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Addition to Kaven Hall - Performance-Based Design Using Energy Simulation Tools

Yan Zhang
Worcester Polytechnic Institute

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Addition to Kaven Hall – Performance-based Design Using Energy Simulation Tools

A Major Qualifying Project

Submitted to the Faculty of

Worcester Polytechnic Institute

in partial fulfillment of the requirements for the

Degree in Bachelor of Science

in

Architectural Engineering

By

Yan Zhang

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Project Advisor:

Professor Steven Van Dessel

Abstract

In this project, a high-performance building design for the Addition to Kaven Hall is proposed that addresses the space needs of the Department of Civil, Environmental, and Architectural Engineering at Worcester Polytechnic Institute. The addition is a multi-use academic building with three floor levels and one mezzanine level. It offers dedicated studio space and labs for the Architectural Engineering Program, classrooms, offices, and a reading room, and aims to provide an excellent educational environment for the CEE Department. Studies of solar radiation, daylighting conditions and energy consumptions were conducted to optimize the building's performance, including visual and thermal comfort and energy usage. Parametric studies of the energy performance were conducted in the DesignBuilder software to optimize the building envelope systems. The final design of the building incorporates a double skin facade and utilizes mechanical and natural ventilation. The construction of the double skin facade was presented in detailed section drawings. The energy simulation reports that the EUI of the new building is 36.08 kBtu/ft^2, which is 65.3% less than the median Site EUI for College/University buildings in U.S. and meets the 60% target in the 2030 CHALLENGE.

Executive Summary

High-performance buildings have attracted much attention in recent decades, as there is a growing awareness of the importance of energy consumption in buildings. Architects and engineers have therefore been more deliberate in designing and constructing energy efficient and environmental friendly buildings.

Kaven Hall houses the Department of Civil, Environmental, and Architectural Engineering (CEE) at Worcester Polytechnic Institute (Worcester, MA). As the student body is growing and the needs of the programs are changing, there is a need to address the space requirements of the CEE Department. To accommodate these changes, an addition to Kaven Hall is proposed and studied as part of this MQP. The site condition, building codes, zoning ordinance, local climate and the site circulation were studied and an architectural design for an addition to Kaven Hall was developed. The proposed design solution is a multi-use high-performance academic building. It offers dedicated studio space and labs for the Architectural Engineering Program. It also provides classrooms, offices, a computer lab, a reading room, and an exhibition space for the Department. In order to develop the high-performance building, this MQP project entailed: (i) conducting a parametric study of daylighting conditions, (ii) developing a building interior lighting design, (iii) developing a detailed design for the most prominent building facade, and (iv) conducting building energy simulations and performance analysis of the architectural design solution.

The daylighting condition was simulated in the DesignBuilder software, a graphic user interface (GUI) package using the Radiance as the ray-tracing engine. Interior lighting system was designed based on the IESNA guidelines. The lighting design for a typical studio was also simulated in the DIALux software package to visualize the lighting condition and assess the luminance level.

The building energy performance was simulated in the DesignBuilder software, which uses EnergyPlus as the energy simulation engine. Parametric studies of the different types of building facades were conducted to finalize the building design and optimize the building performance. Detailed reports of the energy consumption in different design schemes were generated and used for analysis and comparison. Boundary conditions and assumptions were defined for the energy simulation. The limitations of this study were also discussed. Some of the limitations included:

(1) The building geometry was simplified and remodeled in DesignBuilder. Therefore, the building geometry modeled in the DesignBuilder is not exactly the same as the architectural model. The modification of the geometry can affect the simulated energy consumption, however, differences should be small.

(2) The simulation used the Worcester weather data file provided by the Department of Energy. The actual local microclimate can be different from data present in the weather file. Existing buildings surrounded the newly proposed building, which can for example reduce the localized wind speed.

The building system was optimized with a double skin facade that utilizes both mechanical and natural ventilation. Energy simulations indicated that the EUI of the finalized design of the addition is 36.08 kBtu/ft^2. These results are 65.3% less than the median Site EUI for College/University buildings in U.S. The design meets the 60% target of the 2030 CHALLENGE.

A detailed design for the double skin facade was also developed. This report provides section drawings to show the construction of the facade. The building facade consists of an exterior facade functioning as a rain screen, and an interior facade with built-in vents to allow natural ventilation. Individual control over the interior environment, glare issues and overheating by solar radiation were taken into considerations when developing the facade design.

Nomenclature

CEE	The Department of Civil, Environmental, and Architectural Engineering
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
DB	DesignBuilder
EIA	Energy Information Administration
EUI	Energy Use Intensity
GUI	Graphic User Interface
HDD	Heating Degree Day
HVAC	Heating, Ventilating, and Air Conditioning
IBC	International Building Code
IECC	International Energy Conservation Code
IESNA	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
SHGC	Solar Heat Gain Coefficient
UDI	Useful Daylighting Illuminance
USGBC	US Green Building Council
WPI	Worcester Polytechnic Institute

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1 Introduction

Worcester Polytechnic Institute (WPI) is a leading national university founded in 1865 in Worcester, Massachusetts. Kaven Hall (Fig. 1) at WPI houses the Civil and, Environmental Engineering Department (CEE). CEE provides undergraduate programs in Civil Engineering, Environmental Engineering and Architectural Engineering, and graduate programs in Civil Engineering, Environmental Engineering, and Construction Project Management. Kaven Hall was built in 1954, named after Moses Kaven. The building was originally built to only house the Civil Engineering Program. The current size of the student body in the CEE Department, and the addition of two new majors, were not anticipated when the building was constructed. As new programs have been established in recent years and more students are enrolled, the CEE Department now faces an issue of accommodating more students in the limited space in Kaven Hall. To address this issue, additional study space is needed to meet the growth of the student body. This is especially true for the newly established Architectural Engineering Program, which requires dedicated studio space, labs and classrooms to facilitate the educational activities. These drivers bring forth the desire to expand Kaven Hall in the near future.

Figure 1 Existing Kaven Hall

This Major Qualifying Project (MQP) involves the design of a high performance building that will address the space needs of the CEE Department. The proposed building is a 30,779 square foot expansion to Kaven Hall, and is intended to become an example of sustainable design strategies based on the local climate conditions and the function of the space. Parametric studies of daylighting conditions and computer-aided building energy simulation will be performed in order to obtain a good architectural solution. The design effort will focus on the integration of architectural design and building technology by using Autodesk graphic design software, simulation software such as DIALux and DesignBuilder, and applying state-of-the-art façade technologies available in the building industry. The design proposal strengthens the architectural design intentions, by (i) conducting a parametric study of daylighting condition, (ii) developing building interior lighting design, (iii) developing a detailed design for the most prominent building facade, and (iv) performing building energy simulation and analysis. The architectural design deliverables include a 3D Revit Model, a site plan, floor plans, sections, elevations, detail drawings, and exterior and interior renders.

The proposed addition to Kaven Hall is a multi-use academic building, which offers different types of spaces to be used for educational activities. The new addition connects Kaven Hall to the upper campus and Gordon library. The first floor of the addition is conceived as lab space. The second floor is used for classrooms and offices. The third floor provides large open studio spaces, an exhibition space, and a cafeteria on the west wing. The third-floor mezzanine functions as a student lounge, and is also used as circulation space. Two doors on the west wing, located on the third floor and the third-floor mezzanine respectively, serve as alternative entrances to the Gordon Library. The rooftop is accessible to pedestrians and features a green roof. Portion of the existing Kaven Hall are also renovated. An elevator is installed in Kaven Hall to comply with ADA requirement and to provide accessibility for disabled people.

2 Background

Many factors need to be considered when designing a high performance building, including but not limited to the local climate, the orientation of the building, the building enclosure, the mechanical system, the lighting systems, and the electrical systems. The building geometry and the building facade are usually the first things that attract people's attention to a building. A proper building geometry can maximize the occupancy space and attract people's attention while a well-designed building envelope can provide a safe and comfortable enclosed or semi-enclosed space. The lighting systems, including daylighting and artificial lighting, provide visual comfort and HVAC systems are designed to offer the occupants with thermal comfort and good indoor air quality based on the local climate. An integrated building design requires the collaboration of architects, engineers and professions from other related industries, and involves architectural design, structural system design, electrical system design, mechanical system design, and fire protection system design. This project will focus on the architectural design, building façade, lighting system design, and energy performance.

2.1 High-performance Buildings

Energy efficient and environmental friendly buildings attract much attention, as there is a growing concern and awareness about the energy consumption in buildings. According to annual energy consumption data released by the U.S. Energy Information Administration, in 2011, residential and commercial buildings' energy use accounts for 41% of the total energy consumed in U.S. (22% by residential sector and 19% by commercial sector)[1]. In order to reduce the energy consumption in the building sector, many professionals have worked on developing better design solution to minimize building energy use. Sustainable high-performance buildings use energy more efficiently and provide high-quality indoor environment. Compared to traditional buildings with similar scale and functions under similar climate conditions, high-performance buildings consume less energy over their life cycles and also provide safe and more comfortable indoor environment for their occupants. Particularly, Well-designed building enclosure and Heating, Ventilating, and Air Conditioning (HVAC) system play an important role in occupant thermal comfort and indoor air quality.

The bulk of the energy consumed during building operations is for space conditioning and lighting. According to a recent review on buildings energy consumption, 48% of energy consumption by typical office buildings in the USA is for space heating, cooling and ventilation [2]. The indoor microclimate varies as the outdoor temperature and relative humidity change over years. As the indoor temperature and humidity are expected to be maintained within the comfort zone, HVAC systems are used to balance heat gain and loss resulting from the heat transfer through the building enclosure. Heat transfer occurs through conduction, convection and radiation. In addition to sensible heat storage within the thermal mass of a building, phase change processes may also be used to attenuate a building's thermal performance. Conduction occurs by direct contact between two solid materials. Convection occurs between fluids and solids, or within fluids. Radiation occurs by electromagnetic waves through a gas or vacuum [3]. Heat flows across the layers within the building enclosure by conduction, and then is transferred from the enclosure to the air by convection and radiation processes. The energy from the sun is transferred to the building by solar radiation. People and equipment also produce heat within the building and transfer it to the ambient environment by convection and radiation. This internal heat gain adds to the cooling loads in hot days and can be used to offset heating loads in cold days. However, complicated situations can occur when the building perimeter area requires heating while the interior area needs cooling.

In high-performance buildings, in order to reduce the energy use for mechanically heating, and for cooling and ventilating the indoor spaces, the buildings can be designed to use natural ventilation to cool the interior and maintain good indoor air quality. Natural ventilation relies on the buoyance effect and wind pressure [4]. There are three types of natural ventilation, stack ventilation, cross ventilation and cooling towers or solar chimneys. Nowadays, stack ventilation and cross ventilation are commonly used in building design. Stack ventilation is assisted by the buoyance effect while cross ventilation is driven by wind pressure [5].

2.2 Daylighting

Daylighting, as an alternative lighting solution, can be used to reduce the required artificial lighting demands during daytime to satisfy visual comfort. A lot of studies have been done to explore strategies for applying natural daylighting in buildings and to evaluate the lighting requirement and metrics. In 2005, the definition of Useful daylight illuminance (UDI) was introduced by Mardaljevic and Nabil [6]. UDI is a climate-based daylight metric used to assess the adequacy and usability of daylight in buildings. The lower limit of UDI was 100 lux and the upper limit was 2000lux. The range of UDI was later updated to 100 - 3000lux and is divided into two sub-levels, UDI supplementary (100 - 300lux) and UDI autonomous (300 - 3000lux) [7]. For a space where the daylighting is within the 100-300lux levels, artificial lighting may be required for achieving the desired illuminance for general tasks such as reading and drafting. A space with 300-3000lux daylighting is most likely visually comfortable for all indoor activities[7].

Daylight availability, visual comfort and energy consumption are three factors which are interrelated with each other and which influence a building's livability and sustainability. It is often found that it's hard to obtain an optimized solution because in order to optimize the benefit of one factor one may need to compromise the benefit of the others. For example, more daylighting may introduce glare issues and increase heat gain in the cooling season, which may increase the energy consumption. The useful daylight illuminance may therefore have to be compromised in order to reduce the predicted energy consumption and to increase visual comfort. Also, optimizing visual comfort may increase electricity use. However, there are still many probabilities for obtaining more than one solutions that can lead to good results.

2.3 Computer-aided Simulation

As sustainable design has become an important topic in the building design industry, computer-aided simulation has become more widely used to assess dynamic energy performance of buildings. Such simulations involve solar studies, daylighting and artificial lighting simulation, and total building energy use and comfort simulations. Green Building Studio is a cloud-based energy analysis software developed by Autodesk. A building modeled in Revit can be directly sent to the Green Building Studio to run energy simulations. Radiance is a software package for architectural lighting simulation that uses ray tracing. DesignBuilder software is a comprehensive tool which can simulate the energy consumption for a whole building, and conduct daylighting analysis and CFD calculation. DesignBuilder software uses EnergyPlus as the engine for energy and comfort analysis and HVAC modeling. It also uses Radiance for daylighting analysis.

In the past, studies have been done to validate various energy simulation software such as DesignBuilder and Radiance, in order to assess their usability and accuracy. In a case study of energy modeling in DesignBuilder by Wasilowski and Reinhart, the analysis results of using building simulation software to predict the energy use is very positive and suggestions are given for properly choosing climate data in order to obtain reliable simulation results [8]. A Radiance-based daylight simulation method DAYSIM is validated under more than 10,000 sky conditions in a test office [9].

Computer-aided simulation has been used for many studies related to building energy consumption and daylighting conditions. In one study for the daylight condition in an atrium-type house, DIVA and Radiance were used to assess the visual comfort conditions in the house in two different locations [10]. In a study of energy saving and thermal comfort, DesignBuilder was used as the simulation tool to understand how much energy consumption can be reduced by widening the air temperature setpoints without compromising thermal comfort [11].

3 Procedures

3.1 Site Survey

A site survey was conducted to gather pertinent design information for developing the architectural design and models. Photos and measurements were taken on site in order to model Kaven Hall and the adjacent buildings accurately. The site study involved research on the neighborhood, including local traffic and zoning requirement. The zoning ordinance in the City of Worcester was used for developing the architectural design baseline. Existing drawings were collected to develop the site model in Revit, with the help offered by Milad Zabeti Targhi, a PhD candidate in the Department of Civil, Environmental and Architectural Engineering.

3.2 Architectural Design

The architectural design was developed in AutoCAD and Revit. Floor plans were developed in AutoCAD. The 3D model was constructed in Revit. As part of the design development, a solar study was conducted using the solar study function that comes with Revit. Four individual sun path studies were conducted for the summer solstice, winter solstice, spring equinox and fall equinox. The results were used for interior lighting design and shading design. A study of incident solar radiation on the vertical surfaces was conducted in Ecotect Analysis software.

3.3 Lighting System Design

Both daylighting and artificial lighting are important parts of the building system as they provide adequate light for the building occupants. In order to provide a high-quality lighting solution in the new building, the daylighting design requirement in LEED V.4 was used as a reference, and the artificial lighting system design was developed according to the interior lighting requirement described in LEED V.4 [12] and IESNA Guidelines.

LEED specifies the requirements for UDI in order to obtain 1-3 points for daylight. Simulation is required to show the achievement of autonomy illuminance on a minimum percentage of the occupied floor area on specific days. In order to obtain 1 point, LEED requires demonstrating through simulation that on a clear-sky day at the equinox, at least 75% of the regular occupied floor area is illuminated by daylight at an illuminance level between 300 – 3000 Lux for 9a.m. and at 3p.m.

Daylight simulations were performed using the DesignBuilder software tool, in order to predict the daylighting conditions in the new building. Simulation results were then analyzed and daylighting conditions were evaluated. Adjustment was made to optimize the design.

For the artificial lighting, LEED requires that individual controls should be available for no less than 90% individual occupant spaces and should have at least three lighting levels [12]. Illuminating Engineering Society of North America (IESNA) recommends various comfort illuminance levels for different spaces. For instance, the illuminance levels recommended for classrooms is 300lux and 500lux depending on the nature of the tasks and the illuminance level recommended for drafting room (studio) is 750 lux.

3.4 Building Energy Simulation

To assess the energy performance of the new addition and the renovated existing Kaven Hall, local weather data is needed. The research results published in the "Modelling an Existing Building in DesignBuilder/E+: Custom versus Default Inputs" [13] shows that the difference between the on-site measured weather data and the weather data provided in the DesignBuilder is very small and insignificant for the building energy simulation. Due to the time limitation of this project and based on the abovementioned recommendation, the author decided to directly use the Worcester weather file that is available in DesignBuilder.

The architectural design was simplified and remodeled in DesignBuilder. The energy model included an HVAC system and corresponding operation schedules. The heating system was assumed to use fan-coil units fueled by natural gas. The cooling system was assumed to use electricity from grid. The performance of the HVAC system was assumed to have a coefficient of performance (COP) for both heating system and cooling system equal to 1. Activities were scheduled in the model based on architectural design.

The electricity use for exterior and interior lighting systems was calculated based on IECC1998, using the available IECC1998 template in DesignBuilder. Simulations with different facade designs, different types of glazing, and three ventilation options were conducted in

DesignBuilder. The architectural design was finalized to have the optimal energy performance based on the simulation results.

The following assumptions have been made for the energy model:

1. The adjacent buildings, including Kaven Hall, Fuller Laboratories and Gordon Library have the same occupant zones and were modeled as adiabatic component blocks. The effect of shading and reflection was taken into account for the simulations and the material property of the component blocks was defined as brick.
2. The hill and surrounding terrains were modeled as ground component blocks. The effect of shading and reflection was taken into account for the simulations, and the material property of the component blocks was defined as soil.
3. To model the double skin facade, the space between the exterior facade and interior facade was defined as unoccupied and was modeled as a cavity.
4. Electricity use by the interior equipment was included in the calculations.
5. Heating setpoint temperature was defined as 68°F (20°C) and cooling setpoint temperature was defined as 73.4 (23°C).
6. The building enclosure was assumed to be not perfectly airtight. The infiltration was determined at 0.300 ac/h.
7. The operation of the space heating and cooling system was scheduled based on the zone occupancy, using the corresponding schedule templates in DesignBuilder.

3.5 Comparison of Two HVAC Calculation Methods

After the architectural design was finalized, the building cooling and heating loads were calculated in spreadsheet templates provided by Professor Kenneth Elovitz. The cooling and heating loads calculated by using the spreadsheets and the cooling and heating loads calculated by DesignBuilder were compared. Difference between two calculation results was expected.

Main formulas used for heating and cooling load calculation in the spreadsheet:

1. Heat gain through wall and roof: $Q = U \times A \times CLTD$
2. Heat gain through glass: $Q = A \times (SC \times SHGF \times CLF + U \times CLTD)$
3. Heat loss through wall, roof and glass: $Q = U \times A \times (T_{in} - T_{out})$

3.6 Facade Design

A detailed facade design was developed in keeping with the overall architectural design. Detail Drawings were prepared in AutoCAD. Glazing panels, support brackets, and anchors were designed or selected from products in the market.

4 Scope of Work

4.1 Architectural Design Development

An architectural design will be developed considering the site, local climate, functions and aesthetics. The new building will include large studio spaces, a lighting lab, HVAC lab, building science lab, classrooms, offices and lobby areas. The design result will be delivered by a set of drawings including site plans, floor plans, sections, and exterior and interior perspective views.

4.2 Parametric Study of Daylighting

A parametric study of the daylighting will be integrated into the architectural design phase to finalize the design. The simulation results will be used for lighting system design.

4.3 Lighting System Design

Based on the function of each individual space and daylighting conditions, a conceptual design of a building lighting system will be proposed to emphasize the architectural design and provide visual comfort by following IESNA guidelines and meeting LEED requirement.

4.4 Building Energy Simulation

Building energy models will be developed in the DesignBuilder to assess the building's energy efficiency and estimate the energy consumption. The analysis and conclusion made based on the simulation results will be used for detailed façade design and HVAC system design.

4.5 Comparison of Two HVAC Calculation Methods

The heating and cooling load will be calculated with two methods, computer simulation and Commercial Load Calculation Method. The calculation and results will be assessed and compared. The advantage and limitations of two methods for HVAC calculation will be discussed.

4.6 Facade Design

Case study will be carried out for the purpose of exploring the possibility of applying double skin facade design in the New England Area. A detailed building façade design will be developed after the architectural design is finalized. The design solution will be delivered by detail drawings.

5 Design Development

5.1 Architectural Design

5.1.1 Design overview

This project aims to design a multi-use academic building, adjacent to Kaven Hall, in order to offer more available spaces for the Department of Civil, Environmental and Architectural Engineering to use for educational activities. The addition compromises 3 lecture classrooms, 6 offices, 3 building science laboratories, 3 large studio spaces and other essential academic spaces and functions. The addition also connects Kaven Hall to the main campus and, and as a result, attracts more circulation on this part of campus. The addition is designed to function as a large laboratory for architectural engineering students to develop a deep and comprehensive understanding of building systems. The HVAC system remains exposed to the interior space, aiming at helping architectural engineering students to better develop their understanding of HVAC systems. All the weather and energy usage data will be recorded for educational and academic purposes. Continuous research will be conducted to document building operation and follow up the actual energy performance. The concepts of high-performance building and sustainable design are applied and articulated through the whole design process. The addition is envisioned to become a LEED accredited building on the WPI campus and demonstrate WPI's support for green buildings and sustainability.

The newly proposed addition has an accessible roof for people to walk across. The building features a green roof to manage water run-off, improve indoor air quality, and reduce energy consumption for space heating and cooling. [13] The green roof also reduces the effects of heat aging from natural exposure and the thermal stress on the roofing membrane, which as a result increase roof membrane durability. [14]

5.1.2 Site analysis

The existing Kaven Hall is a U-shape building located on the lower campus, next to a hill. There are two options for locating the addition. The first option is to place the addition on the hill (Fig. 2). The second option is to design it on the east side of the existing Kaven Hall (Fig. 3). An analysis and comparison of these two options was conducted by taking various factors into consideration, including usable areas, anticipated circulations, the location of Kaven Hall, and the expected function of the addition. While the addition could also be envisioned on the Boynton parking lot, this option was not considered to allow future campus expansion in that area.

