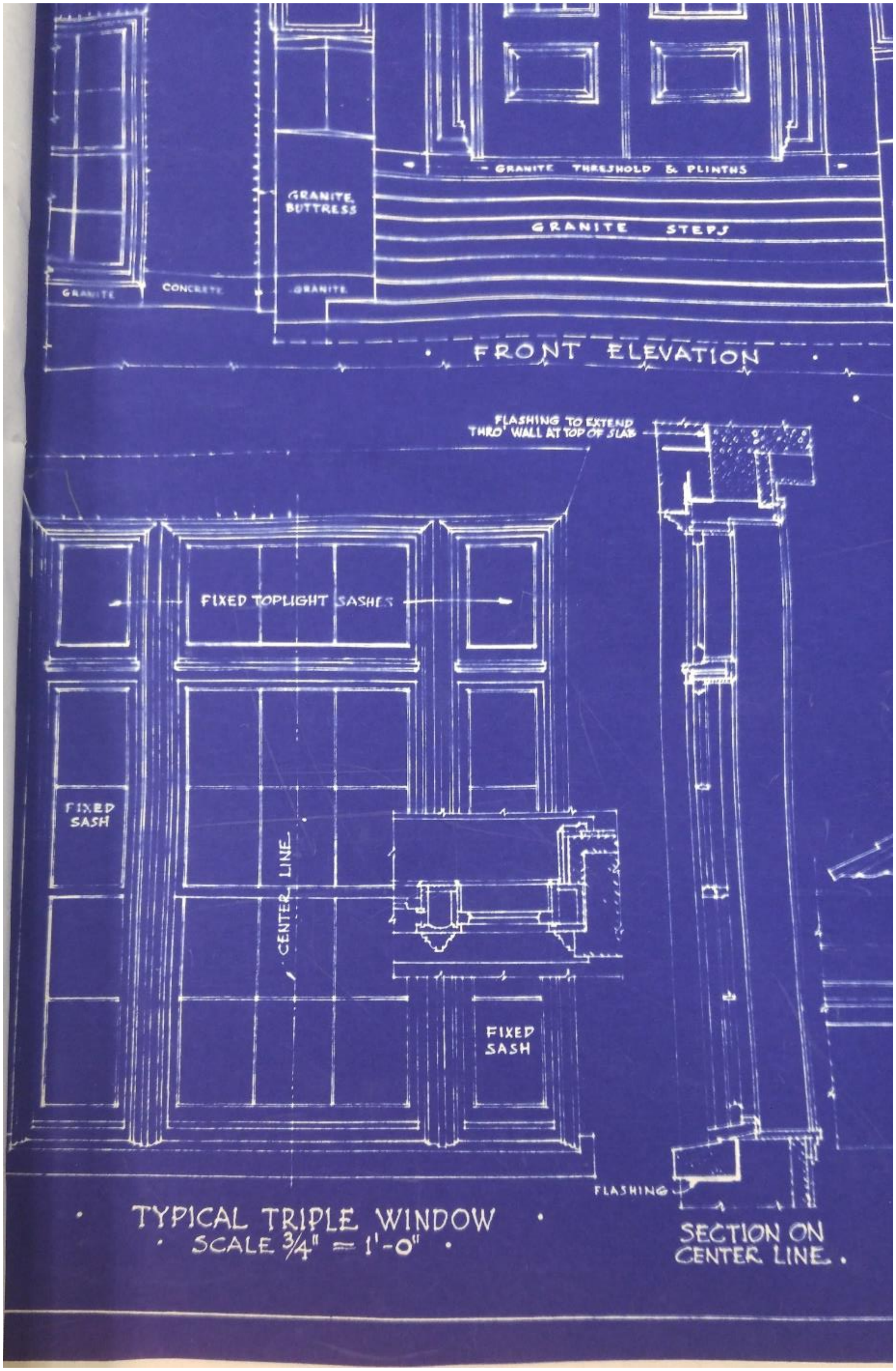
2nd Floor Kaven Hall Original Blueprint Circa 1952 (WPI Archives)