Figure 2 Potential Site 1

Figure 3 Potential Site 2

The addition is expected to offer large studio spaces, lab space, and more classrooms and offices in order to provide enough space to meet the rapid growth of the CEE Department. Thus, a site with larger usable area is preferred. The total site area in option 1 is approximately twice of the site area in option 2. According to the Zoning Ordinance issued by the City of Worcester, there is no restriction or requirement for setback for option 1. However, building on site 2 is required to have a setback requirement of 15ft for the frontage, 10ft from the side, and 10ft from the rear. [8] Therefore, the option 1 promises more usable area than option 2.

To pick the best site, the location of Kaven Hall and expected circulations are also important factors. Kaven Hall is located on the northeastern corner of the main campus. However, most of the academic buildings on the main campus are located on the upper campus. Thus, it is desirable to make a strong connection between Kaven Hall and the rest of the campus. Currently, from Kaven Hall, people can walk up the hill either by a staircase located on the west side of Kaven Hall or through Fuller Laboratory. However, it is inconvenient for disabled people to walk from Kaven Hall up to the other buildings on the upper campus. Thus, an addition that can facilitate the circulations from Kaven Hall to the upper campus is favored. Based on the reasons mentioned above, option 1 is preferred to option 2.

5.1.3 Building codes

The design was designed to comply with the International Building Codes and Zoning Ordinance issued by the City of Worcester.

Referring to the International Building Code, the occupancy group of an academic building on the university campus is Business Group, Group B. [15] According to the Zoning Map of the City of Worcester, Worcester Polytechnic Institute is located in District IN-S. [16] According to the Zoning Ordinance issued by City of Worcester, the minimum depth for the front setback is 15ft, for the side setback is 10ft, and for the rear setback is 10ft. There are no restrictions or requirements for area, frontage, height and maximum floor to area ratio for buildings in District IN-S. [17] Because the addition is not built off the street, there is no requirement of the yard setbacks for the addition.

5.1.4 Kaven Hall 3D model

The Revit model of existing Kaven Hall was obtained and was modified and further developed by the author, based on the architectural design of the addition. Parts of the interior space were rearranged to accommodate the addition and the installation of an elevator.

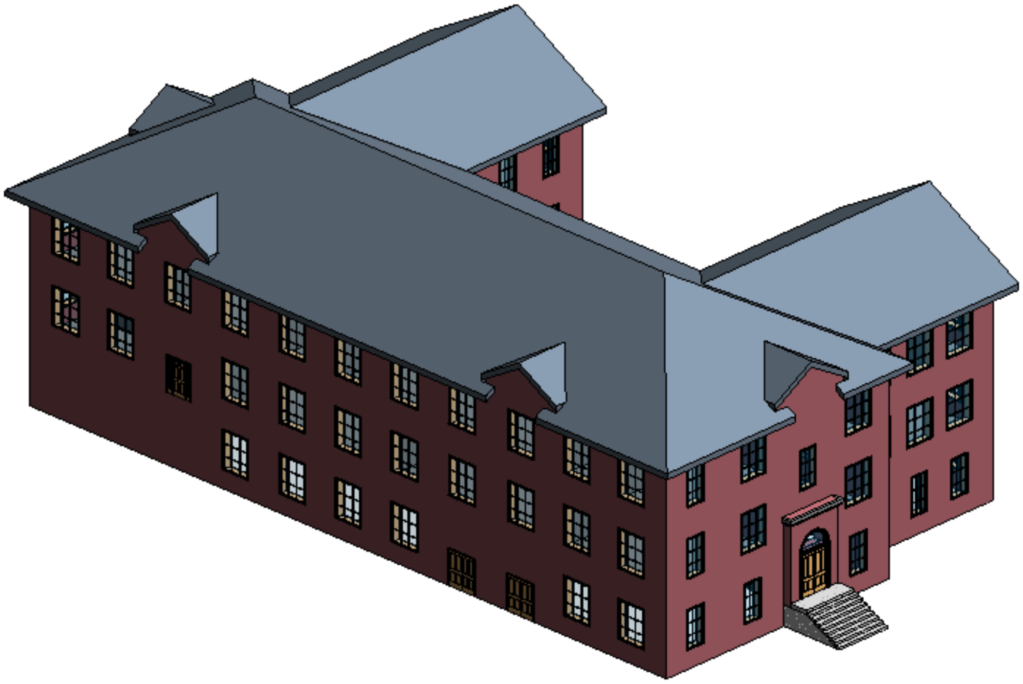


Figure 4 Perspective view of Kaven Hall Revit Model (Credit to Milad)

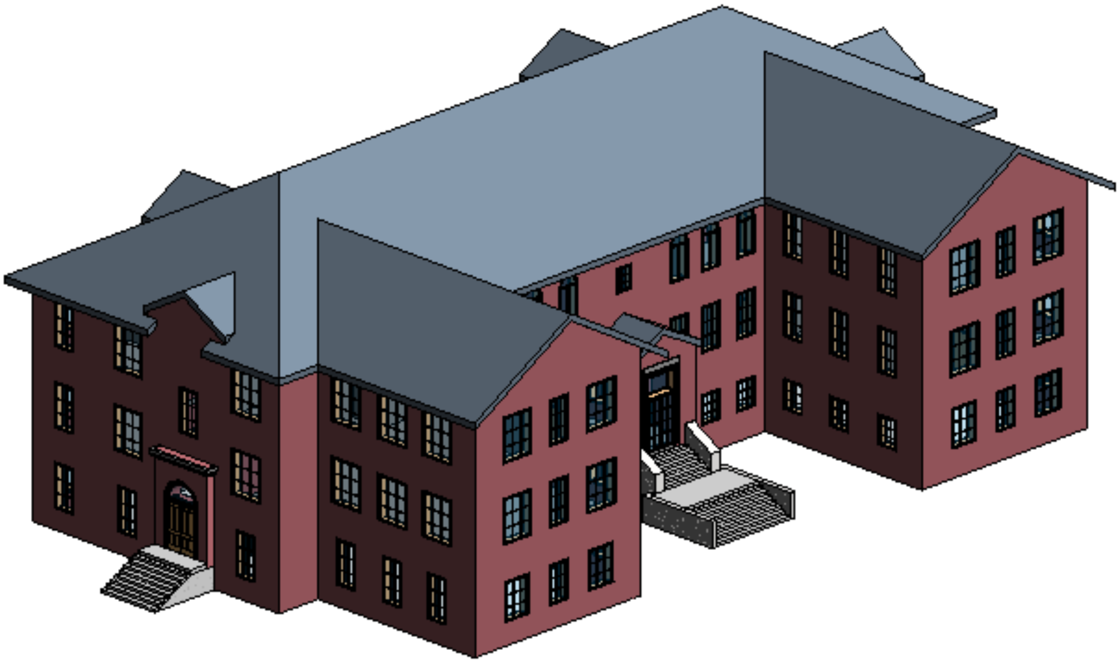


Figure 5 Perspective view of Kaven Hall Revit model (Credit to Milad)

5.1.5 Architectural design solution

5.1.5.1 Geometric form

Function, structure and beauty are the three elements that form a building. [18] Thus, a building as a whole creates a usable interior space and represents a form of art. The geometric form of the addition was inspired by the surrounding landscape and the concept that "less is more". The design aimed to offer large usable spaces and convenient transitions between destinations. Function and geometry resulted in the architectural design of the addition. The structural solution was developed from the geometry and function. Function, structure and geometry impacted each other and led to the final design solution.

Inspired by "less is more", the initial design concept was developed and the design elements were taken from the landscape and the existing forms in the surrounding natural environment. The designer wanted to let the building itself express how the form evolves from the environment and also differentiates itself from other buildings on the WPI campus. The hill had a rounded shape and smooth curves. These elements were used to develop the geometry of the addition. The addition also serves as a bridge to connect the existing Kaven Hall to the

Gordon Library and the upper campus. To achieve this design goal, the addition was designed in an “L” shape, following the outlines of the hill, turning to the south direction and connecting to the second floor of the Gordon Library. The second floor of Gordon Library is four-floors higher than the basement of Kaven Hall. The first floor of the Addition is expected to align with the basement of Kaven Hall. Thus, the new addition has four floors. The first, second and third floors align with the corresponding floors in Kaven Hall, which are the basement, the first floor and the second floor, separately.

5.1.5.2 Circulation

Kaven Hall was located on the north entrance of the WPI campus, at the southwest corner of the intersection between Boynton Street and Salisbury Street. However, the traffic through the north entrance and the circulation through Kaven Hall are currently not much, compared with the other entrances of WPI. The diagram of existing circulation (Fig. 6) presents that people avoid walking into Kaven Hall unless their destination is Kaven Hall. Only students who have class in Kaven Hall and faculty working in the Department of Civil, Environmental, and Architectural Engineering will walk into this building. Students and visitors coming from the Boynton Parking Lot usually walk uphill by the ramp and then take the stairs next to the Fuller Laboratories. For disabled people, the only way that they can enter Kaven Hall is to enter the third floor of the Fuller Laboratories, take the elevator down to the first floor and pass through northeast entrance, and go through the west entrance of Kaven Hall. In addition, they are only able to move around on the first floor in Kaven Hall due to the fact that there is no elevator inside this building. In order to increase the circulation through Kaven Hall, it is proposed to install an elevator in Kaven Hall and design and provide an accessible means of egress for disabled people.

The local climate also affects the circulation through Kaven Hall and along the hill. In the winter when the snow covers the external ramps and stairways, they are so slippery that people will choose other routes to travel to their destinations. The circulation through Kaven Hall and along the hill thus decreases due to the weather. The addition is intended to provide a safer indoor passageway for people uphill, and thus will attract more circulation through the northeast corner of the WPI campus.

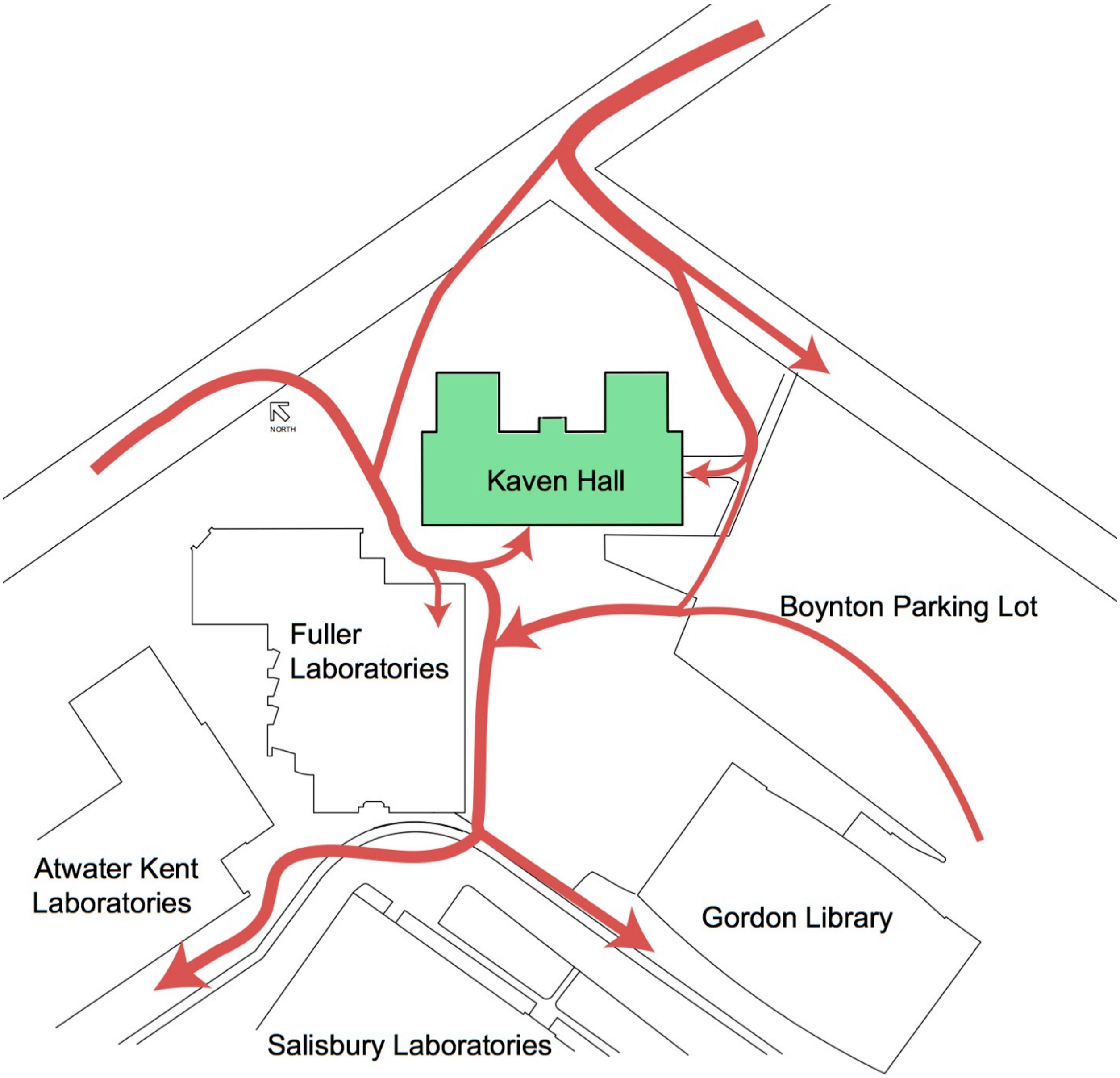


Figure 6 Existing circulation

The newly proposed addition aims to handle pedestrian traffic coming from the Boynton Parking Lot, Gordon Library, Fuller Laboratories and the rest of the WPI campus and make Kaven Hall more accessible to people. The west wing of the addition attaches to the first- and second-floor of Gordon Library. Students are able to walk directly into the library from the west wing, without taking a detour. Also, students are able to enter Kaven Hall directly from Fuller Laboratories through a side door, as shown in the expected circulation diagram (Fig. 7).

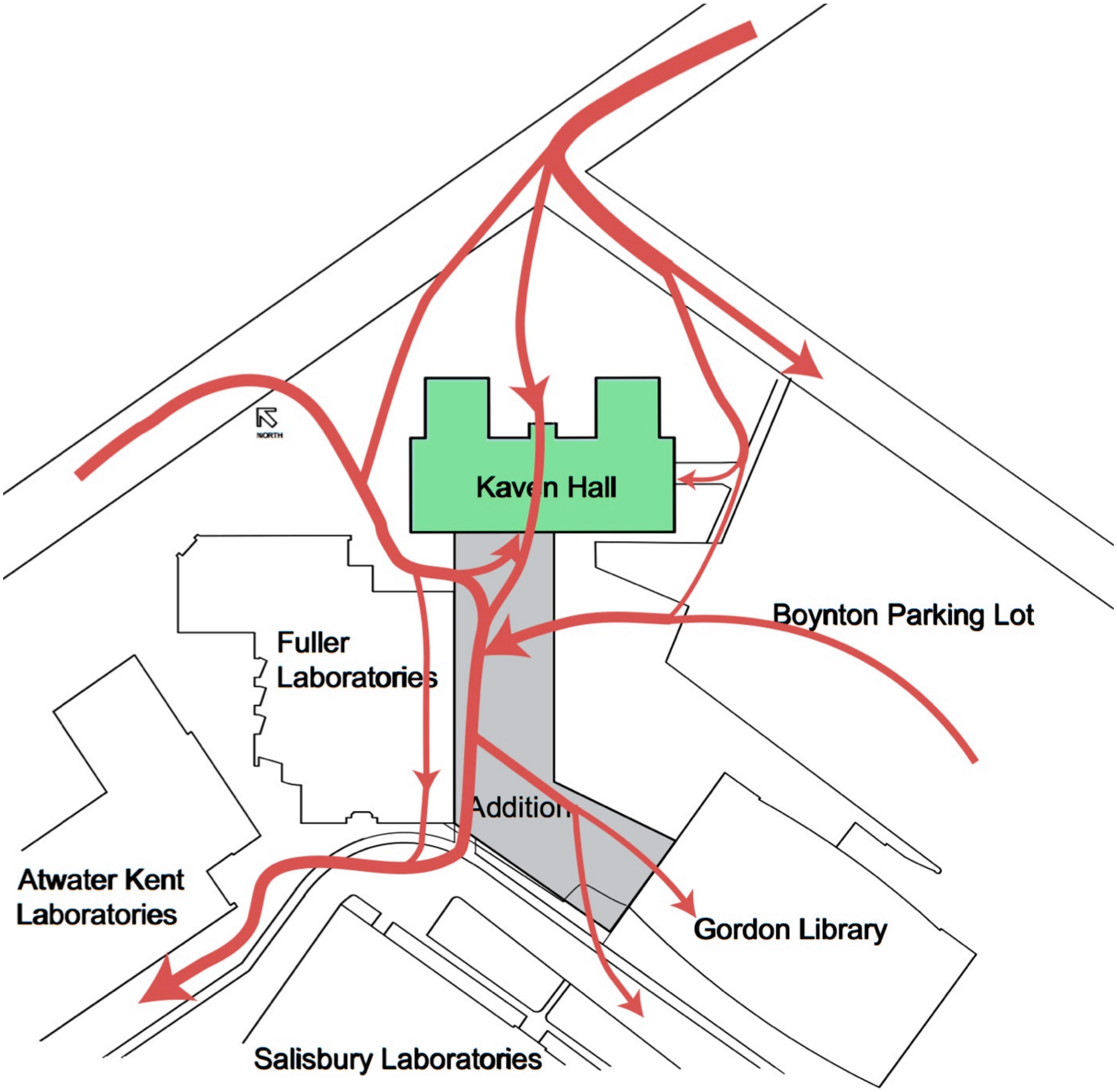


Figure 7 Expected circulation

5.1.5.3 Floor plans and elevations

The proposed addition to Kaven Hall is a three-story multi-use building with different types of space on each floor. The addition has three entrances, including the south entrance on the first floor, the north entrance on the second floor, and the west entrance on the third-floor mezzanine. The space on the first floor is used for laboratories (Fig. 8). A Building Science lab, lighting lab, and an HVAC lab are located on first floor. The space on the second floor is mainly used for lecture classrooms, offices and a computer lab (Fig. 9). The administrative office is also located on the second floor, next to the north entrance. Four large studios are designed on the third floor and can approximately accommodate 120-150 architectural engineering students at the same time (Fig. 10). A student lounge and a café area are designed on the west part of the third floor, for students to study and relax. The fire stairs and restrooms on each floor are located on the same location to facilitate emergency usage.

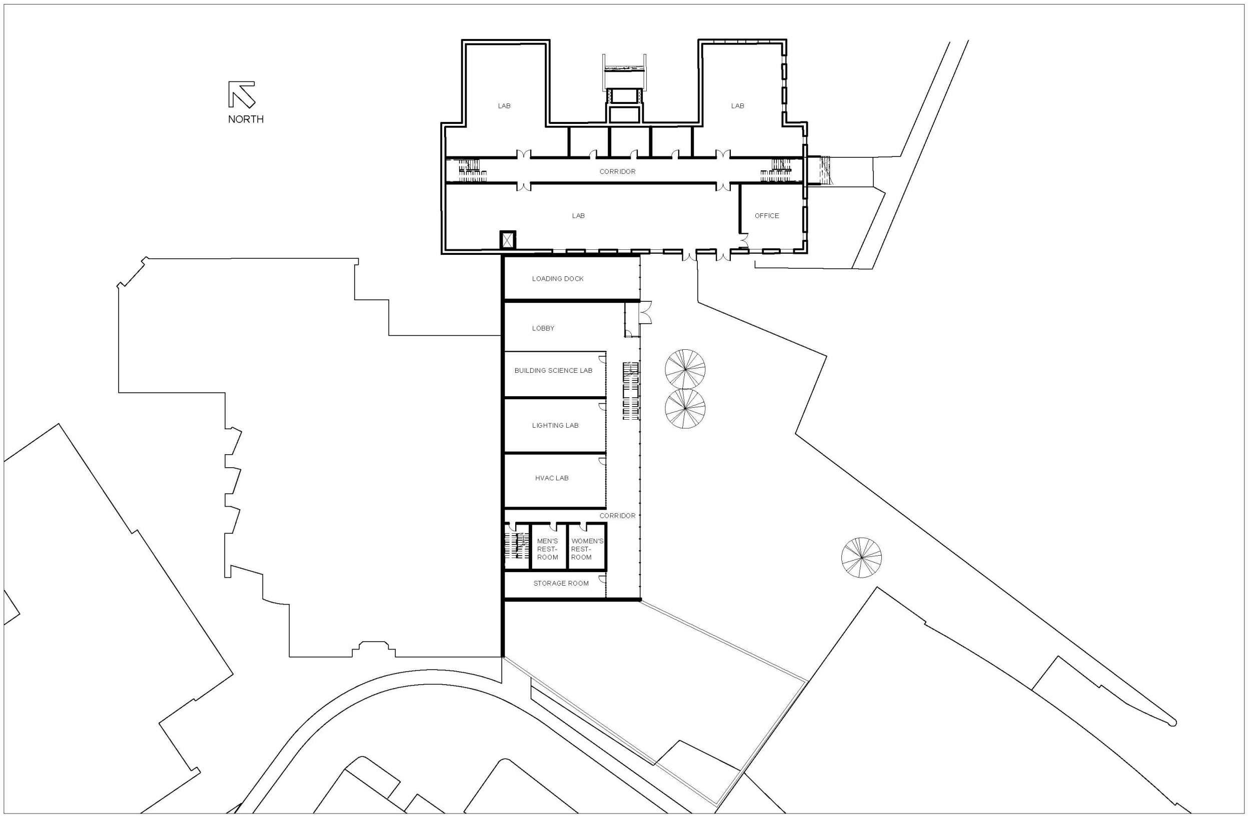


Figure 8 First floor plan

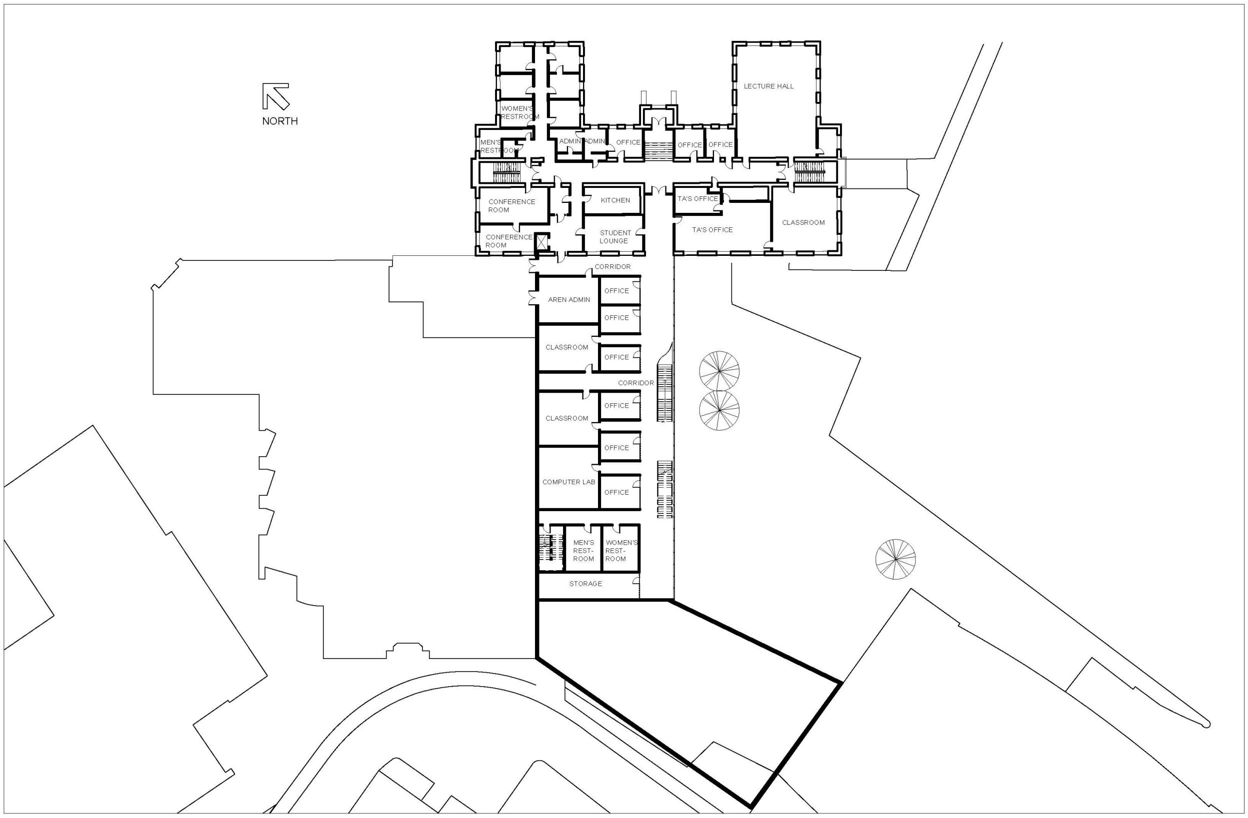


Figure 9 Second floor plan

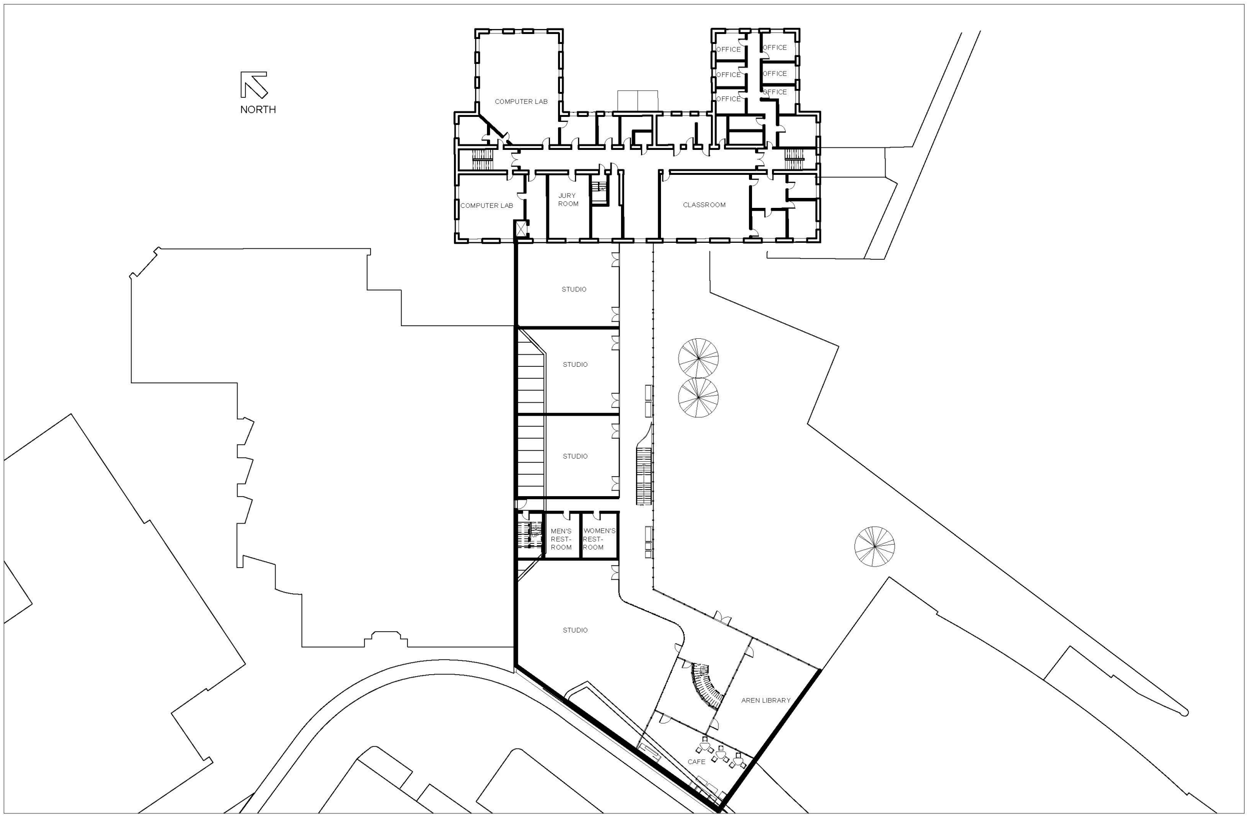


Figure 10 Third floor plan

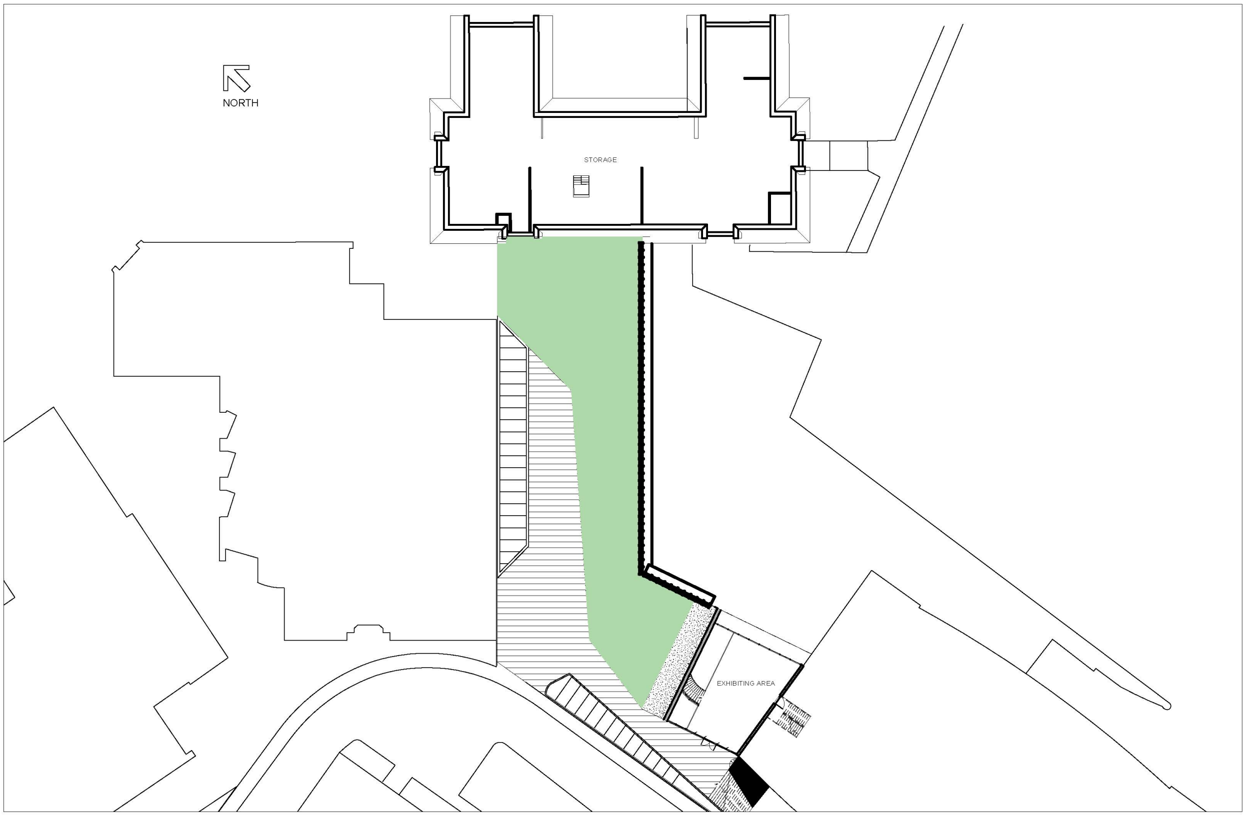


Figure 11 Roof plan and third-floor mezzanine plan

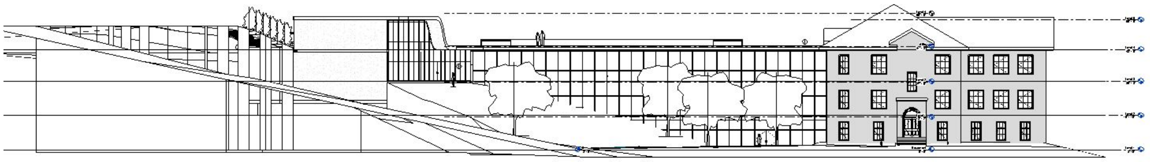
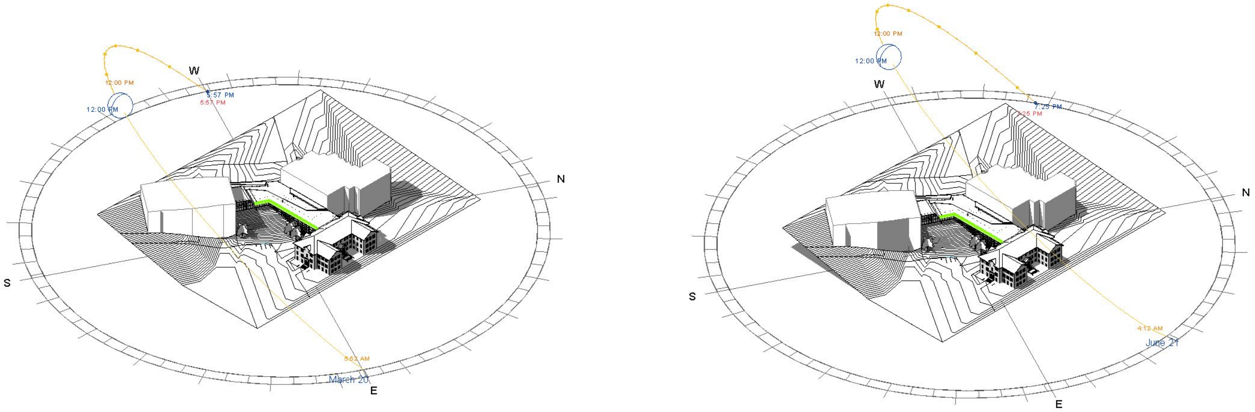


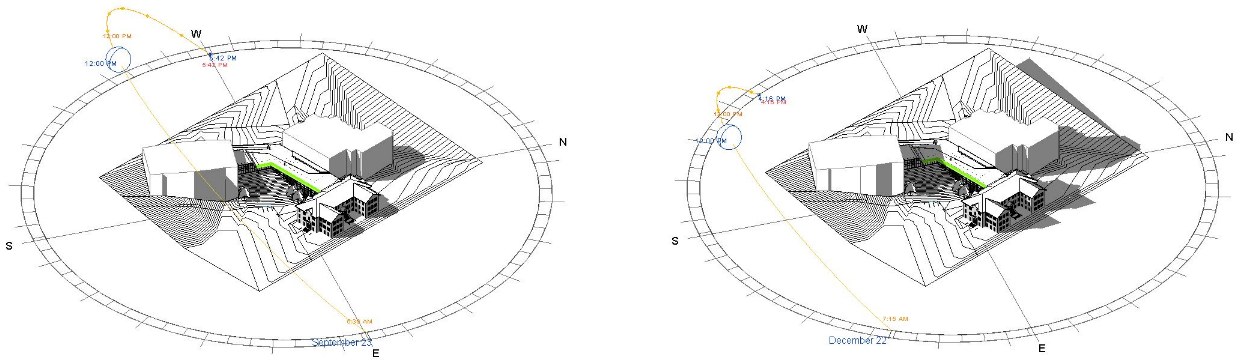
Figure 12 South elevation

5.1.5.4 Shading devices

A solar path study (Fig. 13) was conducted in Revit in order to design proper shading devices. According to the solar path, the south side of the building needs horizontal shading to block the solar radiation in the morning and early afternoon. Controllable blinds with medium reflectivity were selected as the horizontal shading devices on the southern facade. Because of the low sunlight from the west in the afternoon, vertical shading device were preferred for the west side of the building in the afternoon. Permanent vertical fin shading devices were designed for the west entrance. In order to keep the facade simple and neat, the shading devices were designed on the interior side of the curtain wall. The design of interior shading reduced undesirable direct sun lighting and solar heat gain through the facades.



Spring equinox Summer solstice



Fall equinox Winter solstice

Figure 13 A solar path study for equinoxes and solstices

5.1.5.5 Architectural renders

Renders generated from Autodesk Revit software and modified in Adobe Photoshop show how the building interacts with the surrounding landscape and adjacent academic buildings. While most of the buildings on the WPI campus are built with bricks, this new addition will bring a modern taste to the campus (Fig. 14).

Figure 14 A daytime exterior view from the Boynton Parking Lot

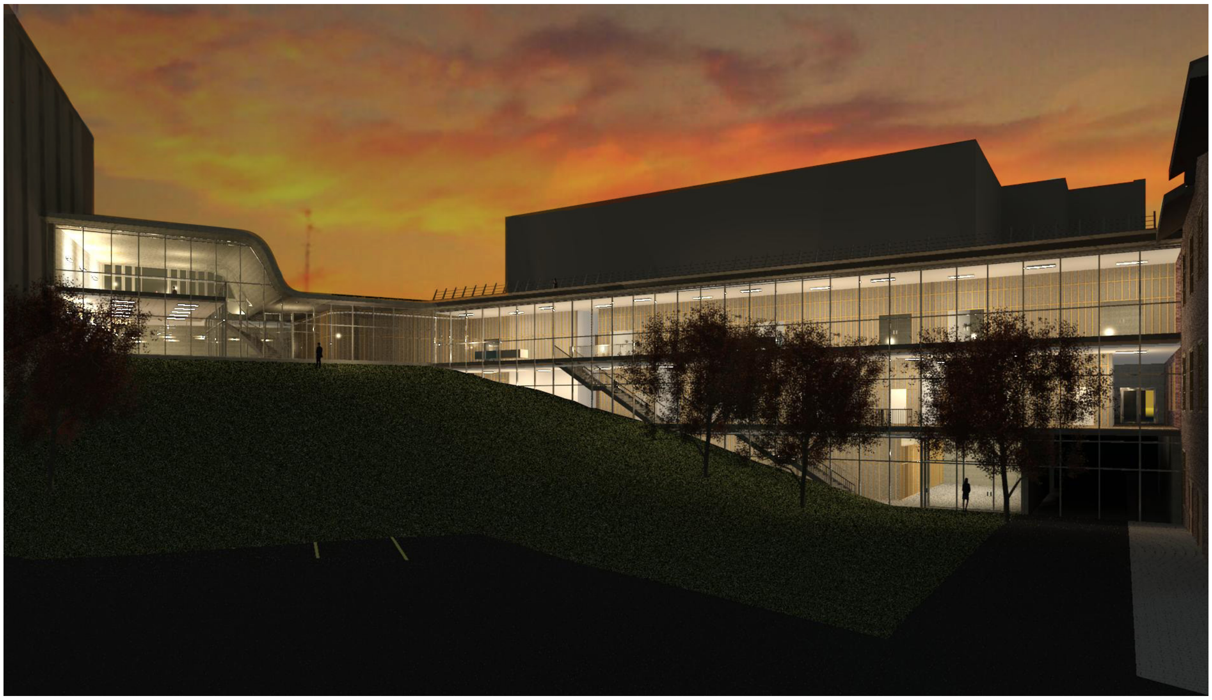


Figure 15 A late afternoon exterior view from the Boynton Parking Lot

Figure 16 A nigh exterior view from the Boynton Parking Lot

Figure 17 A bird’s eye view of the addition to Kaven Hall

Figure 18 An exterior view from the west entrance

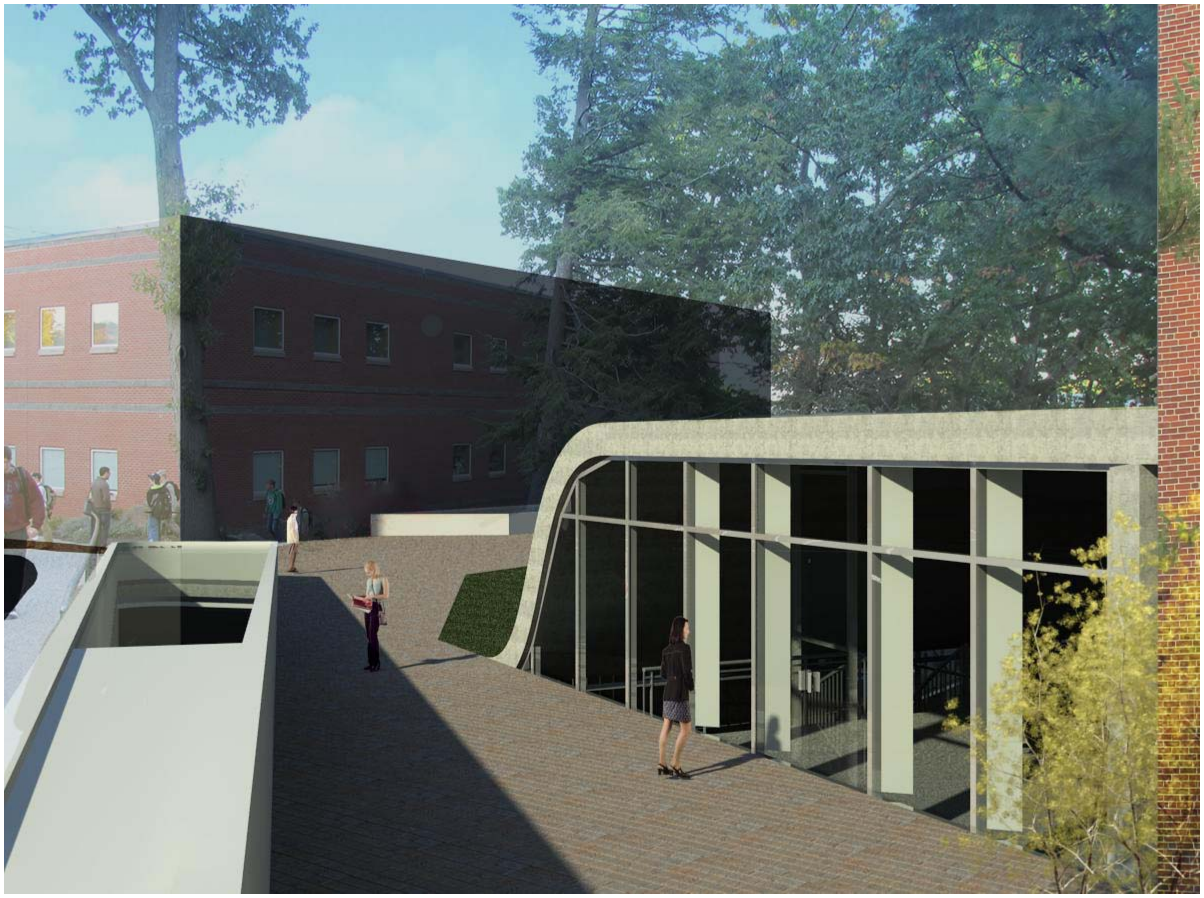


Figure 19 Another exterior view from the west entrance

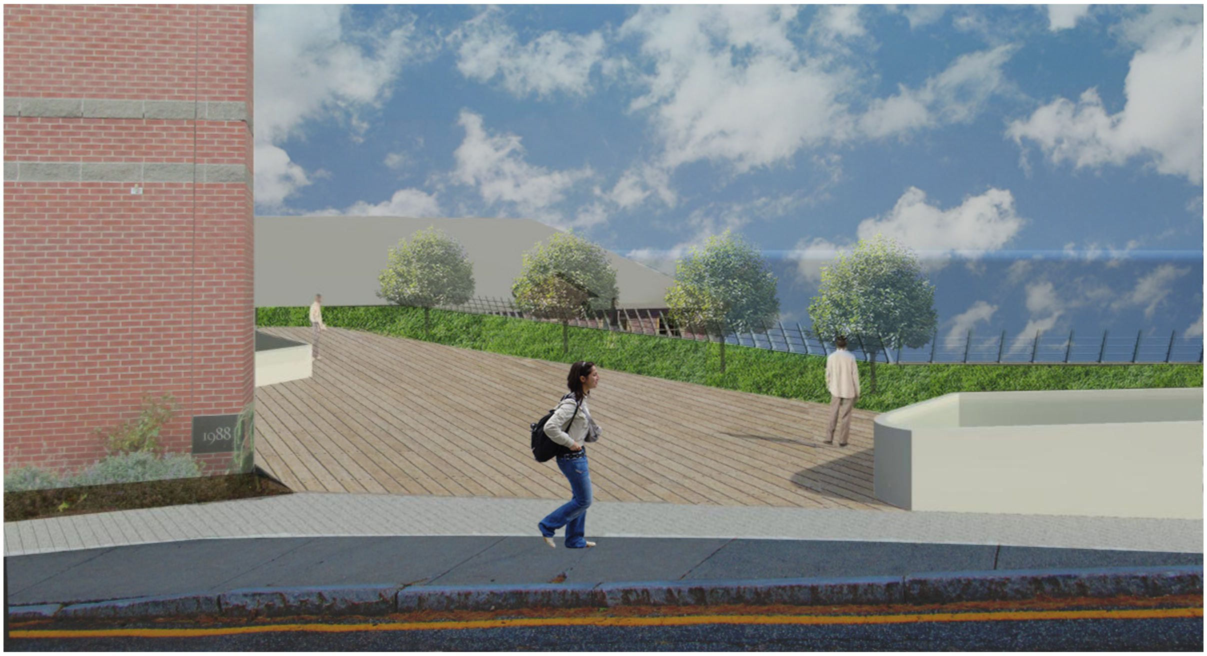


Figure 20 A roof view from the upper street

The interior partitions were designed as wood-framed glass walls which were not see-through. Pilkington Optifloat^{TM} Opal translucent glass was selected for the interior partitions. This acid-etched glass product has high light transmittance and admit sufficient light to filter through. It also offers required privacy and diffused natural light for the labs, studios and classrooms.