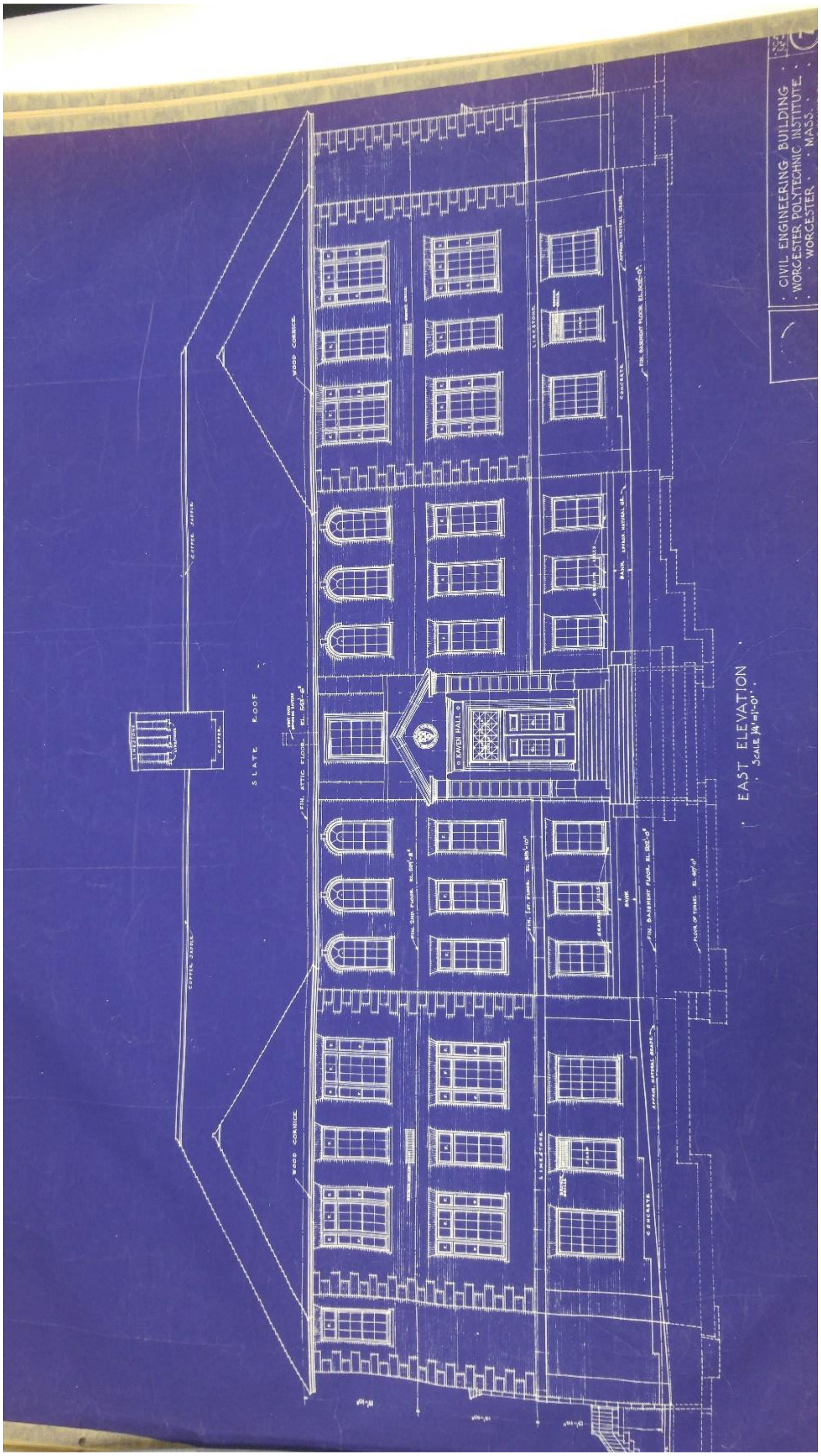
Basement Kaven Hall Original Blueprint Circa 1952 (WPI Archives)



Foundation Kaven Hall Original Blueprint Circa 1952 (WPI Archives)



Window Kaven Hall Original Blueprint Circa 1952 (WPI Archive)



Front of Kaven Hall Original Blueprint Circa 1952 (WPI Archives)

Appendix C

Meeting with Elizabeth Tomaszewski and Bill Spratt (3/30/16):

Contact: Elizabeth Tomaszewski ltomasz@wpi.edu

Bill Spratt wpspratt@wpi.edu

The majority of this meeting was a discussion of topics with no specific questions being asked. The goal of this meeting was to develop an understanding of the systems and properties of Kaven Hall as of March 2016. The leftmost bullet points depict the topics discussed in the meeting and as the bullet points move in, the more details describing those topics are noted.

- Kaven Hall Heating System
    - Heated by steam and radiators
        - System is tried and true
    - Overheating in the winter due to steam valves
        - Every year approximately 20% of steam valves fail
    - Look into a steam trap survey
- Kaven Hall Cooling System
    - No central cooling system
    - 2 air handlers, pulls air from the outside and distributes in building
        - No ducts
    - Most air is pulled in from the windows
    - Not much insulation
    - Mitsubishi split system
        - Fan and coil inside room with AC compressor outside
        - Installed in KH116
    - Unit ventilators sit under windows and send in heat
- Windows
    - Original to building
    - Previous project looked at windows and it would cost 900K to replace them
- Radiators/Steam System
    - Original to building
    - Direct digital controls are installed
- Other Renovations
    - Previous renovation from a donor fell through
    - Other projects looked at:
        - Elevator access in Kaven
        - Windows replaced
        - AC systems