An alternative design for the interior partition is to use wood-framed fabric partitions. Fabric also offers privacy through light diffusion and admits light into the room. However, fabric allows more sound transmission and is less thermally insulated than glass, and also raises fire-safety and durability concerns.

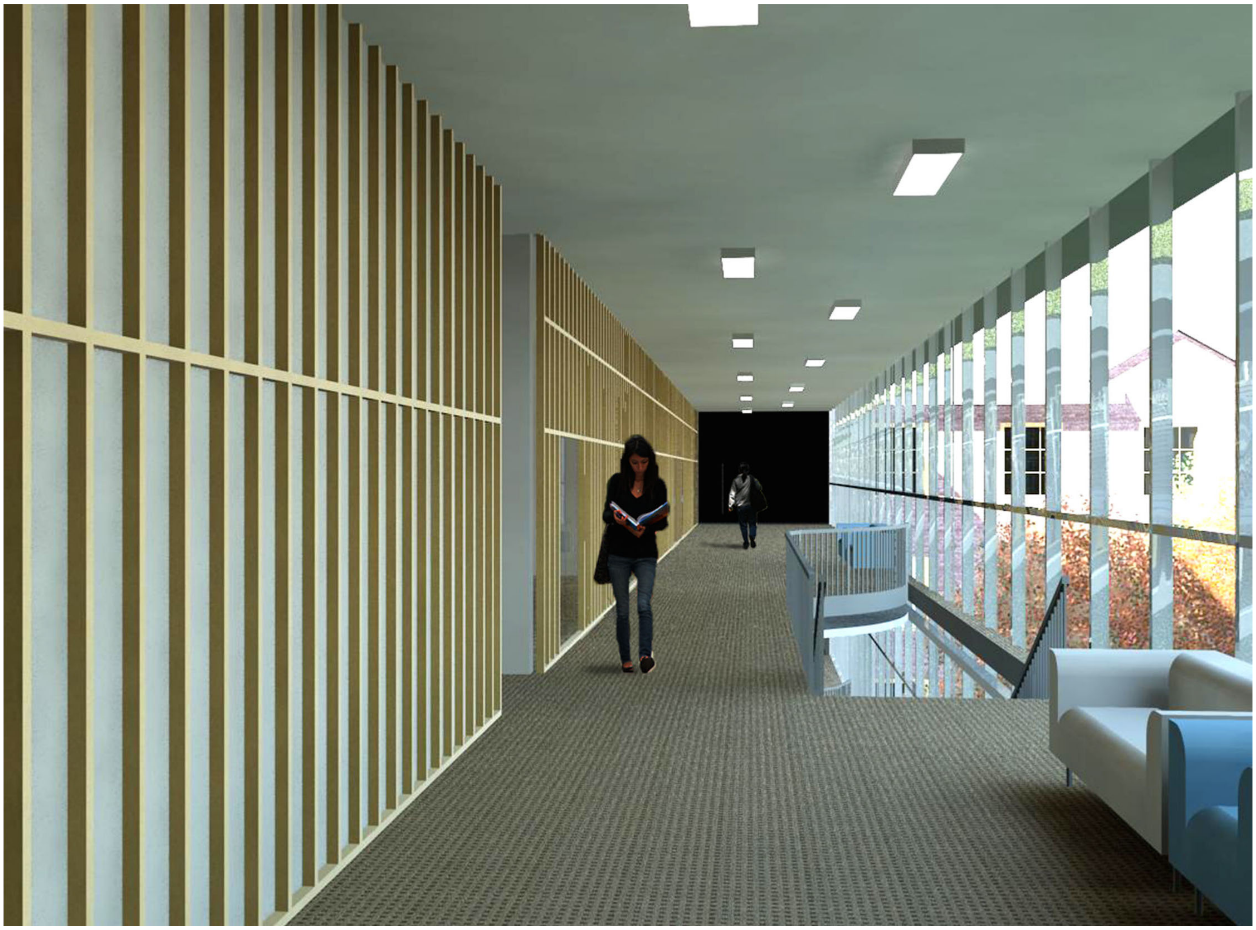


Figure 21 A daytime interior view of the third-floor corridor

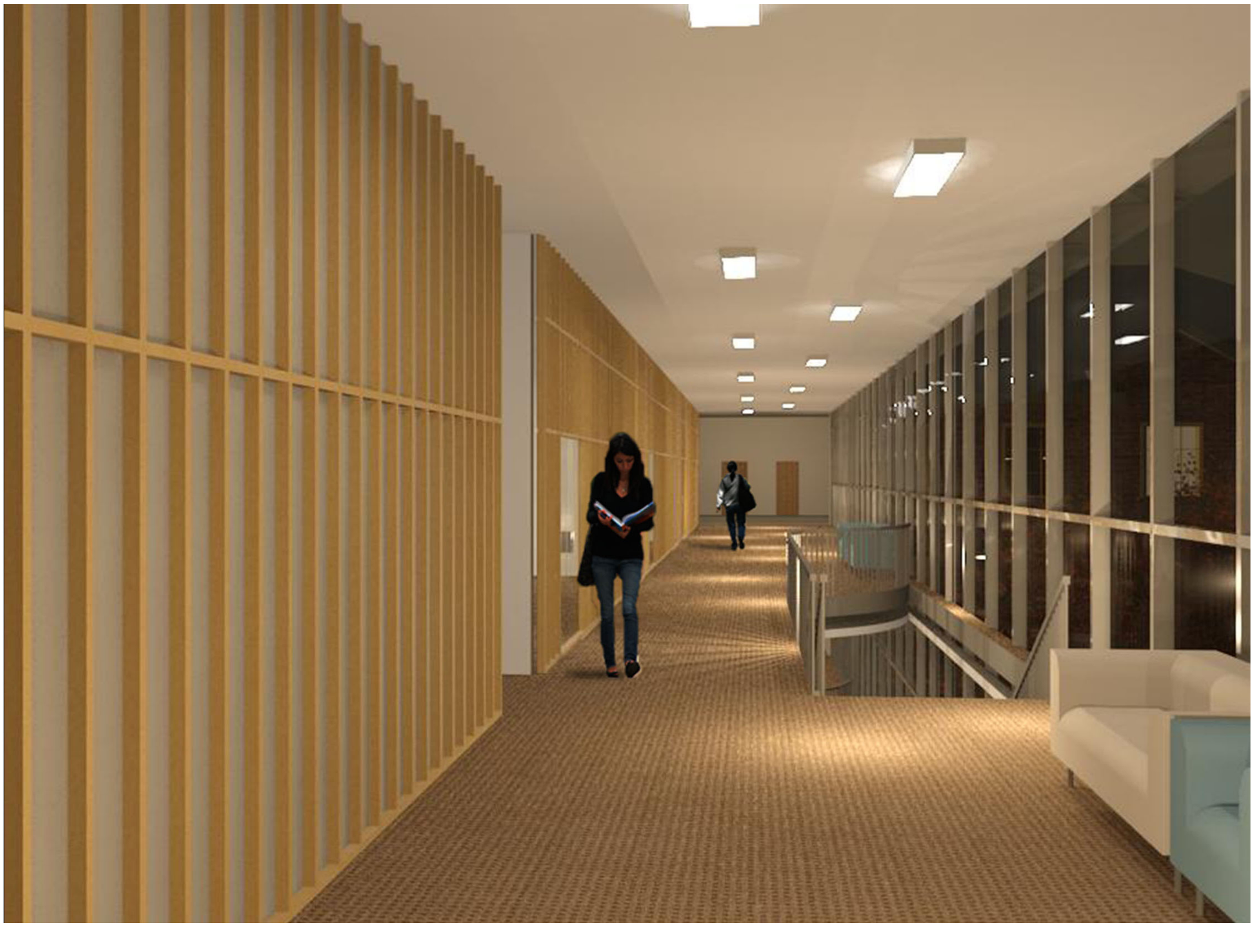


Figure 22 A night interior view of the third-floor corridor

Another interior render shows the interior space in the west wing of the addition and the view of the hill and existing Kaven Hall through the glass facade (Figure 23).

Figure 23 An interior view of the west wing

5.1.5.6 Conclusions

The architectural design was developed from the considerations for function, structure and geometry. The addition offers lab spaces, studio spaces, classrooms and offices that meet the space needs of the CEE department. The building serves as a bridge between Kaven Hall and the upper campus and handles the circulations appropriately. Large glazing area on the building facade admits sufficient daylight into the building, and shading device are appropriately designed to block undesirable solar heat and direct sunlight. Patterned glass partition allows daylight into the rooms while also offering desirable privacy. Wooden frames blend into the building well and offer a warm feeling.

5.1.6 Solar study

A solar study was conducted using the Ecotect Analysis software, in order to understand how solar radiation interacts with the various building surfaces. The Addition, Kaven Hall, and the surrounding buildings are included in the solar studies.

To have a good model for solar study, the architectural model was first simplified in Revit. The simplified model, which includes the Addition, Kaven Hall, Fuller Lab, Gordon Library, Salisbury Lab and the landscape, was then exported as a DXF file. The model was further modified in AutoCAD. The edited CAD model was then imported into Ecotect Analysis to conduct the solar study. The model was rotated 63° counterclockwise in order to comply with the true orientation. The Worcester weather file for the solar study in Ecotect Analysis was downloaded from the U.S. Department of Energy (DOE) website, same as the weather file used in the DesignBuilder model. [19] The building type was defined as office building in Ecotect Analysis.

Figure 24 shows the annual incident solar radiation for Worcester, MA. The graph was produced based on the input from the Worcester weather data downloaded from DOE in Ecotect Analysis. From the graph, it has been found that the average incident solar radiation from January 1st to December 31st is between 2000 kWh/m^2 and 3000 kWh/m^2. The incident solar radiation peaks in mid March. Worcester has less incident solar radiation in April through August, and also in December. Worcester has more incident solar radiation in January through March, and in September through November.

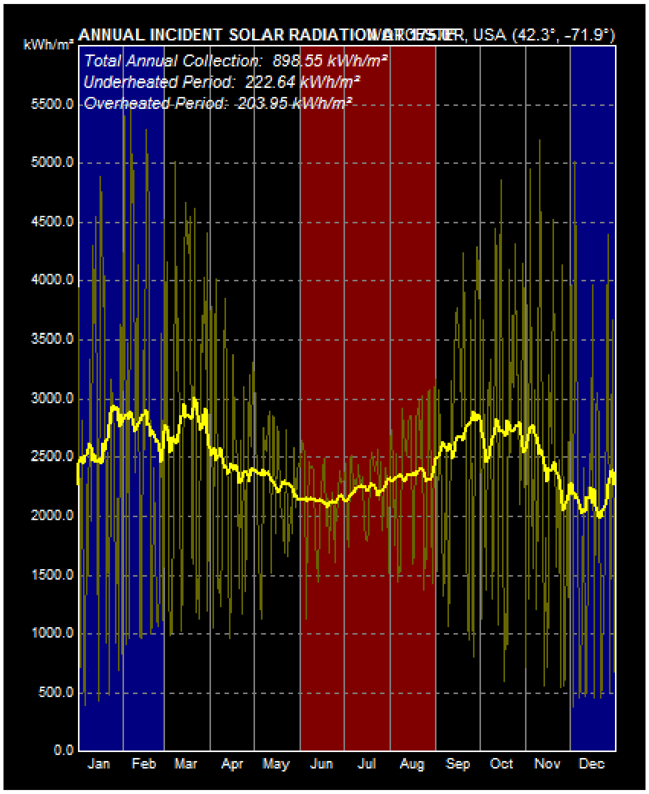


Figure 24 Annual incident solar radiation in Worcester, MA

Based on the weather data and the model, Ecotect Analysis produces a diagram showing the best and worst orientations for the addition, in terms of average daily incident solar radiation on a vertical surface. The yellow area presents the favorable orientations. The optimum orientation is 175° clockwise from north. For a building whose orientation is within the yellow area, it receives desirable solar heat in different seasons; it receives more passive solar heating in the winter, and less passive solar heating in the summer. More passive solar heating in the winter will reduce the heating loads. Less passive solar heating in the summer will reduce the cooling loads. Results indicate that the chosen orientation of the addition falls under the range of the suggested orientations.

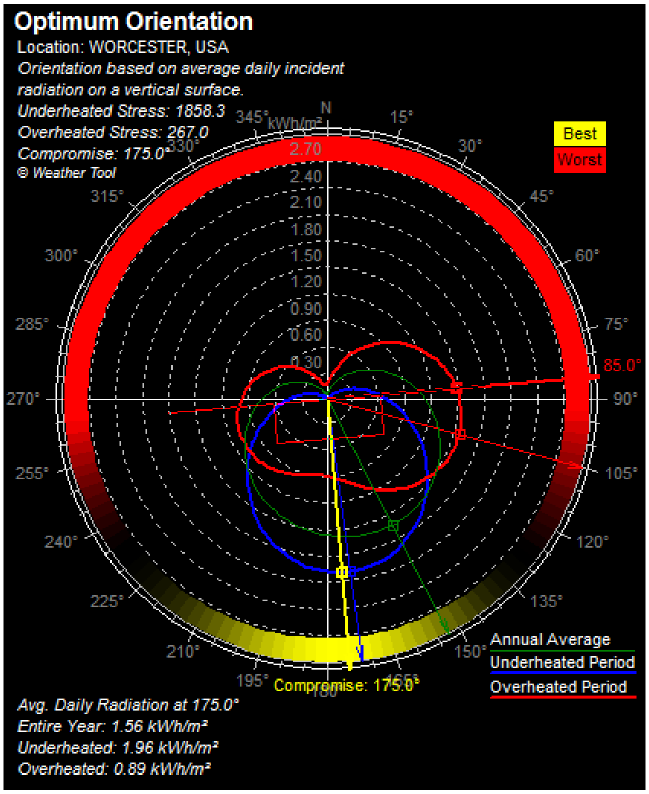


Figure 25 Diagram of orientation based on average daily incident radiation

In the first solar access analysis, the incident solar radiation on the building surfaces was calculated for average daily values over summer, June 1st to August 31st, by using the existing shading tables. In Figure 26, the daily average incident solar radiation on the south facade (crimson surface) is about 4000 Wh/m^2; the daily average incident solar radiation on the east facade (orange surface) is 7000 Wh/m^2. In Figure 27, the daily average incident solar radiation on the west facade (red surface) is 5000Wh/m^2.

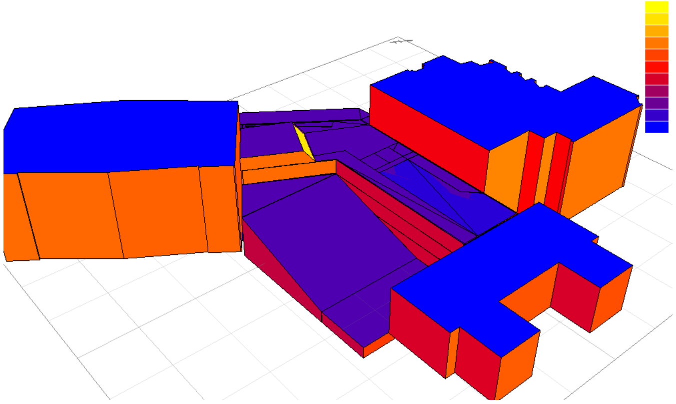


Figure 26 Daily average incident solar radiation in summer (June 1st to August 31st), a south view

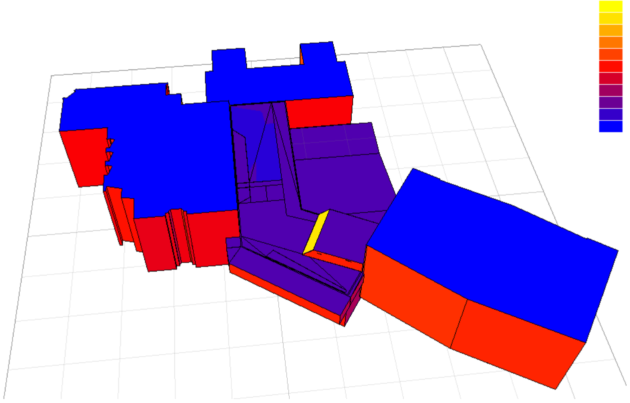


Figure 27 Daily average incident solar radiation in summer (June 1st to August 31st), a west view

In the second solar access analysis, the incident solar radiation was calculated for average daily values over winter, December 1st to February 28th, by using the existing shading tables. In Figure 28, the daily average incident solar radiation on the south facade (crimson surface) is about 1600 Wh/m^2, 60% less than summer time; the daily average incident solar radiation on the east facade (crimson surface) is 3200 Wh/m^2, 54% less than summer time. In Figure 29, the daily average incident solar radiation on the west facade (crimson surface) is 3200 Wh/m^2, 36% less than summer time.

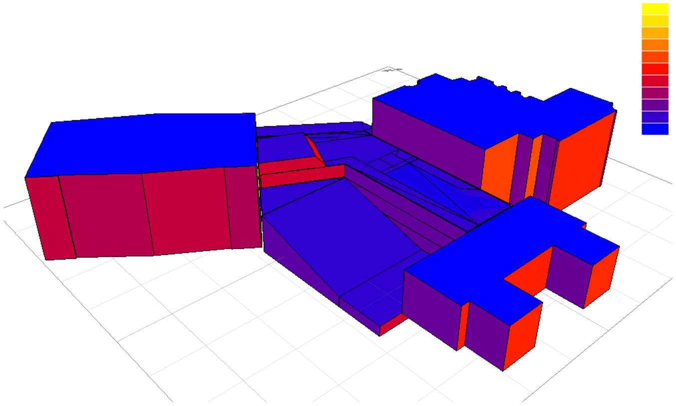


Figure 28 Daily average incident solar radiation in winter (December 1st to February 28th), a south view

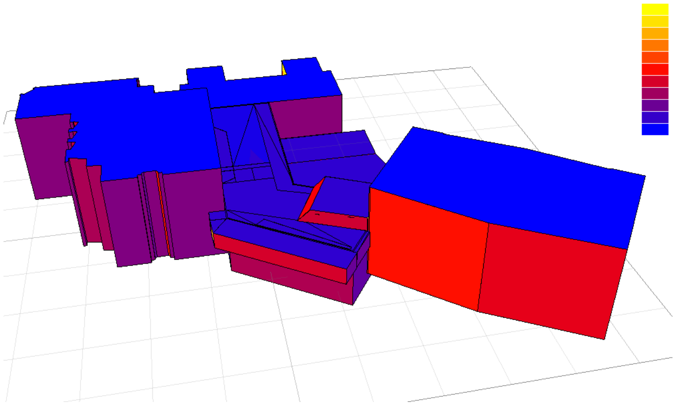


Figure 29 Daily average incident solar radiation in winter (December 1st to February 28th), a west view

Ecotect Analysis results show that the proposed building's orientation and location allow for ample solar exposure. In both seasons, the east facade receives the most solar radiation. The south facade with the largest surface area, receives the least solar radiation in both underheated and overheated days. The ample solar radiation in the summer time requires permanent or switchable shading devices in overheated days.

5.2 Parametric Study of Daylighting

5.2.1 Daylighting requirement

The International Building Code (IBC) requires that "the minimum net glazed area shall not be less than 8 percent of the floor area of the room served" [20]. Illuminance level between

300 lux and 3,000 lux is considered as useful daylight. LEED V.4 requires sufficient useful daylight within the occupied space in order to obtain points. By demonstrating through computer simulations that 75% of regularly occupied floor area has illuminance levels between 300 lux and 3,000 lux for 9a.m. and 3 p.m., on a clear-sky day at the equinox, the building project can obtain 1 point. If over 90% of regularly occupied floor area achieves autonomous UDI, the building project can get 2 points [12].

5.2.2 Methodology

In order to optimize the indoor daylight quality by taking the usage of space and privacy into consideration, different types of partition walls (Table 1) were simulated in DesignBuilder to study their impact on the natural daylight distribution inside the building. The simulation results of daylight distribution were compared. The objective of this study is to optimize the partition wall design based an analysis of the daylight availability and visual comfort. Two types of materials, patterned glass and fabric, were proposed for the partition wall design. In the primary design, the partition wall that separates the other space from the corridor is proposed to use patterned glass panels to prevent glare and offer privacy. The alternative design is to use wood-framed fabric curtain as a partition wall. Fabric admits daylight, while at the same time, permits air flow and offer privacy.

In the simulation, the daylight distribution was calculated on the working plane with a height of 2.4606ft (0.75m) from the floor surface and under the CIE overcast day sky model. A model with lightweight concrete partition wall was used as a reference model to demonstrate the effectiveness of using light-through partition wall. Two type of glass partition with different light transmission were modeled and simulated in DesignBuilder.

Partition wall facing corridors	Lightweight concrete	Single-pane glass	Single-pane glass
		A	B
Light transmission	0	0.881	0.749

Table 1 Partition wall properties

5.2.3 Daylighting simulation results

5.2.3.1 Concrete wall with no light transmission

In the first iteration of daylight simulation, all the partition walls were modeled as lightweight concrete walls, which have zero light transmission and block all natural light. In this scenario, limited floor area received daylight. Artificial lighting was essential for lightening up the classrooms, labs, offices and most of the studio spaces during the daytime. Less than 75% of regularly occupied space had illuminance levels between 300 lux and 3,000 lux. The daylight requirement by LEED V.4 was not met.

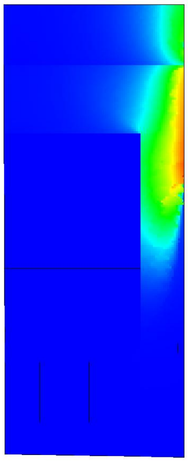


Figure 30 Distribution of natural daylight on the first floor with concrete partition wall

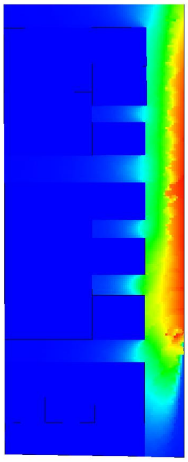


Figure 31 Distribution of natural daylight on the second floor with concrete partition wall

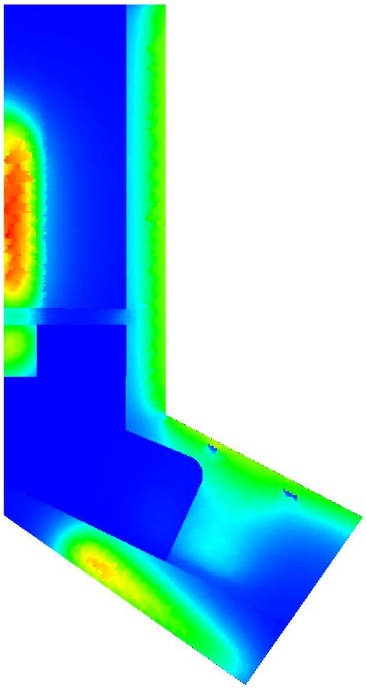


Figure 32 Distribution of natural daylight on the third floor with concrete partition wall

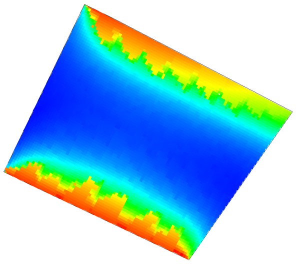


Figure 33 Distribution of natural daylight on the third floor mezzanine with concrete partition wall

5.2.3.2 Single-pane glass A (light transmission = 0.881)

In the second iteration of daylight simulation, all the partition walls were modeled as single-pane glass with the light transmission of 0.881. In this scenario, daylight was admitted through the glass partitions and skylight to the classrooms, labs, offices and the studio spaces during the daytime. 21.4% of the regular occupied floor area on the first floor had illuminance levels between 300 lux and 3,000 lux. 31.1% of the regular occupied floor area on the second floor had illuminance levels between 300 lux and 3,000 lux. 71.5% of the regular occupied floor area on the third floor and 100% of the gross floor area on the third floor mezzanine had illuminance levels between 300 lux and 3,000 lux. The illuminance level was still not achieved due to the fact that there is almost no direct sunlight into the building from the north and east. The daylight requirement by LEED V.4 was not met. Therefore, artificial light is needed, especially on the first and second floors.

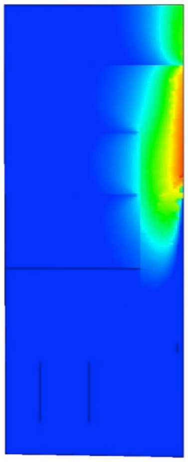


Figure 34 Distribution of natural daylight on the first floor with single-pane glass partition wall

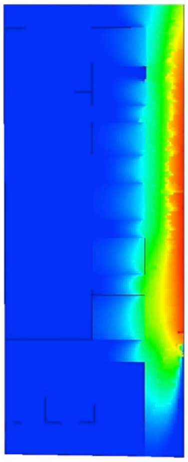


Figure 35 Distribution of natural daylight on the second floor with single-pane glass partition wall

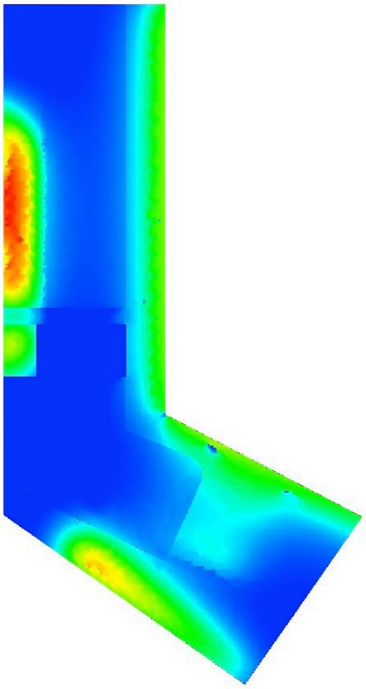


Figure 36 Distribution of natural daylight on the third floor with single-pane glass partition wall

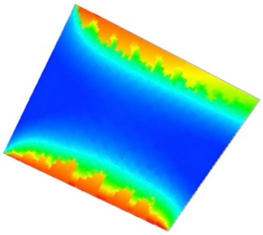


Figure 37 Distribution of natural daylight on the third floor mezzanine with single-pane glass partition wall

5.2.3.3 Single-pane glass B (light transmission = 0.749)

In the third iteration of daylight simulation, all the partition walls were modeled as single-pane glass with the light transmission of 0.749. In this scenario, daylight was admitted through the glass partitions and skylight for lightening up the classrooms, labs, offices and most of the studio spaces during the daytime. The first, second and third floor failed the LEED requirements. 19.8% of the regular occupied floor area on the first floor, 28.3% of the regular occupied floor area on the second floor, and 68.4% of the regular occupied floor area on the third floor achieved illuminance levels between 300 lux and 3,000 lux. The third floor mezzanine passed the LEED test with 100% of the regular occupied floor area having illuminance levels between 300 lux and 3,000 lux. The illuminance level was slightly less than the second scenario, and didn’t meet the LEED requirement.

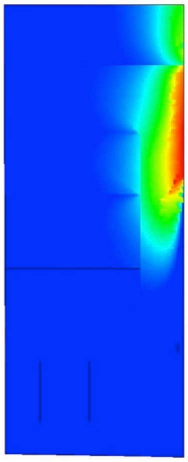


Figure 38 Distribution of natural daylight on the first floor with single-pane glass partition wall

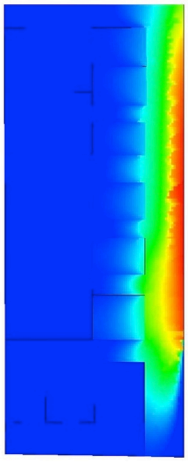


Figure 39 Distribution of natural daylight on the second floor with single-pane glass partition wall

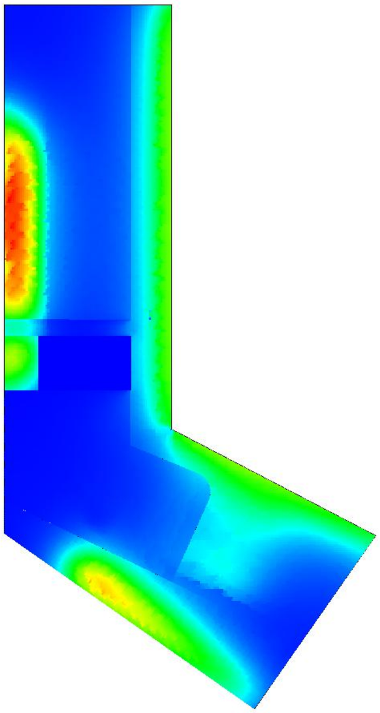


Figure 40 Distribution of natural daylight on the third floor with single-pane glass partition wall

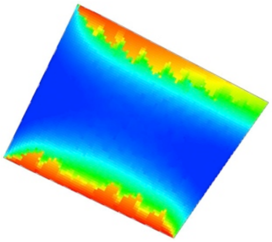


Figure 41 Distribution of natural daylight on the third floor mezzanine with single-pane glass partition wall

5.2.3.4 Analysis and conclusions

A fully glazed partition wall allows more natural light to enter the spaces adjacent to the corridor. The effect of different light transmission rates of the glazing materials makes little difference on filtering natural light. Therefore, the difference between two types of single-pane glazing with different light transmission didn't have significant impact on the light distribution in the building. Though, single pane glass with higher light transmission will admit slightly more daylight. High illuminance presents in the corridor near the glass facade, which will potentially cause glare issues. The installed blinds will help to reduce the glare. High illuminance also presents in the space right below the skylight on the third floor. Installing skylight diffuser can help to prevent glare issues and localized overheating.

In both simulations, the proposed design didn't meet the LEED's requirement for daylighting. Facing the limitation that there is almost no daylight getting into the building from the north and east, it is extremely hard to design the new building to meet the LEED requirement for daylighting. In the second scenario, the third floor and the third floor mezzanine, with 73% and 71% of the floor area having the required illuminance levels respectively, almost meet the requirement.

Pilkington Optifloat^{TM} Opal glass, with light transmission of 0.83, was selected as the glass panels installed in the interior partitions. Being acid etched, it creates excellent privacy and also allows light in.

5.2.4 Alternative daylighting design solution

Based on the simulated daylighting condition in the new building, an alternative design was proposed to improve the daylighting on the second floor. Glass floors are proposed to be partially installed in the three rectangular studios, addressing the daylighting deficiency issue on the second floor. The hatched area in the second floor plan shows the location of the added glass floor (Fig. 42). The daylighting condition was simulated in DesignBuilder. The result in Fig. 43 shows that the added glass floor improved the daylighting condition on the second floor, and useful daylight was introduced to the classrooms, the computer lab and the corridor on the second floor. The percentage of area above illuminance threshold was increased to 38.9%, however, it still didn't meet the LEED's requirement.

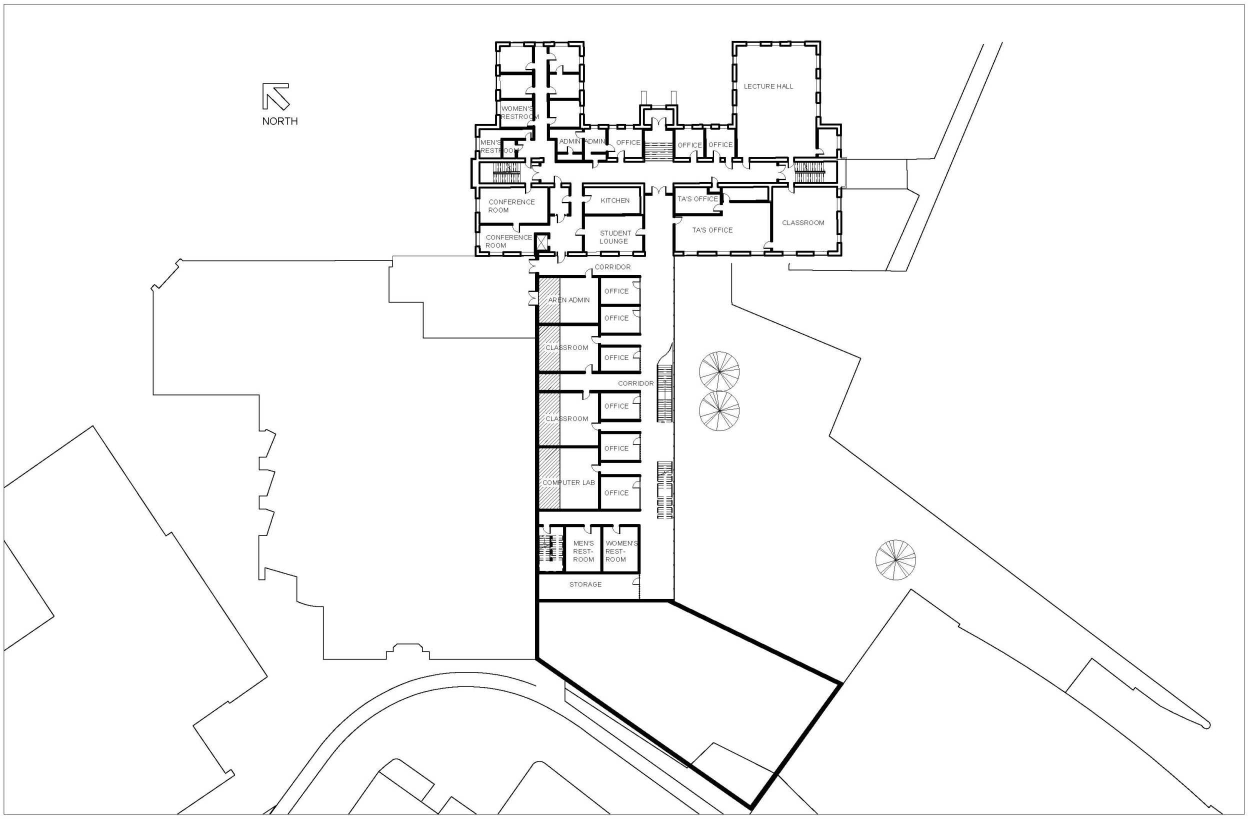


Figure 42 Second floor plan of an alternative design

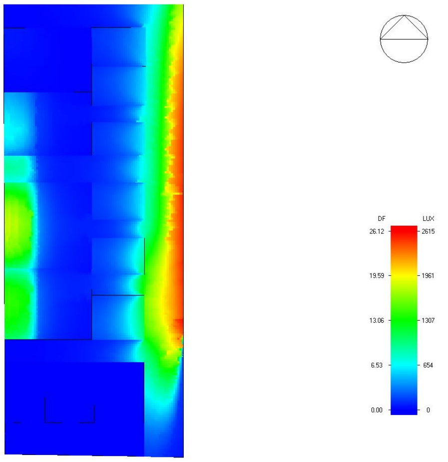


Figure 43 Distribution of natural lighting on the second floor in the alternative design

Glass flooring solutions were looked up on manufacturers' websites. One suggested option is the DEKO HG Fire Floor Glass, produced by DEKO in Denmark (Fig. 44). The DEKO HG Fire Glass is fire rated glass. The glass floor is supported by fireproof steel substructure and is coated with translucent antislip serigraphy. The non-transparent glass panel protects privacy while admitting diffused light into the rooms below.

Figure 44 DEKO glass floor coated with translucent antislip serigraphy (By DEKO)

5.3 Interior Lighting Design

A building's lighting system has a significant impact on the occupant's visual comfort and the electrical energy consumption in the building. The addition to Kaven Hall is expected to have a flexible lighting system with layered lighting in order to adapt to the varied usage of the space during different time. The building's lighting system consists of daylighting and artificial lighting. In the daytime, space, such as corridors, lobby and the exhibition rooms, is lit up by daylight. Both daylight and artificial light are utilized to provide sufficient lighting levels to the spaces such as studios, classrooms and the computer lab. This section focuses on the artificial lighting system design. A conceptual design for the lighting system was developed based on the space usage and the recommended lighting levels published by Illuminating Engineering Society of North America (IESNA).

Layered lighting provides the occupants with flexibility of adjusting the lighting levels in the space for specific activities (Table 2).

Space	Category of lighting
Classrooms, offices, computer lab	General lighting, task lighting
Studio	General lighting, task lighting
Labs	General lighting, task lighting
Corridor, lobby, exhibition space, café shop	General lighting, accent lighting
Reading room	General lighting, task lighting, accent lighting

Table 2 Layered lighting in the addition to Kaven Hall

When designing the lighting system, factors such as activities, system operations and future replacement were taken into consideration. The following objectives were made for the lighting design:

1. Design layered lighting to balance the uneven daylight distribution in the building during daytime.
2. Design layered lighting to provide switchable lighting levels to meet the occupants' specific needs for illuminance when different activities are going on in the space.
3. Design multiple switching and dimming controls to achieve the flexibility of light plan.
4. Minimize the number of lighting fixture types for each category of lighting, to ease the future maintenance and replacement.

For general lighting, T8 linear fluorescent lamps were selected because of their good color rendering, appropriate color temperature and visual comfortable diffused light. Linear fluorescent can achieve a color temperature of 5000K, which is close to natural light [21]. Fluorescent lamps also have excellent lumen maintenance, high average rated life, and low life cycle cost. A T8 fluorescent tube typically has a CRI of 75-98 [21].

According to the suggested luminance level of 750 lux for a studio, the lighting design of a typical studio was developed in the DIALux to visualize and assess the illuminance in the room. (Fig. 45 and 46) The suggested layout of the lighting fixtures in this new building is presented in Fig. 47 to Fig. 49.

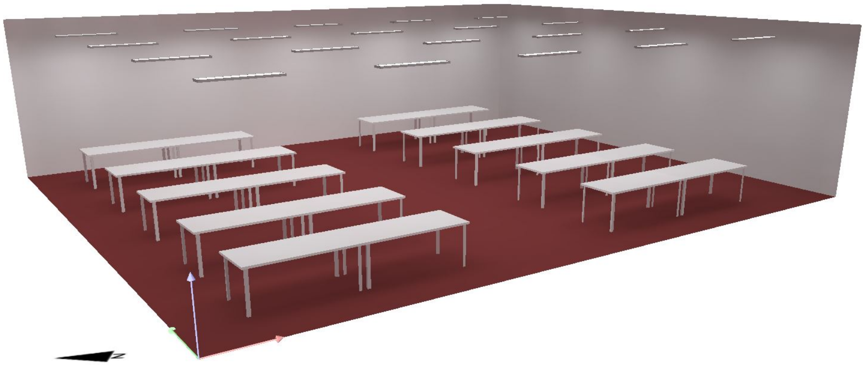


Figure 45 Rendering produced in DIALux

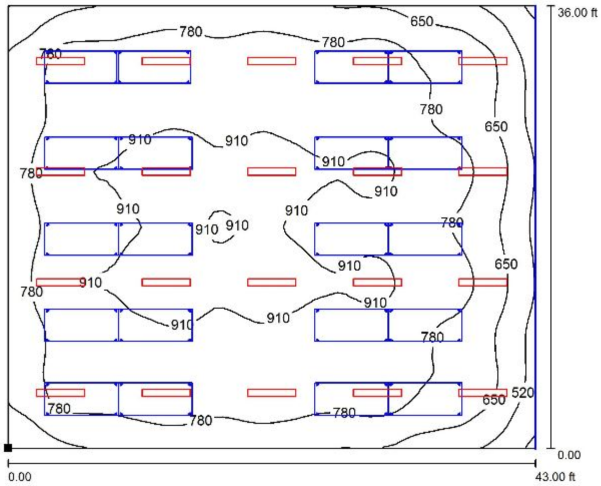


Figure 46 Isoline of the illuminance on the workplane in the studio

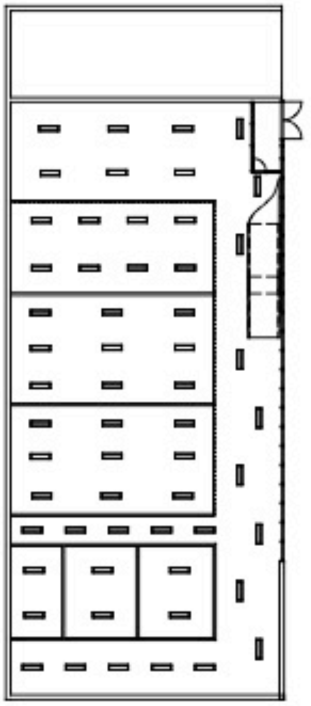


Figure 47 Lighting fixture layout of the first floor

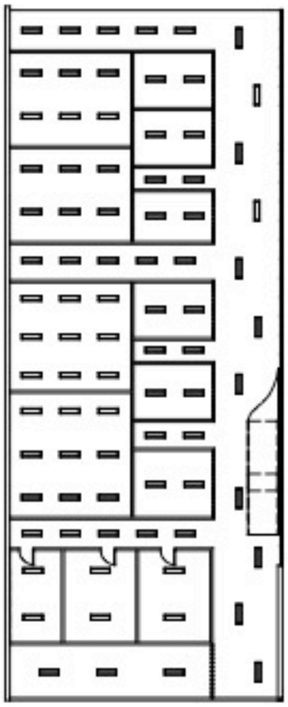


Figure 48 Lighting fixture layout of the second floor

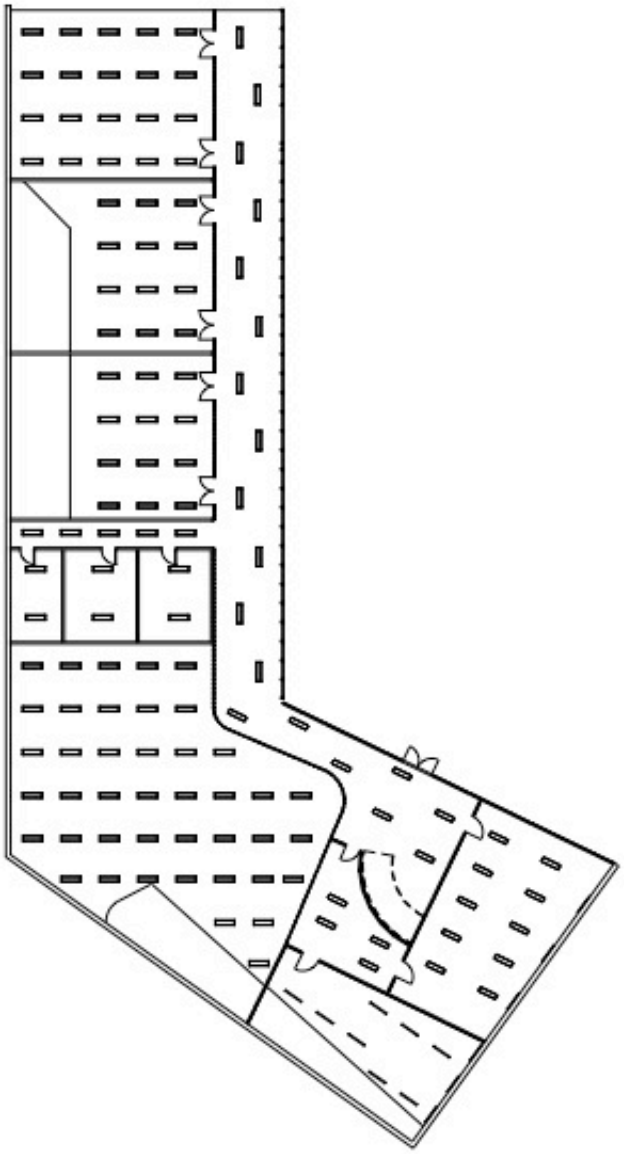


Figure 49 Lighting fixture layout of the third floor

5.4 Building Energy Simulation

5.4.1 Methodology

5.4.1.1 Climate analysis

The U.S. is categorized into different climate zones. Worcester is in climate zone 5A (Fig. 50). The heating degree days (HDD) in Zone 5A is defined as greater than 5400 and less than 7200 HDD's.