  - No Major renovation project put together that combines everything
- AC Units
  - Wall units are sized based on rough estimates
  - Information are on wall units themselves (UL Codes)
  - Consider long term cost
  - Units outside are ugly and loud
  - No place on roof for new systems
  - Mitsubishi split system is measured and correctly sized based on the placement
- Kaven Hall Rooms
  - No integration between heating and cooling systems
  - Multiple systems fight against each other
- Project Team and HVAC Team
  - May have electricity and blueprint information
  - Kaven Hall takes both electricity and steam
    - Untrackable
    - Not one of 11 that were fitted with trackers
    - Possible to gather data
      - Attachable meters
- How many buildings are in need of HVAC work?
  - We will receive more information from Bill to answer this (percentage)
  - Salisbury has a chiller and is 60% cooled
  - Stratton has some window units but no central AC
  - Olin also doesn’t have central AC
    - Olin 107 is cooled
  - Atwater Kent receives most of cooling from Fuller
- Water Cooling
  - Chilling tower required
  - Takes up a lot of room
- Mitsubishi Variable Refrigeration Flow
  - Expensive
  - Uses heat pump and cooling in the same system
  - Very efficient
  - Massachusetts College of Pharmacy has a building run off this
- Controlled Environments within Kaven Hall
  - AC is piecemeal, it is installed as requested/ needed
- Foisie Studio
  - Send optimal learning climate information to Bill
  - They want 76F to achieve LEED certification and save on money but this isn’t bearable for users
- Things to Consider:
  - New Heat Valves
  - New Control Systems

    - New Wall AC Units
        - These can help the building as is, at a fraction of the cost

Meeting with Professor Salazar (3/25/16):

Contact: salazar@wpi.edu

The majority of this meeting was a discussion of topics with no specific questions being asked. The goal of this meeting was find out if a Revit model of Kaven Hall existed and if it could be provided to us with notes on how to use Revit. The leftmost bullet points depict the topics discussed in the meeting and as the bullet points move in, the more details describing those topics are noted.

- Revit Model
    - A model of Kaven Hall does exist
        - It was created by an MQP
        - Full model that will work with energy analysis
    - Worcester City Hall
        - We can get this and follow methods from the MQP on this building
        - It will help us learn Revit
    - East Hall
        - Same as Worcester City Hall
- Notes on Revit
    - Professor Salazar will provide us with his class notes and several other MQP's that used Revit for our assistance.
- Professor Salazar
    - He would like a copy of our IQP when completed.
    - Provide him with the model of Revit if it is updated to a more current system.

Meeting with Professor Cewe-Malloy (4/5/16)

Contact: lemalloy@wpi.edu

The majority of this meeting was a discussion of topics with no specific questions being asked. The goal of this meeting was find out if Professor Cewe-Malloy had any experience in climate control systems. The leftmost bullet points depict the topics discussed in the meeting and as the bullet points move in, the more details describing those topics are noted.

- What improvements could be made to Kaven Hall?
    - Two systems could be made to have a major impact
        - Windows

        - HVAC
- AC Units
    - In class these are noisy and distracting
    - Major classrooms are air conditioned
- Control Systems
    - Automatic Control System
        - Expensive but unifies the system
        - Units will not fight each other