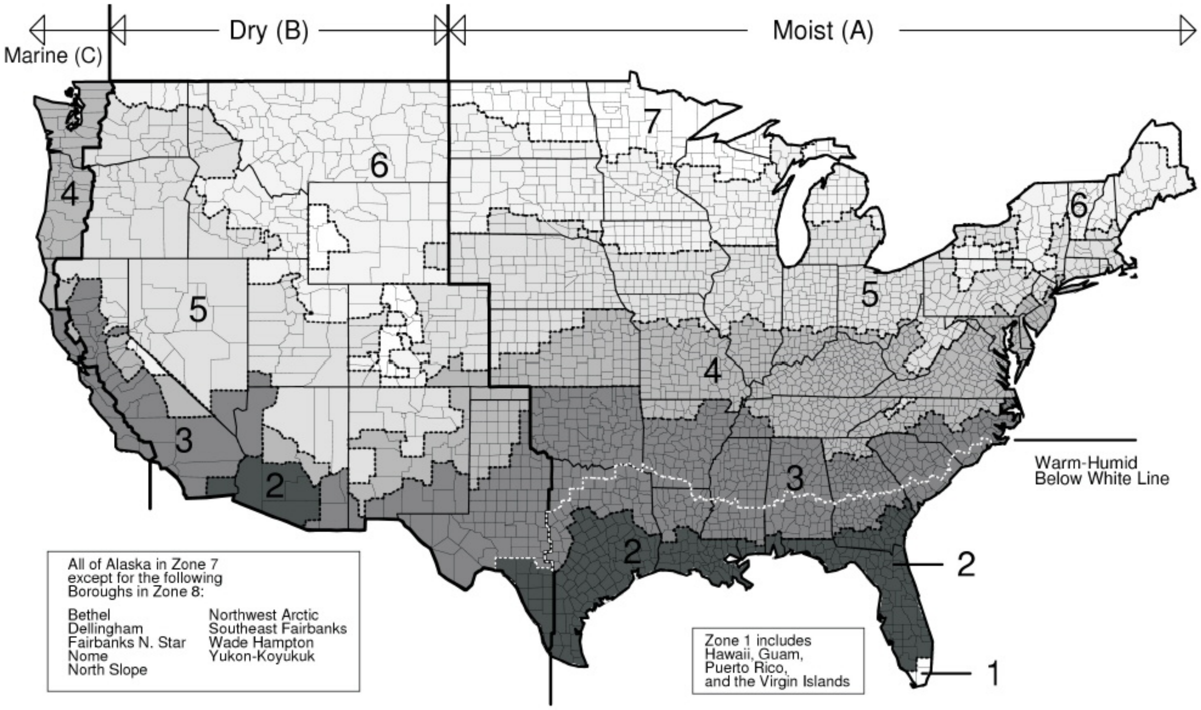


Figure 50 Climate zones in the U.S. (C301.1 IBC 2012)

The climate information of Worcester, including dry bulb temperature, humidity, wind speed and solar radiation, can be obtained from the Worcester weather file downloaded from the U.S. Department of Energy's website. After importing the weather file into Ecotect Analysis, the weather tool in this software is able to produce graphic diagrams that show the weather conditions. The annual prevailing winds diagram in Fig. 51 below, produced by Ecotect Analysis, shows that the prevailing winds in Worcester come from west. The prevailing wind diagrams for spring, summer, fall and winter are helpful for predicting the wind condition in different seasons.

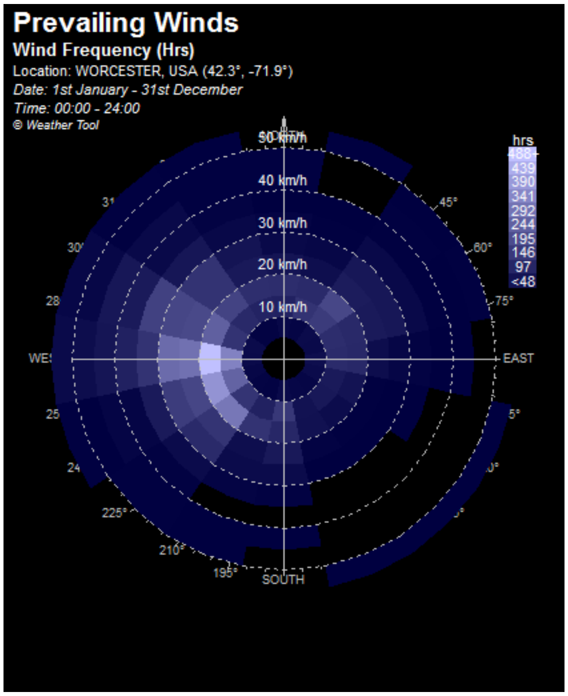


Figure 51 Annual prevailing winds in Worcester

Recently recorded Worcester weather data can be found on National Oceanic and Atmospheric Administration's Website. The 2013 weather data provided by National Oceanic and Atmospheric Administration tells that, in 2013, January, February and December have the monthly average maximum temperature below 40F and average minimum temperature around 20F. July has the monthly average maximum temperature above 80F and average minimum temperature above 60F. (Fig. 52)

The weather is mainly heating-dominated. A heating season continues from November to April. Thus, it presents a big challenge for passive design and utilizing natural ventilation. Based on the weather data from 2013, it is predicted that natural ventilation in the winter will significantly increase the heating load.

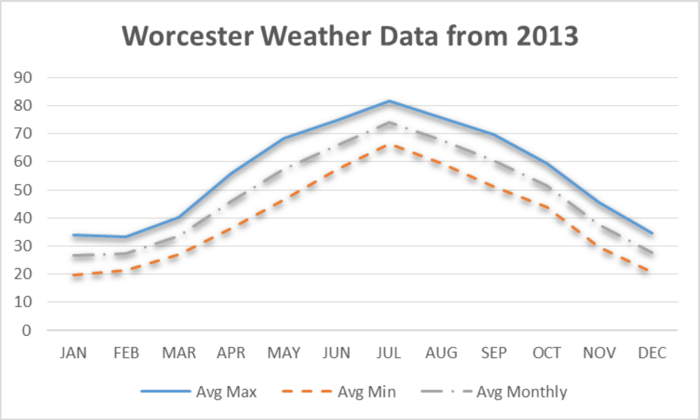


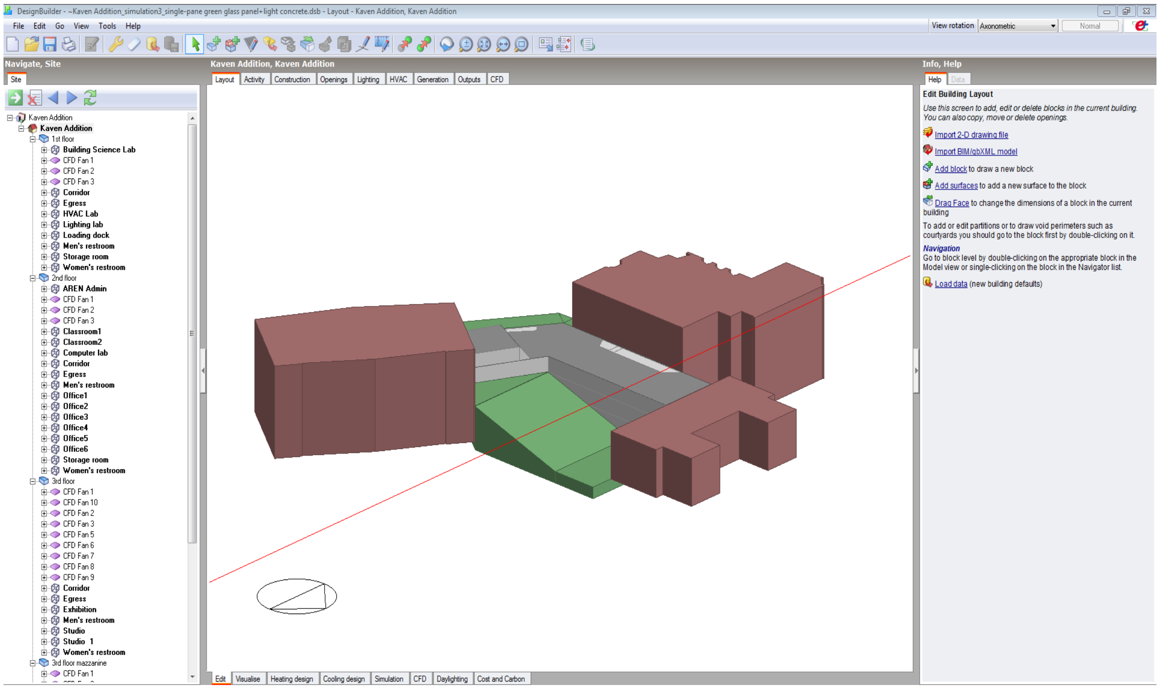
Figure 52 Worcester Weather Data from 2013 (Data are from NOAA website and are subject to revision.)

5.4.2 Energy model set up

Energy simulations were conducted in DesignBuilder software to analyze the building performance. DesignBuilder software is a Graphic User Interface (GUI) for the EnergyPlus simulation engine. It also uses Radiance as the ray-tracing engine to analyze daylight condition. It has functions of daylighting analysis, HVAC system design, building energy performance analysis and CFD calculation. It can be used for simulations of common HVAC systems, double skin facades, and natural ventilated buildings. The user-friendly modeling environment in DesignBuilder offers capability of testing thermal and visual comfort and energy consumption. The DesignBuilder is also capable of modeling natural ventilation air flow in details. Therefore, DesignBuilder is a good choice for both architects and engineers to assess the energy performance during early stage design.

5.4.2.1 Model geometry, zoning and assumptions

An energy model was first set up in the DesignBuilder software (Fig. 53). The geometry was modeled based on the architectural design. The floor plans created in AutoCAD were imported into DesignBuilder and used as references to build up the geometry. The activities schedules were set up based on the function of the space. Electric cooling system and gas-fired heating system were used. Corresponding operation schedules were modeled based on the building type and space functions.



Edit Building Layout

Use this screen to add, edit or delete blocks in the current building. You can also copy, move or delete openings.

Import 2-D drawing file

Import BIM/gbXML model

Add block to draw a new block

Add surfaces to add a new surface to the block

Drag Face to change the dimensions of a block in the current building

To add or edit partitions or to draw void perimeters such as courtyards you should go to the block first by double-clicking on it.

Navigation
Go to block level by double-clicking on the appropriate block in the Model view or single-clicking on the block in the Navigator list.

Load data (new building defaults)

Figure 53 Energy model set up in DesignBuilder

Space activities were scheduled in the model based on architectural design. Corresponding activity template was selected for each zone. The activity schedules were listed in Table 3.

Zone	Activity schedule
Labs on the first floor	Laboratory
Corridor and exit egress	Circulation area
Classroom, studio and exhibition space	Classroom
Computer lab	Computer lab
Offices and AREN administration	Office and consulting areas
Restrooms	Toilet

Table 3 Activity schedules in DesignBuilder model

The following assumptions have been made for the energy model:

1. The adjacent buildings, including Kaven Hall, Fuller Laboratories and Gordon Library have the same thermal condition and there is no heat transfer in between buildings. The adjacent buildings were modeled as adiabatic component blocks. The effect of shades and reflects was taken into account for the simulations.

2. The hill and surrounding terrains were modeled as ground component blocks. The effect of shades and reflects was taken into account for the simulations and the material property of the component blocks was defined as soil.
3. The space between the exterior facade and interior facade was defined as unoccupied and was modeled as cavity.
4. The performance of HVAC system was assumed to be perfect and the coefficient of performance (COP) of heating system and cooling system equals 1.
5. Electricity use by the interior equipment was included in the calculations.
6. Heating setpoint temperature was defined as 68°F (20°C) and cooling setpoint temperature was defined as 73.4 (23°C).
7. The building enclosure was defined as not perfectly airtight. The infiltration rate was determined at 0.300 ac/h.
8. The operation of the space heating and cooling system was scheduled based on the zone occupancies. Corresponding schedule template was selected for each zone occupancy.
9. Lighting design was defined as code-complied. The electricity consumption for exterior and interior lighting system was calculated based on IECC1998.

5.4.2.2 Model validation

The accuracy of this energy model was first assessed before studying the energy performance. When running the first simulation for the annual energy consumption and building performance, the coefficient of performance (COP) of the heating system and cooling system were both set to 1. The annual energy consumption calculated in this model should therefore equal the total thermal cooling and heating loads in a year. In the second simulation, the COP was changed from 1 to 10 and the energy consumption simulated in the second model was expected to be 1/10 of the total heating and cooling load in a year. The fuel usage in the first model was 10 times of the fuel usage in the second model, which validated that the energy model works and doesn’t have conspicuous errors (Figure 54).

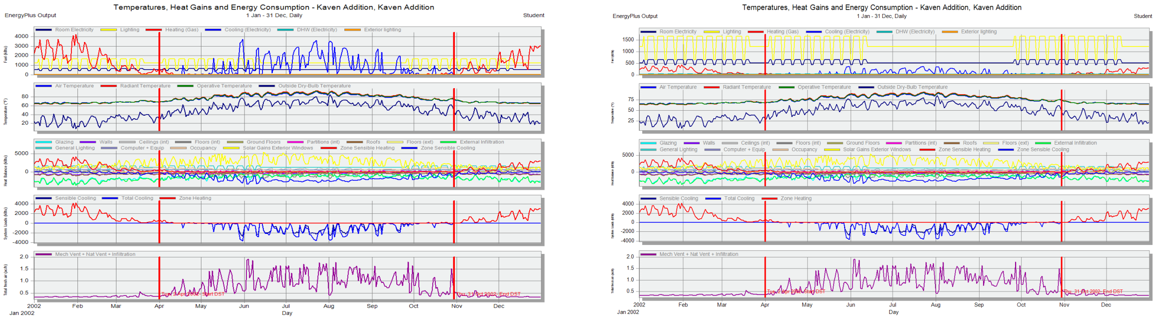


Figure 54 Left: Energy Consumption Outputs (COP=1). Right: Energy Consumption Outputs (COP=10).

5.4.3 Parametric studies

Indoor thermal comfort and air quality are important factors in evaluating the performance of a building. The performance of different types of building facades and different types of ventilation was studied by simulating the energy performance for different design schemes. The application of natural ventilation, mechanical ventilation and mixed-mode ventilation was also studied.

A parametric study of the thermal effects of different facade glazing designs was conducted in DesignBuilder. Metrics were developed to assess facade performance (Table 4). The building was expected to be thermally comfortable all year round based on thermal comfort standards. The indoor temperature was maintained at 75.2°F (24°C) in the cooling seasons and at 71.6°F (22°C) in the heating seasons when the building is occupied. The parametric study assessed the building energy performance based on the simulation results generated from DesignBuilder under the same thermal comfort model. The energy performance of single-pane glazing, double-pane glazing, triple-pane glazing, and a double skin façade was compared.

Type	Descriptions
Single-pane A	Single glazing, clear, no shading, 6mm
Single-pane B	Single glazing, clear, slatted blinds, 6mm
Double-pane A	Double glazing, clear, Low-e, argon-filled, no shading
Double-pane B	Double glazing, clear, Low-e, argon-filled, slatted blinds
Triple-pane A	Triple glazing, clear, Low-e, argon-filled, no shading
Triple-pane B	Triple glazing, clear, Low-e, argon-filled, slatted blinds
Double skin	Double glazing, clear, Low-e, argon-filled, slatted blinds

Table 4 A metric of facade design

Properties such U-value and Solar Heat Gain Coefficient (SHGC) significantly influence the energy performance of the facade. Other factor such as light transmission also plays an important role in facade design. Economic costs also affect the design decision since there are always better facade solutions, however they may incur higher costs. A trade-off between energy performance and economic costs is often required for optimized design. Table 5 shows the numerical values of these factors that influence the energy performance, and the initial costs.

Construction type	**Single-pane**		**Double-pane**		**Triple-pane**		**Double skin**
	A	B	A	B	A	B	
U-value (Btu/h·ft·F°)	1.078	1.078	0.264	0.264	0.138	0.138	-
SHGC	0.810	Varied	0.564	Varied	0.470	Varied	0.564
Light transmission	0.881	Varied	0.745	Varied	0.661	Varied	-
Cost (GBP/ft^2)	100	160	190	250	200	260	440
Cost (USD/ft^2)	157	251	298	392	314	408	690

Table 5 Facade properties

In the DesignBuilder model, all internal glazing was modeled as single-pane glass, and 50% of the glazing area was set as open. In all Type-B designs, blinds were installed on the interior side of the glazing. Operation of blinds was controlled by solar radiation and the setpoint was 11.15 W/ft^2.

The first round of simulations was conducted, assuming that all the external glazing is fixed and that the spaces are solely ventilated by a mechanical system. The second round of simulation assumed that facade glazing and skylight were operable. In this scheme, the building used both mechanical ventilation and natural ventilation. The results showed that the energy consumption was reduced significantly by incorporating natural ventilation into the building system.

5.4.4 Energy Model and Energy Simulation

5.4.4.1 Energy Model Validation

A modular block 12’×12’×24’ was modeled in DesignBuilder with a glass facade on the south side with a size of 12’×12’. (Fig. 55) The energy consumption for cooling and heating was simulated for a summer design week and a winter design week separately. Parametric studies were conducted to validate the energy model.

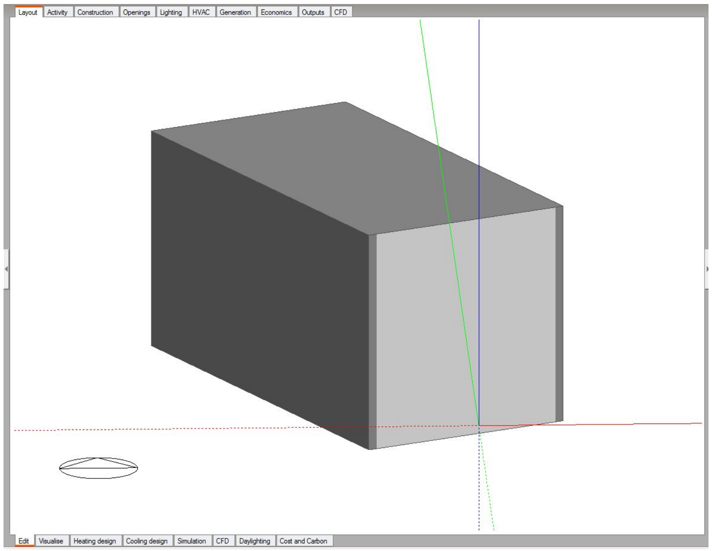


Figure 55 A modular block modeled in DesignBuilder

The model was built to study the effect of solar heat gain coefficient (SHGC) on introducing heat through a window into an interior space and effect of blinds on blocking solar radiation. The south facade was modeled as fully glazed. The other walls were modeled as opaque walls with R-13.1+R-7.4 c.i. The roof was modeled as R-19.9 c.i. The effects of other factors that impact on energy consumption were minimized. The opaque wall was modeled adiabatic, so no heat transfer happens through the wall. Both mechanical ventilation and natural ventilation were turned off, so there is no heat loss or heat gain through ventilation.

The following assumptions have been made for the energy model:

1. This building has only one occupied zone.
2. The zone occupancy was defined as lecture classroom. Corresponding schedule template for lecture classroom was used for simulation.

3. The performance of HVAC system was assumed to be perfect and the coefficient of performance (COP) of heating system and cooling system equals 1.
4. SHGC was defined as 0.01-0.99.
5. Heating setpoint temperature was defined as 71.6°F (22°C) and cooling setpoint temperature was defined as 75.2 (24°C).
6. There was not heat transfer through the floor, the concrete wall and the roof.