Appendix D

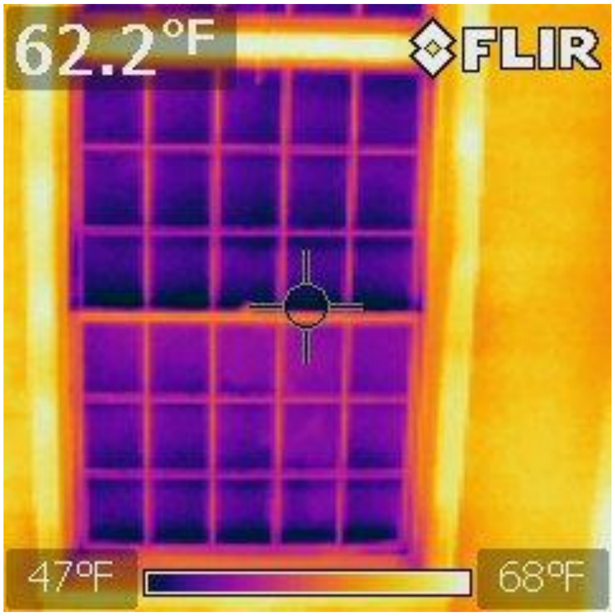
Run Name	Annual Electricity Cost	Annual Fuel Cost	Annual Electricity Use (KWh)	Annual Fuel Use (Therms)	EUI
Infiltration 3.5 Air Changes per Hour	9647.42	8111.43	70936.90	21345.88	68.21
Max Form	19514.45	6582.43	143488.60	17322.19	63.76
Uninsulated framed Wall	6243.00	6616.77	45904.40	17412.55	54.47
Max Internal Loads	41831.19	1290.45	307582.30	3395.91	39.87
24/7 Usage	22236.54	2237.69	163504.00	5888.66	32.91
2.0 ACH	3739.93	3673.78	27499.50	9667.84	30.44
Uninsulated Walls	2464.97	2902.41	18124.80	7637.92	23.70
Max Energy Envelope	1628.99	2665.94	11977.90	7015.64	21.31
1.6 ACH	2449.35	2446.75	18009.90	6438.82	20.24
R2 Concrete Masonry Unit Wall	1528.90	2001.38	11241.90	5266.79	16.22
1.2 ACH	1427.59	1481.10	10497.00	3897.64	12.21
PlugLoad 3.00 W/sqft	31863.51	-1583.94	234290.50	-4168.27	10.98
R13 Metal Frame Wall	1041.52	1281.17	7658.20	3371.49	10.43
12/7 Usage	14050.53	2.43	103312.70	6.39	10.13
2.6 Average Equipment Power Density W/sf	25090.68	-1258.10	184490.30	-3310.79	8.56
ASHRAE Variable-Air-Volume	14256.68	-417.59	104828.50	-1098.91	7.11
ASHRAE 90.1-2010	14159.46	-417.59	104113.70	-1098.93	7.04
0.8 ACH	610.26	700.88	4487.20	1844.43	5.73
1.9 Average Light Power Density W/sf	13603.51	-614.52	100025.80	-1617.15	5.15
2.0 Average Equipment Power Density W/sf	15001.24	-747.97	110303.20	-1968.33	5.15
12/6 Usage	10562.92	-422.02	77668.50	-1110.58	4.42
1.6 Average Equipment Power Density W/sf	8291.25	-409.74	60965.10	-1078.27	2.88
1.5 Average Light Power Density W/sf	7571.05	-348.06	55669.50	-915.94	2.82
Lighting 1.5 W/sqft	7571.05	-348.06	55669.50	-915.94	2.82
R13 Wood Frame Wall	262.79	290.46	1932.30	764.36	2.38
1.3 Average Equipment Power Density W/sf	3278.36	-147.74	24105.60	-388.79	1.24
1.1 Average Light Power Density W/sf	1563.13	-75.29	11493.60	-198.12	0.56
Single Clear Window	-398.81	88.44	-2932.40	232.75	0.38
Base Run	0.00	0.00	0.00	0.00	0.00
0.4 ACH	-69.63	4.39	-512.00	11.54	-0.02
0 Rotation	-69.63	4.39	-512.00	11.54	-0.02
No Controls	-69.63	4.39	-512.00	11.54	-0.02
Single Low Iron Window	-69.63	4.39	-512.00	11.54	-0.02
Single Low Iron Skylight	-69.63	4.39	-512.00	11.54	-0.02

Run Name	Annual Electricity Cost	Annual Fuel Cost	Annual Electricity Use (KWh)	Annual Fuel Use (Therms)	EUI
Triple Low Emissivity film Skylight	-69.63	4.39	-512.00	11.54	-0.02
Double Low Emissivity High Performance Skylight	-69.63	4.39	-512.00	11.54	-0.02
Quad Krypton Clear Window	-69.63	4.39	-512.00	11.54	-0.02
Uninsulated framed Roof	-69.63	4.39	-512.00	11.54	-0.02
BaseRun w/DC No Change	-69.63	4.39	-512.00	11.54	-0.02
Occupancy Sensors No Change	-69.63	4.39	-512.00	11.54	-0.02
Daylighting Controls	-982.94	63.26	-7227.50	166.48	-0.23
BaseRun w/Daylight Controls on	-982.94	63.26	-7227.50	166.48	-0.23
Single Pane Low Iron Window w/DC	-982.94	63.26	-7227.50	166.48	-0.23
Single Low Iron Skylight w/DC	-982.94	63.26	-7227.50	166.48	-0.23
Triple Low Emissivity film Skylight w/DC	-982.94	63.26	-7227.50	166.48	-0.23
Double Low Emissivity High Performance Skylight w/DC	-982.94	63.26	-7227.50	166.48	-0.23
Quad Krypton Clear w/DC	-982.94	63.26	-7227.50	166.48	-0.23
1.0 Average Equipment Power Density W/sf	-1720.55	116.27	-12651.10	305.97	-0.36
45 Rotation	-174.08	-43.99	-1280.00	-115.75	-0.46
Orientation (+)45	-174.08	-43.99	-1280.00	-115.75	-0.46
Occupancy Controls	-2289.64	102.47	-16835.60	269.67	-0.87
Occupancy Sensors On	-2289.64	102.47	-16835.60	269.67	-0.87
0.90 W/sqft	-3386.47	201.39	-24900.50	529.97	-0.92
315 Rotation	-344.43	-96.88	-2532.60	-254.94	-0.98
Orientation (-)45	-344.43	-96.88	-2532.60	-254.94	-0.98
Daylighting & Occupancy Controls	-3066.28	159.14	-22546.20	418.78	-1.01
270 Rotation	-166.26	-122.56	-1222.50	-322.53	-1.05
Orientation (-)90	-166.26	-122.56	-1222.50	-322.53	-1.05
12/5 Usage	2623.67	-398.97	19291.70	-1049.93	-1.12
90 Rotation	-359.76	-173.54	-2645.30	-456.68	-1.57
Orientation (+)90	-359.76	-173.54	-2645.30	-456.68	-1.57
0.7 Average Light Power Density W/sf	-4425.92	199.45	-32543.50	524.86	-1.68
225 Rotation	-246.58	-235.54	-1813.10	-619.85	-1.96
Orientation (-)135	-246.58	-235.54	-1813.10	-619.85	-1.96
Lighting 0.55 W/sqft	-6667.14	298.13	-49023.10	784.55	-2.55
0.6 Average Equipment Power Density W/sf	-8367.06	454.78	-61522.50	1196.80	-2.59
135 Rotation	-621.06	-307.91	-4566.60	-810.29	-2.77
Orientation (+)135	-621.06	-307.91	-4566.60	-810.29	-2.77
R13 Wood Frame and R10 Metal Frame wall	-430.43	-332.94	-3164.90	-876.16	-2.82

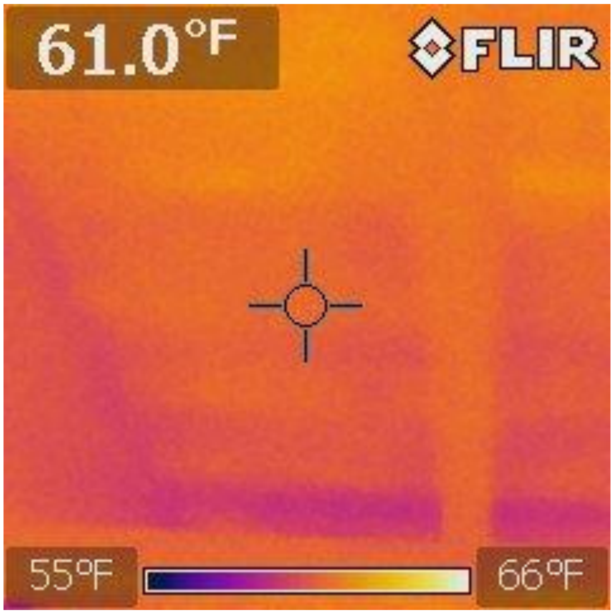
Run Name	Annual Electricity Cost	Annual Fuel Cost	Annual Electricity Use (KWh)	Annual Fuel Use (Therms)	EUI
180 Rotation	-344.64	-354.56	-2534.10	-933.04	-2.93
Orientation (+)180	-344.64	-354.56	-2534.10	-933.04	-2.93
0.3 Average Light Power Density W/sf	-10402.94	457.07	-76492.20	1202.82	-4.04
Uninsulated Roof	-735.11	-499.49	-5405.20	-1314.44	-4.30
0.17 ACH	-678.44	-658.81	-4988.50	-1733.71	-5.46
Infiltration 0.17 Air Changes per Hour	-678.44	-658.81	-4988.50	-1733.71	-5.46
14-inch Insulated Concrete Form Wall	-775.99	-676.55	-5705.80	-1780.40	-5.67
12.25-inch Structurally Ins. Panel	-821.10	-828.60	-6037.50	-2180.53	-6.85
R-44 framed Wall	-821.10	-828.60	-6037.50	-2180.53	-6.85
R38 Wood Frame Wall	-797.98	-838.86	-5867.50	-2207.53	-6.91
High Eff. Variable-Air-Volume	-3293.70	-918.86	-24218.40	-2418.06	-9.31
Double Clear Window	-1893.73	-1117.34	-13924.50	-2940.36	-9.80
Triple Low Emissivity film Window w/DC	-4255.20	-1221.96	-31288.20	-3215.69	-12.29
Triple LowE film Window	-4222.83	-1226.22	-31050.20	-3226.90	-12.30
Min Internal Loads	-20203.10	273.13	-148552.20	718.76	-12.48
Double Low Emissivity High Performance Window	-4037.66	-1323.32	-29688.70	-3482.43	-12.90
Double Low Emissivity High Performance Window w/DC	-4781.26	-1257.40	-35156.30	-3308.94	-12.94
Double Low Emissivity Window	-2018.53	-1652.18	-14842.10	-4347.83	-13.93
Triple Low Emissivity Window	-3758.31	-1905.70	-27634.60	-5014.99	-17.10
Quad Low Emissivity Window	-3599.73	-2146.14	-26468.60	-5647.73	-18.80
Quad Krypton Clear Window	-3599.73	-2146.14	-26468.60	-5647.73	-18.80
Quad Krypton Clear Window w/DC	-4349.81	-2095.73	-31983.90	-5515.08	-18.96
Min Form	-5771.66	-2122.59	-42438.70	-5585.77	-20.19
R10 Roof	-8540.54	-7070.18	-62798.10	-18605.74	-59.55
R19 Roof	-8846.27	-7548.95	-65046.10	-19865.65	-63.38
R15 Roof	-8972.89	-7603.91	-65977.10	-20010.29	-63.89
ASHRAE Package System	-7527.55	-8373.19	-55349.60	-22034.72	-68.66
10.25-inch Structurally Ins. Panel	-9553.33	-8511.57	-70245.10	-22398.87	-71.16
R38 Roof	-9551.91	-8532.55	-70234.60	-22454.07	-71.32
R60 Roof	-9725.58	-8774.67	-71511.60	-23091.24	-73.27