5.4.4.1.1 Effect of Solar Heat Gain Coefficient of glazing

The effect of Solar Heat Gain Coefficients (SHGC) of glazing was studied in order to develop a better understanding of how SHGC impact the heat gain through windows, and to gain confidence in the model developed in DesignBuilder. In DesignBuilder, the mechanical ventilation and natural ventilation were both turned off, and all the concrete walls were set as adiabatic. Therefore, there is not heat transfer through the concrete walls. Only the glazing facade can cause heat gain or heat loss. In this study, the facade of the module was single-pane clear glass. The energy consumption was simulated in a summer design week and a winter design week. The simulation results show that SHGC plays a significant role in introducing solar heat into the space. In the winter design week, sensible heating was reduced by 73% by introducing solar heat gain through the window (Table 6). In the summer design week, sensible cooling was reduced by 83% by blocking solar heat gain through the window (Table 7). Therefore, in the summer, reducing solar heat gain through the window can significantly cut the cooling load; in the winter, introducing solar heat gain into the building can significantly reduce the heating load. However, in the winter, introducing too much solar heat can overheat the interior area near the windows. In this DB model, increasing the SHGC from 0.01 to 0.99 induced a cooling load of 168.4kBTU (Table 6).

SHGC	**Total cooling kBTU**	**Zone heating kBTU**	**Sensible cooling kBTU**	**Sensible heating kBTU**	**Solar gain exterior windows kBTU**
0.01	0	436.6	-0.1	452.1	1.9
0.99	-168.4	72.7	-139.1	121.0	903.1

Table 6 SHGC study in a winter design week

SHGC	Total cooling kBTU	Zone heating kBTU	Sensible cooling kBTU	Sensible heating kBTU	Solar gain exterior windows kBTU
0.01	-197.8	0.1	-122.3	9.4	1.7
0.99	-820.5	0	-720.2	28.0	839.4

Table 7 SHGC study in a summer design week

5.4.4.1.2 Effect of blinds

Blinds can be utilized to block unnecessary solar heat gain through glazing, and reduce glare. One of the design strategies is to install blinds on the interior side of the window to reduce undesired heat gain from solar radiation by proper operations. Different operation schedules were simulated to study how the operation of the blinds affects the solar heat gain through windows.

Blinds with medium reflective slats were tested in a summer design week. The operation of the blinds was controlled by solar radiation. The objective of this validation task was to gain a better understanding of the setpoint of the blinds. To isolate the other factors' effects on the simulation results, all the other factors were kept the same except the solar setpoint of the blinds. The SHGC of the single pane glass was set as 0.99, and the HVAC system and natural ventilation were turned off. It was found from the simulation results (Table 8) that the blinds started to reduce the solar heat gain through windows, when the solar setpoint was lowered to 50W/ft^2. Then the total cooling, sensible cooling and solar gain through the exterior window decreased as reducing the solar setpoint. The results validated that the operation schedule of blinds affect the solar gain through windows. Lower solar setpoint will block more solar radiation and reduce the cooling load in the cooling seasons.

Solar setpoint W/ft^2	Total cooling kBTU	Sensible cooling kBTU	Solar gain exterior windows kBTU
NO BLINDS	-820.53	-734.39	839.36
90	-820.53	-734.39	839.36
60	-820.53	-734.39	839.36
50	-810.19	-726.97	806.68
40	-751.21	-668.11	576.10
30	-716.17	-634.31	439.10
20	-698.62	-616.60	356.69
11.15	-692.49	-610.06	311.56
5	-690.16	-607.19	275.96
0	-689.68	-606.52	269.26

Table 8 A study of blinds operations in a summer design week

5.4.4.2 Building Energy Simulation

A building energy model was constructed to simulate how different facades assemblies affect the building performance in a summer design week, a winter design week, and in one year. Zones and activity schedules were added to the model according to the architectural design. The interior layout and zones of each floor were shown in the floor plans (Fig. 56 – 59).

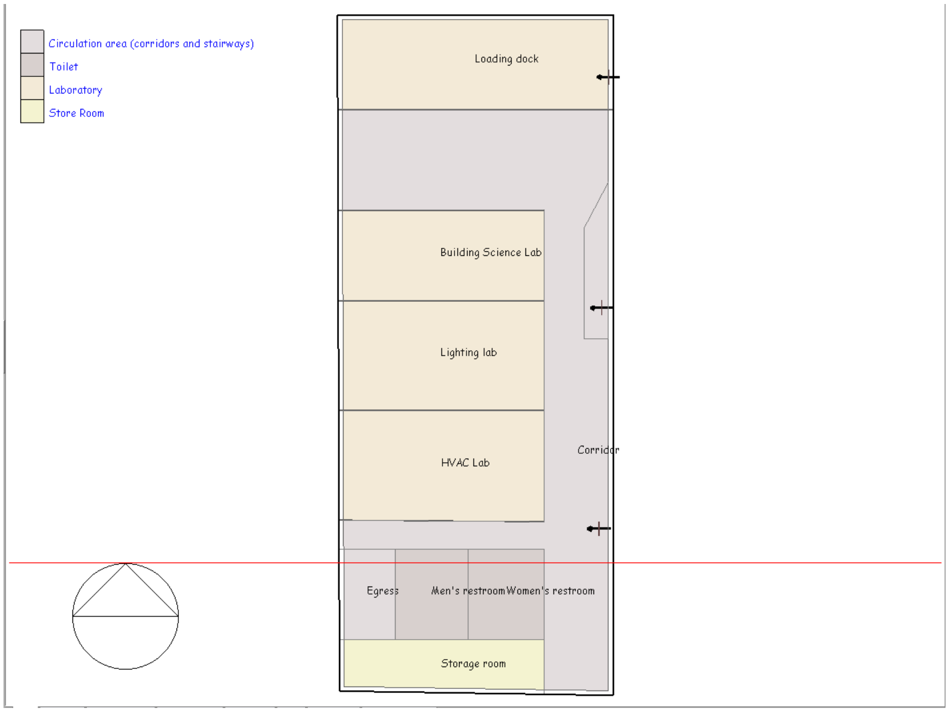


Figure 56 First floor plan in the energy model

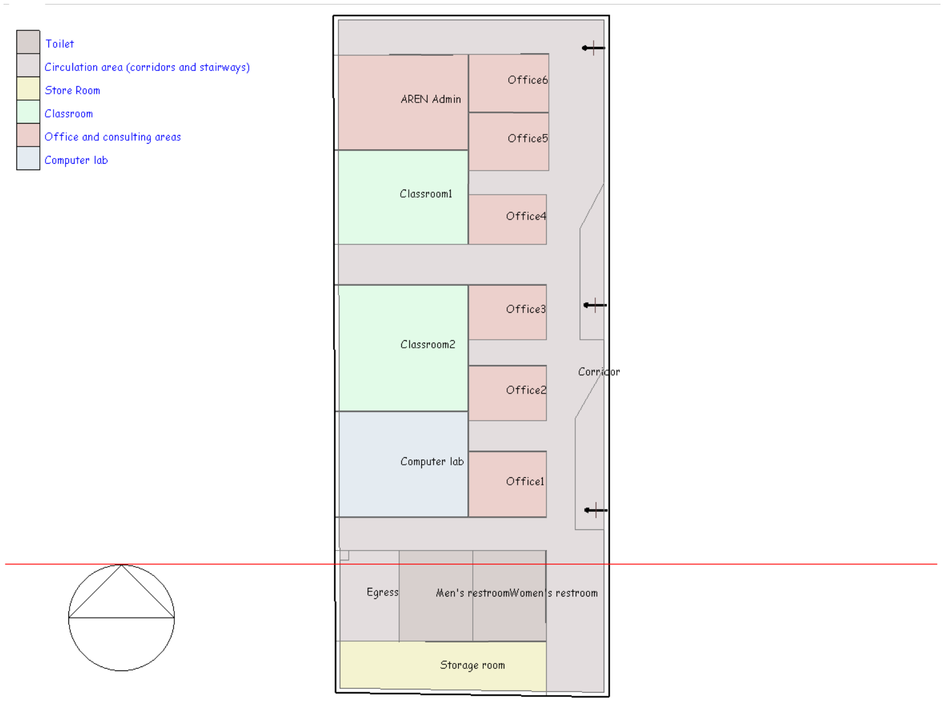


Figure 57 Second floor plan in the energy model

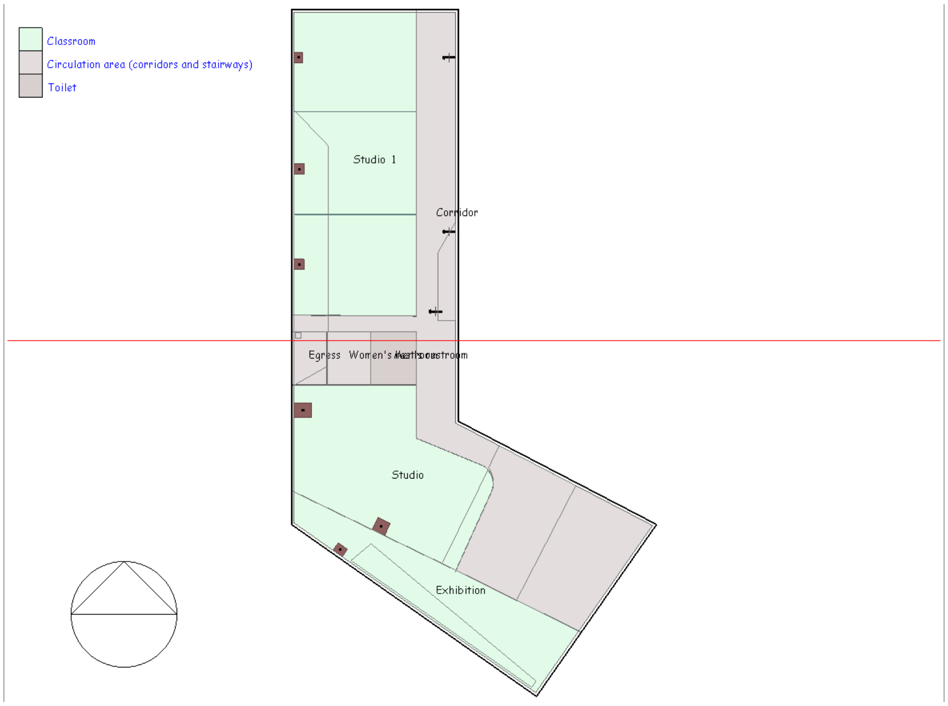


Figure 58 Third floor plan in the energy model

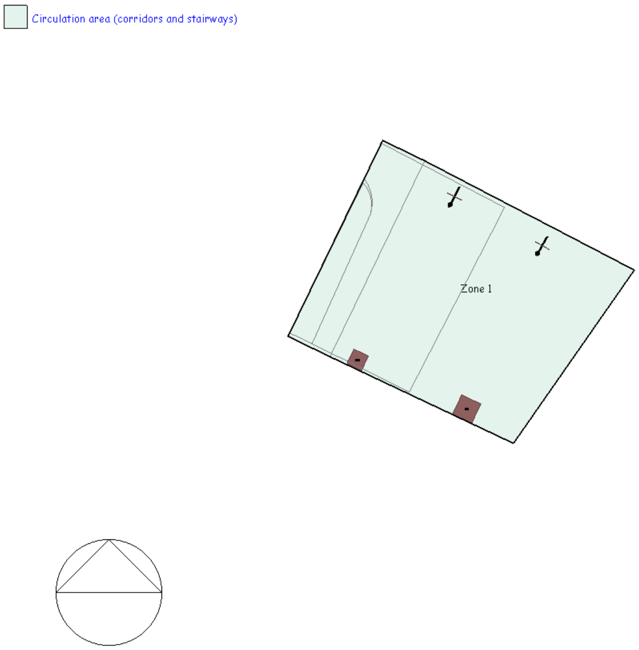


Figure 59 Third floor mezzanine plan in the energy model

When running the simulations, 20% of the glazing area was set as operable and both natural ventilation and mechanical ventilation were turned on. The variables in the parametric study are the type of glazing and the installation of blinds. Blinds were installed on the interior side of Single-pane B, Double-pane B, and Triple-pane B and into the cavity of the double skin façade.

The results in Table 9 show that double skin facade has the best thermal performance in a summer design week, from July 20 to July 26. Taking advantage of the natural ventilation, total cooling in each simulation doesn't change significantly.

	Total Cooling kBTU	**Sensible cooling kBTU**	**Sensible heating kBTU**
Single-pane A	-456.9	-410.8	27.5
Single-pane B	-427.7	-385.1	28.4
Double-pane A	-392.0	-346.8	20.1
Double-pane B	-397.4	-354.2	22.4
Triple-pane A	-356.3	-312.7	18.2
Triple-pane B	-374.0	-331.2	20.5
Double skin (with blinds)	-353.1	-280.3	14.3

Table 9 Simulation results in a summer design week

Each design was then simulated in a winter design week, from January 27 to February 2. The results were presented in the Table 10. The heating load varies significantly among different design. Single-pane window with blinds has the worst performance, requiring zoning heating of 1011.9 kBTU in this winter design week. Double-pane and triple-pane windows have better performance than single-pane. The double skin facade has the best thermal performance, consuming a total of 427.3 kBTU of energy for heating in this winter design week. The zone heating increases when installing blinds on the interior side of the single-pane glass. The explanation of the increased heating load is the use of blinds reduces the solar heat gain in daytime. This also explains the increased heating load when adding blinds to the triple-pane facade. The same pattern is expected for the double-pane glass. However, the zone heating actually decreases in the double-pane design scheme. The double-pane glass with blinds requires 17.6% less zone heating than clear double-pane window without blinds. This may be caused by the varied operation of mechanical ventilation and natural ventilation due to different heat loss.

	Zone heating kBTU	Sensible cooling kBTU	Sensible heating kBTU
Single-pane A	914.8	-2.6	950.0
Single-pane B	1011.9	-2.2	1048.2
Double-pane A	635.7	-3.3	665.5
Double-pane B	523.6	-6.9	523.2
Triple-pane A	599.2	-2.4	625.8
Triple-pane B	610.7	-5.4	641.0
Double skin (with blinds)	427.3	-12.9	451.9

Table 10 Simulation results in a winter design week

5.4.4.3 Energy simulation results

It was found from the simulations in winter and summer design weeks that the building with a double skin facade consumes the least energy among the seven design options. The whole building energy simulation was then conducted for the seven design schemes. The whole building energy simulation results showed that the double skin facade design has the best energy performance. The building performance and annual energy consumption for HVAC, domestic hot water and artificial lighting of the double skin facade design were presented in Fig. 60 and Fig. 61. The monthly energy consumption for heating and cooling was summarized in Table 11. The other simulation results were summarized in the appendix.

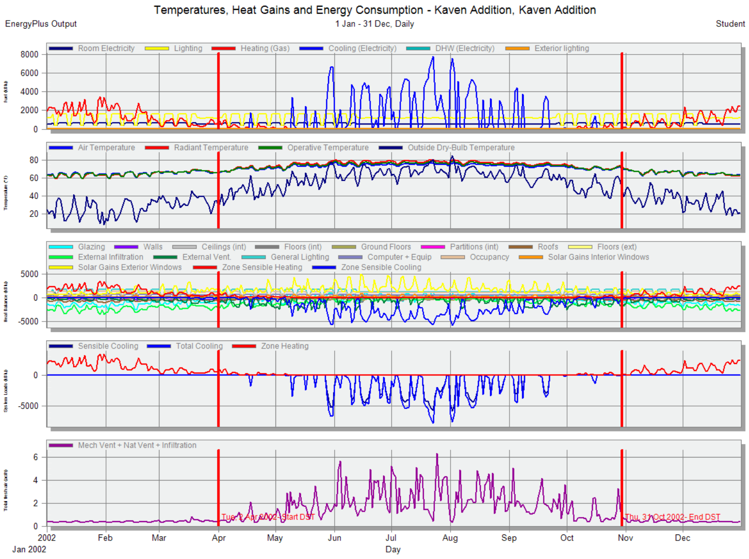


Figure 60 Annual simulation for building performance

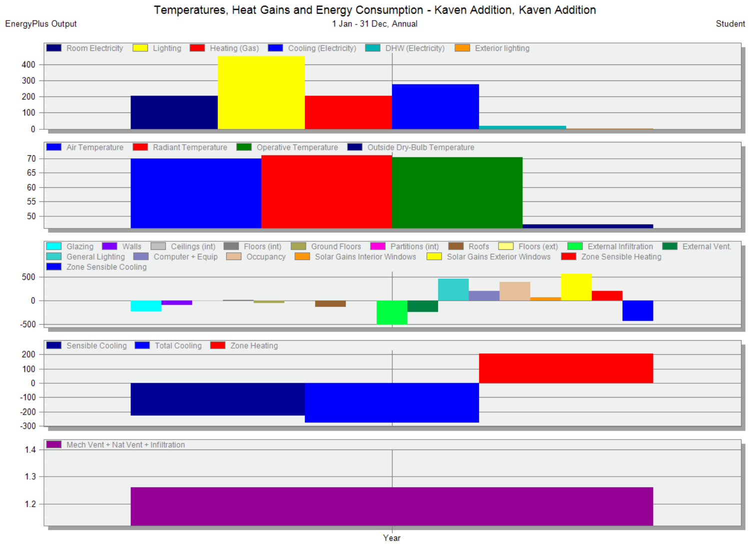


Figure 61 Annual energy usages

Date/Time	Heating (Gas)	Cooling (Electricity)
	kBtu	kBtu
January	65092.08	0.24
February	46113.53	0.40
March	19391.51	2.67
April	8698.81	1752.16
May	831.42	30641.74
June	8.27	60263.95
July	0.00	90575.73
August	0.26	69592.97
September	60.43	22991.36
October	3940.69	2300.91
November	16621.79	0.83
December	45810.22	1.26

Table 11 Monthly energy consumptions for heating and cooling

The general patterns for cooling and heating were observed from the simulation results. From May to September, the building requires cooling. From November to March, the building requires heating. April and September are the two months that the needs for cooling and heating are not significant and can be potentially balanced by solar heating and natural cooling. The cooling peak occurs in late July and early August. The heating peak occurs in late January. From the beginning of April to the end of October, natural and mechanical ventilation plays an important role in delivering fresh air into the interior space and cooling the building (Fig. 60).

From Figure 61, it has been found that the largest energy consumer in this building is the lighting system. Heating and cooling also uses a significant amount of energy among all the energy consumption. Total cooling is larger than total heating. This is a little surprising because Worcester is located at high latitude, requiring 5-month heating and having extremely cold days in wintertime. The lighting system uses about 454.473×10^3 kBtu over a year. Cooling uses about 278.310×10^3 kBtu, while heating uses about 206.707×10^3 kBtu over a year. When adding all the energy use together, the whole building totally consumes 1162.207×10^3 kBtu annually. The energy use per conditioned building area is 36.08 kBtu/ft^2. According to United States Environmental Protection Agency, the average annual energy use for educational buildings in Massachusetts, in U.S. Climate Zone 2, is 88 kBtu/ft^2 [22]. Comparing to the average energy use, the Kaven Hall Addition uses 59% less energy than average. The median site Energy Use Intensity (EUI) for College/University buildings in U.S. is 104 kBtu/ft^2 [23]. Comparing to the national median, the addition uses 65.3% less energy. The annual energy consumption also meets the 60% EUI target in 2030 CHALLENGE, which is 41.6 kBtu/ft^2 [23].

5.4.5 Discussion

The simulation results have shown that the building consumes the least energy with a double skin facade when utilizing both mechanical ventilation and natural ventilation. The building energy end uses breakdown and fuel use breakdown were summarized in Figure 62 and Figure 63. Space conditioning and artificial lighting counts for most of the energy use in the building. Heating and cooling consume 42% of the total energy (Fig. 62). 39% of energy is used by the lighting system. Electricity compromises 81% of the total annual energy consumption (Fig. 63).

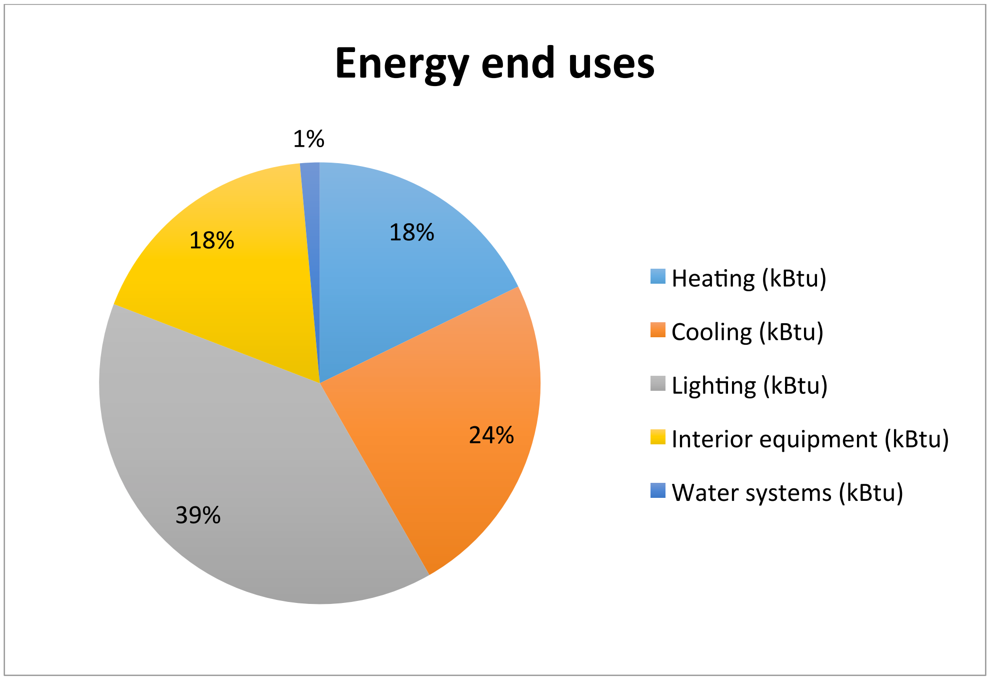


Figure 62 Building energy end uses breakdown

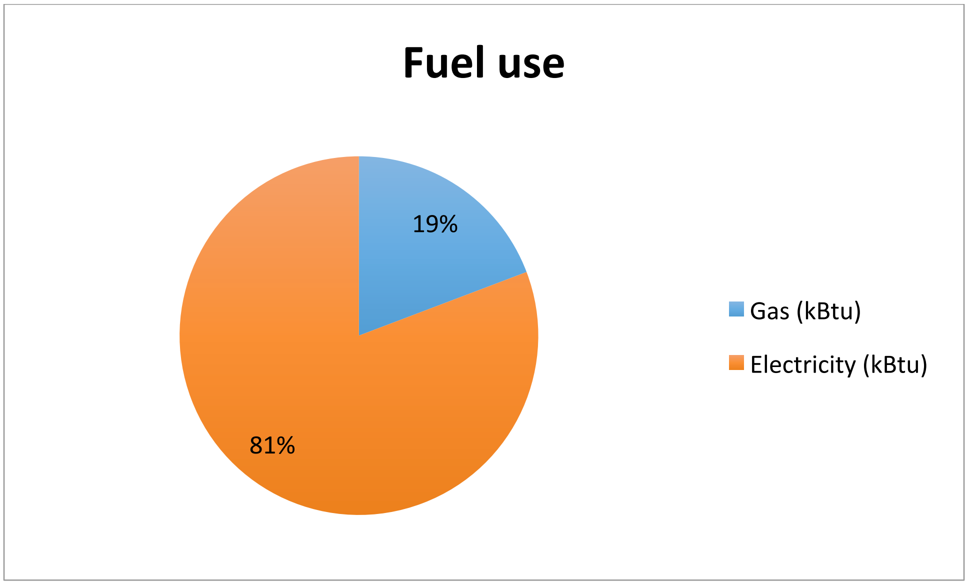


Figure 63 Fuel use breakdown

5.4.5.1 Limitation

The limitations of the energy simulations conducted in this project to assess the design solution were discussed. The two major limitations are:

(1) The building geometry was simplified and remodeled in DesignBuilder. Therefore, the building geometry modeled in the DesignBuilder is not exactly the same as the architectural model. The modification of the geometry can affect the simulated energy consumption.