Run Name	Annual Electricity Cost	Annual Fuel Cost	Annual Electricity Use (KWh)	Annual Fuel Use (Therms)	EUI
R-60 continuous Insulation Roof	-9725.58	-8774.67	-71511.60	-23091.24	-73.27
High Eff. Package System	-10016.32	-9251.99	-73649.40	-24347.34	-77.09
High Eff. Package Terminal AC	-14720.20	-9031.98	-108236.80	-23768.36	-78.81
ASHRAE Package Terminal Heat	42387.88	-17965.50	311675.60	-47277.63	-105.16
ASHRAE Heat Pump	37968.37	-17965.50	279179.20	-47277.63	-108.35
Min Energy Envelope	-14526.15	-13170.50	-106809.90	-34659.22	-109.93
High Eff. Heat Pump	33083.93	-18154.40	243264.20	-47774.75	-113.29

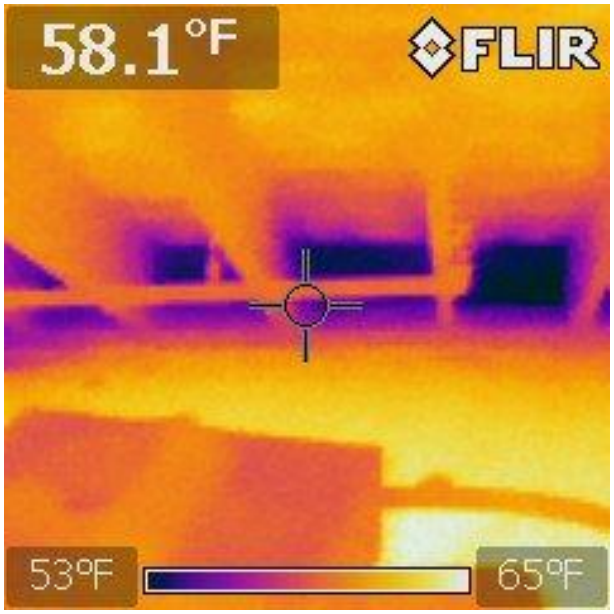
Appendix E



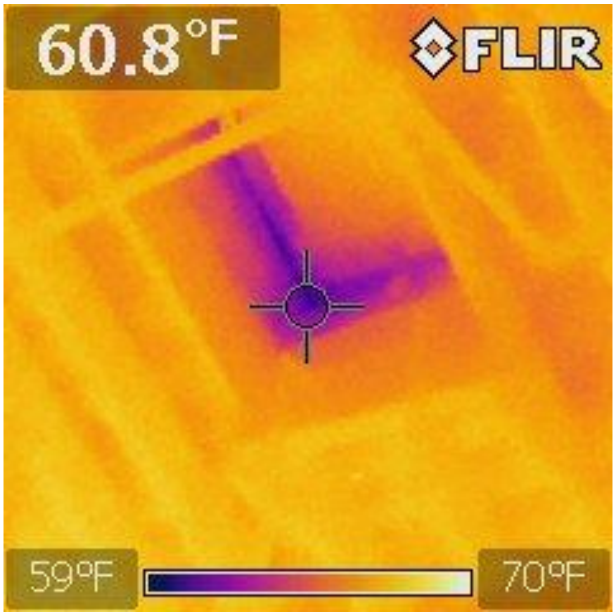
Kaven Hall Window



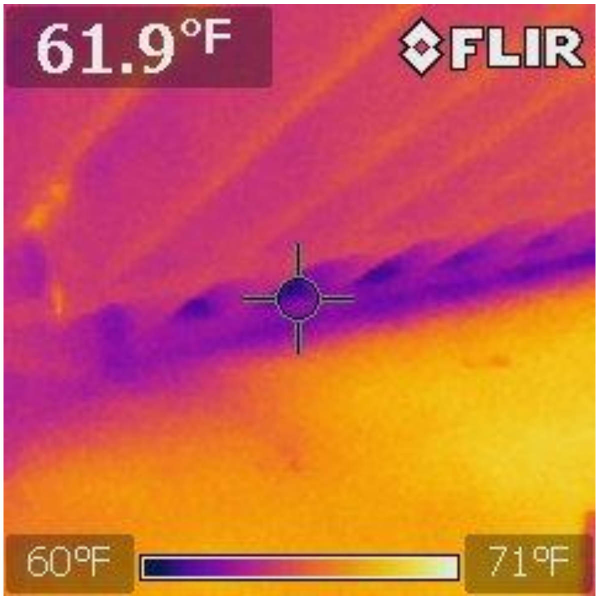
Kaven Hall Attic Ceiling



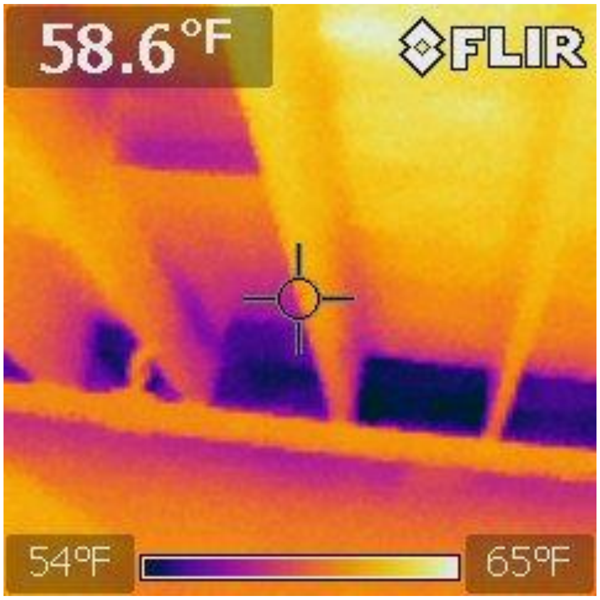
Kaven Hall Attic Edge



Kaven Hall Attic Roof Access



Kaven Hall Attic Edge



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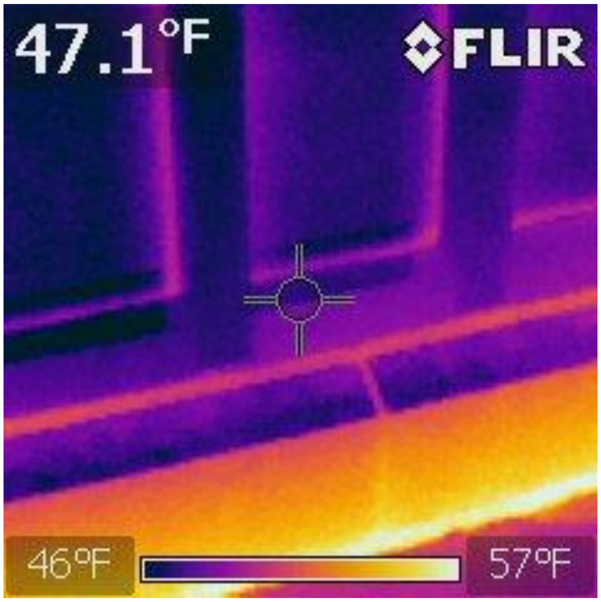
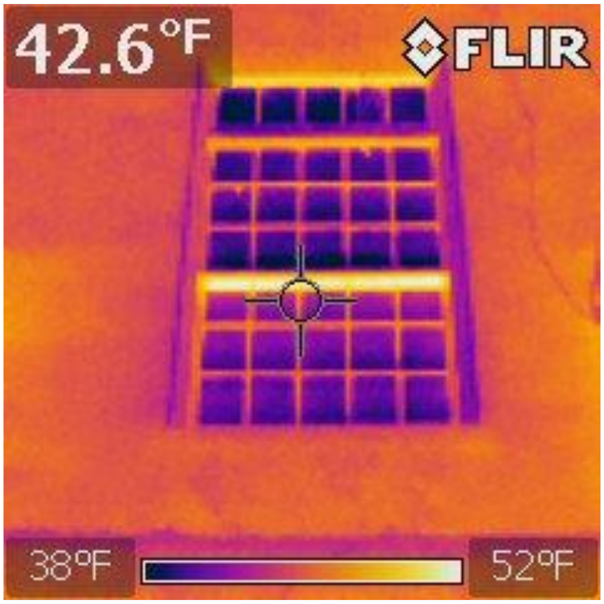
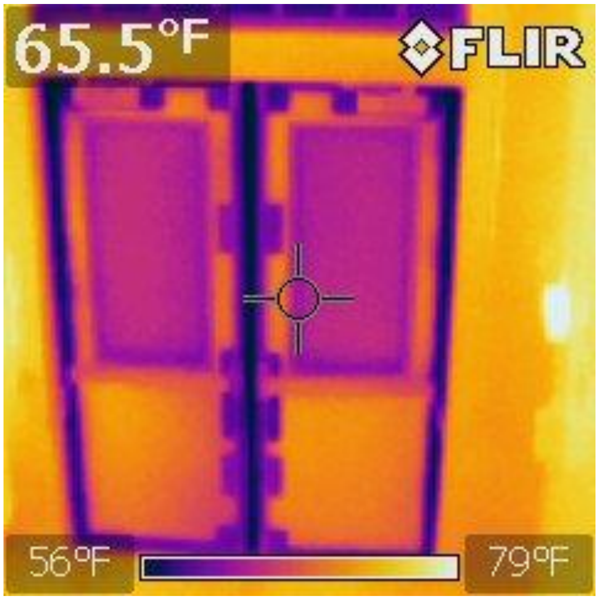


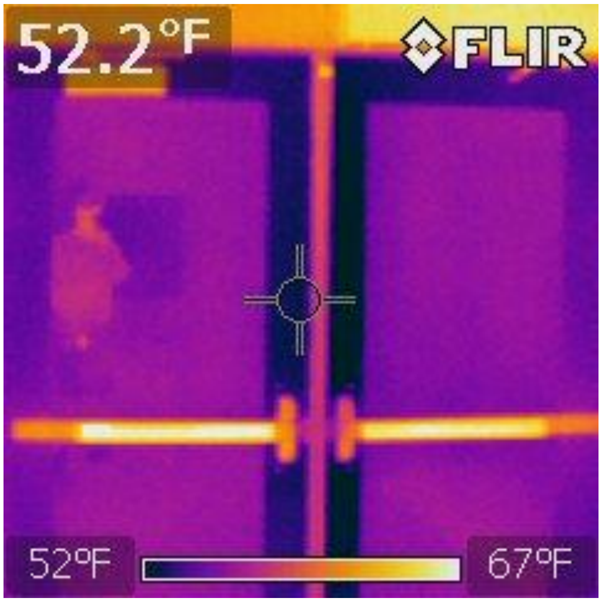
Campus Center Window (Outside)



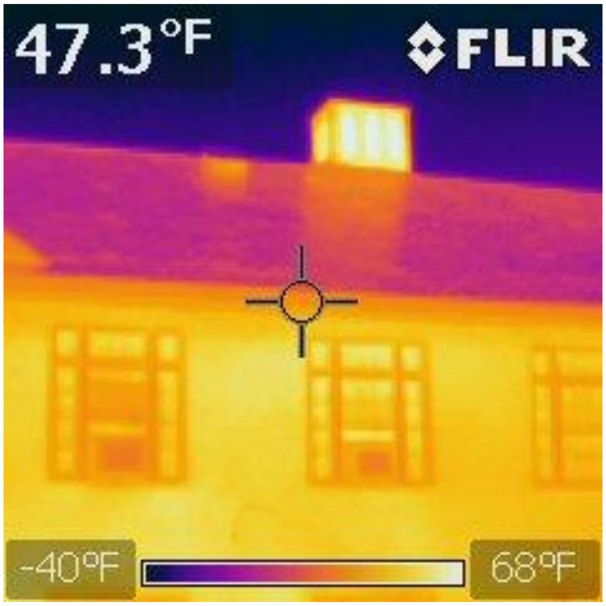
Kaven Hall Window (Outside).



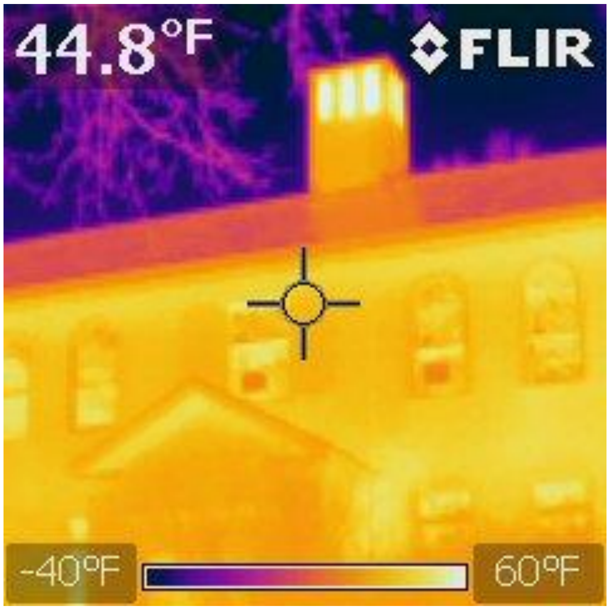
Kaven Hall Double Door (Inside)



Campus Center Door (Inside)



Kaven Hall Roof



Kaven Hall Roof