(2) The simulation used the Worcester local weather data provided by the Department of Energy. The actual on-site climate can be different from it, considering that existing buildings surrounding the new building can reduce the localized wind speed and the amount of direct sunlight.

5.5 Comparison of Two HVAC Calculation Methods

5.5.1 Weather data

Weather data is essential for heating and cooling loads calculation. The annual Worcester weather data from 2008 through 2014 are available on the National Climatic Data Center's website. The data from the National Climatic Data Center was measured from the weather station in Ashburnham North, Massachusetts. The Engineering Weather Data, published by the Department of the Air Force, the Army, and the Navy on July 1st, 1978, is also available. Considering the building has long life cycle, the Engineering Weather Data is chosen for heating and cooling loads calculation because the weather was measured over a longer period of time and it was published for the purpose of facility design and planning.

5.5.2 Heating and cooling loads calculation

There are two methods available for calculating the building's heating and cooling loads. The first method is using commercial load calculation method by hands or in a spreadsheet. The second method is using computer software to simulate the energy consumption. This section intends to obtain heating and cooling loads through both methods and compare the difference.

Annual heating load and cooling load in the new building were simulated in DesignBuilder. The annual cooling load is 278.310×10^3 kBtu and the annual heating load is 206.707×10^3 kBtu. The detailed results were presented in Section 5.4.

Heating and cooling loads were also estimated, using the commercial load calculation method and Bin Calculation Method. The following assumptions have been made for the load calculations:

1. Occupants in this new building were defined as doing moderately active office work. Each occupant generated 250 Btu/h sensible heat.
2. Only the heat gains from occupants and lighting fixtures were included in the calculation for internal heat gains.
3. The thermal property of roof was defined as R-30 and the thermal property of wall was defined as R-20.
4. The double skin facade was defined as exterior window of R-0.264.
5. Cooling and heating loads varied linearly along the temperature change.

The peak cooling load was identified to occur at 17:00 in June. Peak cooling load was 320241.7 Btu/h. Peak heating load in the winter was 175473 Btu/h. The building had a total of 158 lighting fixtures, with two recessed fluorescence lamps in each fixture. Lighting power in the new building was estimated based on the Building Area Method for calculating interior lighting power allowance in IECC 2012. According to IECC 2012, the Lighting Power Density (LPD) for university or school is 1.2 Watts/ft^2. The total heat gain from the artificial lighting was 36934.8 Watts (126027 Btu/h). The total occupant load in the building is 385. The heat gain from people was about 96205 Btu/h. The annual heating load calculated by Bin Calculation Method was 182.375×10^3 kBtu (53449kWh), 34.40% less than the simulated result. The annual cooling load was calculated as 182.570×10^3 kBtu (53505.97 kWh), 11.77% less than the simulated result.

The large difference between heating and cooling loads calculated in the two methods was expected. The calculation done by the second method has many limitations. The limitation includes:

1. Heat gain through equipment such as the lab equipment, computers and printers, were not included in the calculation, which explains why the cooling loads calculated in these two methods have a significant difference.
2. Factors related to building operation, such as the percentage of window opening area and activity schedules, were not considered in heating load calculation.

3. The weather data used in the second method was different from the DOE weather data used in the DesignBuilder.

Computer simulation gives more accurate results. However, it requires more time commitment for energy model development and data input. The second method is good for quickly estimating energy consumption for space conditioning in the early design stage and giving a cost estimation for HVAC system and building operation.

5.5.3 Conclusions

The output in DesignBuilder was based on detailed sub-hourly simulation. The EnergyPlus engine used in DesignBuilder is more capable of dealing with dynamic and complex buildings and the environment. DesignBuilder is able to model and calculate the energy use for space conditioning in a building with double skin facade. However, the Commercial Load Calculation Method is short for this type of buildings. The load calculation using Commercial Load Calculation Method doesn't include many important factors, such as office equipment, different opening area of the windows and the facade, and varied air change rate in different days. Therefore, it is not an ideal method for estimating loads for a large-scale complex building in a more precise manner.

5.6 Façade Design

Building enclosure, as an architectural form, it serves as the primary mode of visual communication between the building and its users. It also functions as an environmental moderator, separating the exterior environment and interior environment. A flexible building enclosure enables the building to adapt to the dynamic exterior environment and save energy.

5.6.1 Design solution

The facade design solution to this new building is a double skin facade (Fig. 64). The exterior facade functions as a rain screen, allowing air to flow through. The interior facade has operable windows and fixed windows installed in an orderly manner. Operable window allows people access to the exterior facade inside of the building and clean the facade. The interior windows have built-in vents on the top. The vents are controllable and allow occupants to adjust them. This design considers occupants' individual desires for thermal comfort, intending to give the occupants individual control over their working environment. Blinds are designed in the space between the exterior facade and interior facade to avoid overheating. It was controlled by the solar radiation, with a setpoint of 11.15 W/ft^2. Manual controls are also installed on the corridor. A roof overhand with a depth of 3'-6" is also designed to reduce solar radiation and direct sunlight in the summer sun. Roof details and first floor details are shown in Figure 65 and Figure 66.

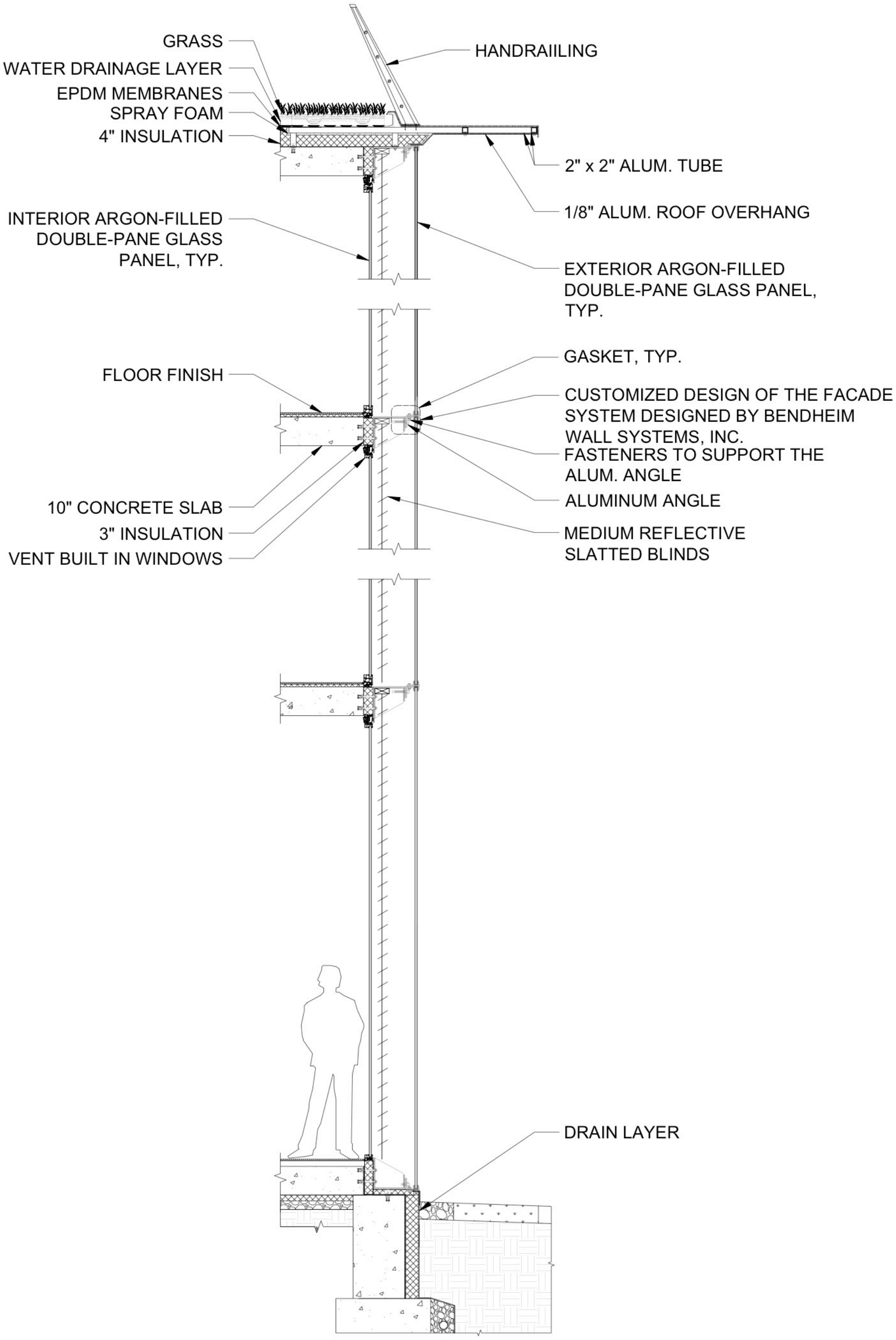


Figure 64 Building facade section

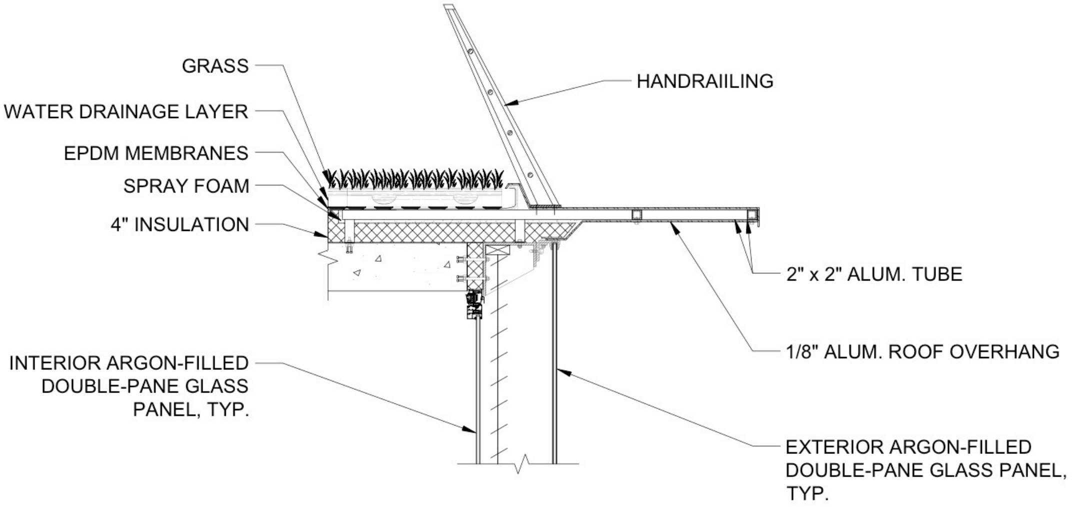


Figure 65 Roof detail section

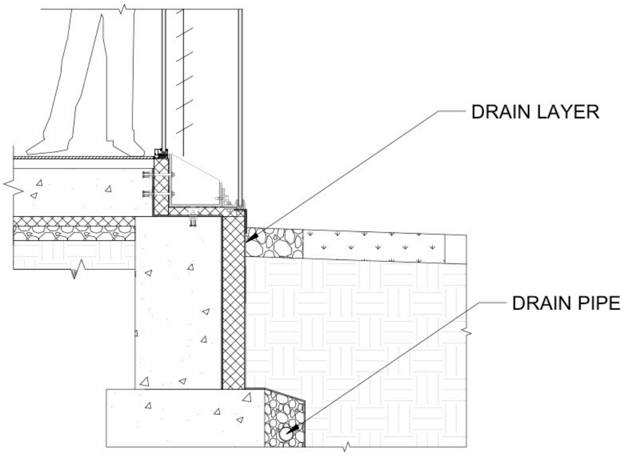


Figure 66 First floor detail section

6 Conclusions

High performance buildings have received more and more attentions and related studies have been done worldwide. Energy simulation software such as DesignBuilder has been in the market, available for architects and designers to use for assess the building energy performance.

This project proposed a design solution for the addition to Kaven Hall, in order to address the space needs of the CEE Department at WPI. The focus of this project was on the architectural design, daylighting study and building energy performance evaluation. This report also proposed a conceptual design of the interior lighting system based on IESNA guidelines. The addition was a four-floor building, containing three floors and one mezzanine level. When matching the roofline with the existing Kaven Hall, the Addition also brings new architectural taste to the WPI campus. A double skin facade was designed for the Addition based on the parametric studies in building energy performance, which showed that the building with a double skin facade consumes the least energy. Energy simulation reported that the EUI of the addition is 36.08 kBtu/ft^2. It is 65.3% less than the median Site EUI for College/University buildings in U.S. and also meets the 60% target in 2030 CHALLENGE.

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Appendix

Section A. DesignBuilder energy simulation results of the Addition to Kaven Hall

Table A.1 Total Site Energy (kBtu)

	Single-pane A (without shading)	Single-pane B (with shading)	Double-pane A (without shading)	Double-pane B (with shading)	Triple-pane A (without shading)	Triple-pane B (with shading)	Double skin
Total Energy (kBtu)	1603080.21	1614469.84	1225812.8	1225681.85	1166038.9	1162984.84	1162206.84
Energy Per Total Building Area (kBtu/ft2)	51.19	51.56	39.15	39.14	37.24	37.14	35.45
Energy Per Conditioned Buiding Area (kBtu/ft2)	51.19	51.56	39.15	39.14	37.24	37.14	36.08

Table A.2 Total Source Energy (kBtu)

	Single-pane (without shading)	Single-pane (with shading)	Double-pane (without shading)	Double-pane (with shading)	Triple-pane (without shading)	Triple-pane (with shading)	Double skin
Total Energy (kBtu)	4480170.4	4527298.55	3242891.72	3243385.85	3103762.17	3093081.31	3192847.98
Energy Per Total Building Area (kBtu/ft2)	143.07	144.58	103.56	103.57	99.12	98.78	97.38
Energy Per Conditioned Buiding Area (kBtu/ft2)	143.07	144.58	103.56	103.57	99.12	98.78	99.11

Table A.3 Site to source energy conversion factors

	Site=>Source Conversion Factor
Electricity	3.167
Natural Gas	1.084
District Cooling	1.056
District Heating	3.613
Steam	0.3
Gasoline	1.05
Diesel	1.05
Coal	1.05
Fuel Oil #1	1.05
Fuel Oil #2	1.05
Propane	1.05

Section B. Detailed DesignBuilder energy simulation report for double skin facade

Table B.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	452984.33	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	205950.04	0.00	0.00	0.00
Heating	0.00	0.00	206706.95	0.00
Cooling	0.00	278309.94	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	660422.72	278309.94	223474.18	76.90

Table B.2 Utility use per conditioned floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.11	0.00	0.00	0.00	0.00	0.00
HVAC	0	0.00	0.00	8.64	6.94	0.63
Other	6.39	0.00	0.00	0.00	0.00	0.00
Total	20.5	0.00	0.00	8.64	6.94	0.00

Table B.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	13.86	0.00	0.00	0.00	0.00	0.00
HVAC	0	0.00	0.00	8.49	6.82	0.62
Other	6.28	0.00	0.00	0.00	0.00	0.00
Total	20.14	0.00	0.00	8.49	6.82	0.00

Table B.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table B.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	3
Time Setpoint Not Met During Occupied Cooling	163.5
Time Not Comfortable Based on Simple ASHRAE 55-2004	4317

Section C. Detailed DesignBuilder energy simulation report for single-pane A facade

Table C.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	449325.82	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	204267.8	0.00	0.00	0.00
Heating	0.00	0.00	532466.32	0.00
Cooling	0.00	398765.01	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	655081.64	398765.01	543233.56	76.90

Table C.2 Utility use per conditioned floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	12.73	17.54	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	12.73	17.54	0.00

Table C.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	12.73	17.54	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	12.73	17.54	0.00

Table C.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table C.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	8.00
Time Setpoint Not Met During Occupied Cooling	161.00
Time Not Comfortable Based on Simple ASHRAE 55-2004	4235.50

Section D Detailed DesignBuilder energy simulation report for single-pane B facade

Table D.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	449325.82	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	204267.8	0.00	0.00	0.00
Heating	0.00	0.00	546191.52	0.00
Cooling	0.00	396429.44	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	655081.64	396429.44	562958.76	76.90

Table D.2 Utility use per conditioned floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	12.66	17.98	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	12.66	17.98	0.00

Table D.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	12.66	17.98	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	12.66	17.98	0.00

Table D.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table D.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	8.50
Time Setpoint Not Met During Occupied Cooling	163.50
Time Not Comfortable Based on Simple ASHRAE 55-2004	4228.00

Section E. Detailed DesignBuilder energy simulation report for double-pane A facade

Table E.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	449325.82	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	204267.48	0.00	0.00	0.00
Heating	0.00	0.00	204429.02	0.00
Cooling	0.00	349534.91	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	655081.64	349544.91	221196.26	76.90

Table E.2 Utility use per conditioned floor

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	11.16	7.06	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	11.16	7.06	0.00

Table E.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	11.16	7.06	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	11.16	7.06	0.00

Table E.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table E.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	3.50
Time Setpoint Not Met During Occupied Cooling	148.00
Time Not Comfortable Based on Simple ASHRAE 55-2004	3908.50

Section F. Detailed DesignBuilder energy simulation report for double-pane B facade

Table F.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	449325.82	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	204267.48	0.00	0.00	0.00
Heating	0.00	0.00	204676.27	0.00
Cooling	0.00	349156.71	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	655081.64	349156.71	221443.51	76.90

Table F.2 Utility use per conditioned floor

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	11.15	7.07	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	11.15	7.07	0.00

Table F.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	11.15	7.07	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	11.15	7.07	0.00

Table F.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table F.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	3.00
Time Setpoint Not Met During Occupied Cooling	147.50
Time Not Comfortable Based on Simple ASHRAE 55-2004	3911.00

Section G. Detailed DesignBuilder energy simulation report for triple-pane A facade

Table G.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	449325.82	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	204267.48	0.00	0.00	0.00
Heating	0.00	0.00	174703.41	0.00
Cooling	0.00	319486.62	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	655081.64	319486.62	191470.64	76.90

Table G.2 Utility use per conditioned floor

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	10.20	6.11	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	10.20	6.11	0.00

Table G.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	10.20	6.11	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	10.20	6.11	0.00

Table G.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table G.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	5.00
Time Setpoint Not Met During Occupied Cooling	138.00
Time Not Comfortable Based on Simple ASHRAE 55-2004	3925.50

Section H. Detailed DesignBuilder energy simulation report for triple-pane B facade

Table H.1 Fuel end use breakdown

	Electricity	District cooling	District heating	Water [gal]
Interior lighting	449325.82	0.00	0.00	0.00
Exterior lighting	1488.35	0.00	0.00	0.00
Interior equipment	204267.48	0.00	0.00	0.00
Heating	0.00	0.00	171787.94	0.00
Cooling	0.00	319348.02	0.00	0.00
Water systems	0.00	0.00	16767.23	20313.96
Total end use	655081.64	319348.02	188555.17	76.90

Table H.2 Utility use per conditioned floor

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	10.20	6.02	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	10.20	6.02	0.00

Table H.3 Utility use per total floor area

	Electricity Intensity [kBtu/ft2]	Natural Gas Intensity [kBtu/ft2]	Additional Fuel Intensity [kBtu/ft2]	District Cooling Intensity [kBtu/ft2]	District Heating Intensity [kBtu/ft2]	Water Intensity [gal/ft2]
Lighting	14.40	0.00	0.00	0.00	0.00	0.00
HVAC	0.00	0.00	0.00	10.20	6.02	0.65
Other	6.52	0.00	0.00	0.00	0.00	0.00
Total	20.92	0.00	0.00	10.20	6.02	0.00

Table H.4 Setpoint not met criteria

	Degrees [delta F]
Tolerance for Zone Heating Setpoint Not Met Time	0.36
Tolerance for Zone Cooling Setpoint Not Met Time	0.36

Table H.5 Comfort and setpoint not met summary

	Facility [Hours]
Time Setpoint Not Met During Occupied Heating	4.50
Time Setpoint Not Met During Occupied Cooling	140.00
Time Not Comfortable Based on Simple ASHRAE 55-2004	3915.50