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Taoning Wang
Worcester Polytechnic Institute

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Energy Retrofit of Kaven Hall with Aerogel Application

Taoning Wang
Advisor: Umberto Berardi
3/28/2014

Abstract

Building energy retrofitting is becoming an unavoidable solution worldwide. This study reports an energy audit and energy retrofitting proposal of an educational building located in a cold climate, Worcester (Massachusetts, U.S.) Measurements of the envelope transmissibility and indoor environment parameters were conducted in several zones of the building. Modelling the building in EnergyPlus provided details of the energy consumptions of the building, and allowed to benchmark this with the consumption of other buildings on the same campus as well as of other buildings evaluated in the same climate zone. Several potential energy conservation measures were then identified. This report focused on the retrofitting of the building envelope, using advanced materials such as aerogels. In particular, the effect of adopting an aerogel-based window is included in this report. The design process involved daylight and energy performance simulations. Further discussions about the climate sensitivity and cost analysis of the energy retrofitting proposal are finally included.

Executive Summary

In 2013, about 40% of the total primary energy use was in the building sector [1]. For this, it has never been more compelling to reduce energy use in buildings. Fortunately, many new buildings are currently equipped with energy saving features. However, most of the energy consumption occurs in existing buildings [2]. Thus, building retrofitting becomes critical.

The U.S. Department of Energy has funded more than 400 million dollar in building retrofitting projects in last year, and different policies have been promoted to push the building retrofitting sector [3]. This would provide secured benefits, including energy saving, low maintenance cost, and higher indoor environmental comfort and occupant experience.

This study reports an energy retrofit plan for an educational building located in a cold climate, Worcester (Massachusetts, U.S.) A level II energy audit was performed. Measurements of the envelope transmissibility and indoor environment parameters were conducted in accordance with ASHRAE and ISO STANDARDS. The building energy performance was analyzed using EnergyPlus, which allows detailed energy consumption analysis. EnergyPlus was operated by a graphic user interface package, DesignBuilder.

Based on the results of the energy audit, several energy conservation measures (ECMs) were hence proposed to reduce the energy consumption. These included 1) modifying set-temperature for heating and cooling of the building, 2) reducing building infiltration, 3) replacing existing single pane windows with double pane windows, and 4) applying aerogel systems to the building envelope.

All the EMCs were simulated incrementally, as every EMC was simulated on the basis of the previously simulated EMC. This approach allows showing the overall energy savings.

The investigation of promising new insulation materials, such as aerogel, is among the focuses of this report. Aerogel is a good candidate for adding insulation from the interior because of its high R-value in thinner layers, nontoxic, low flammable, and air permeable properties. This study proposed two applications of aerogel: one is to apply aerogel blanket as additional insulation from the interior of the external wall; the other one is to replace the air-gap of double-pane windows with aerogel granules. This report presents a study of granular aerogel in combination with regular clear double pane glasses in traditional double-hung windows.

The study was divided into two parts: 1) energy analysis with different configurations; 2) daylight study with corresponding configurations.

The designs intent to preserve the original design of the window. These windows have 25 individual glasses, each with a dimension of about 0.4m x 0.3m. The project proposes several alternative configurations by replacing some of the clear glasses with aerogel panels.

The energy analysis of these designs was carried out by changing the overall U-factor of the windows. The method for calculating the overall U-factor is adopted from National Fenestration Rating Council [4].

This report also presents a sensitivity test and a preliminary cost analysis in the discussion chapter. In order to investigate the feasibility of the previous retrofitting measures under different climates, simulations were repeated under various locations. Such theoretical investigations considered that all parameters in the energy model were kept the same except the location. According the climate zone divisions from Oak Ridge National Laboratory, five locations were chosen from five climate zones [5]. All five locations were chosen also from the east half of North America, having the moisture air property. Results showed that the effect of climate conditions varies among different ECMs; cooling and heating energy consumptions showed expected changes with the changing locations.

Affordability is a key aspect of high performance building insulations system, because it helps ensure large-scale deployment of the systems.

Energy retrofit is an unavoidable option for Kaven Hall, and, as an educational building, Kaven Hall should take the leading role of sustainability. This report shows that the installation of all the proposed retrofitting actions is highly beneficial in the terms of energy saving. Retrofitted Kaven Hall can be served as a research target for further investigations of energy saving validation.

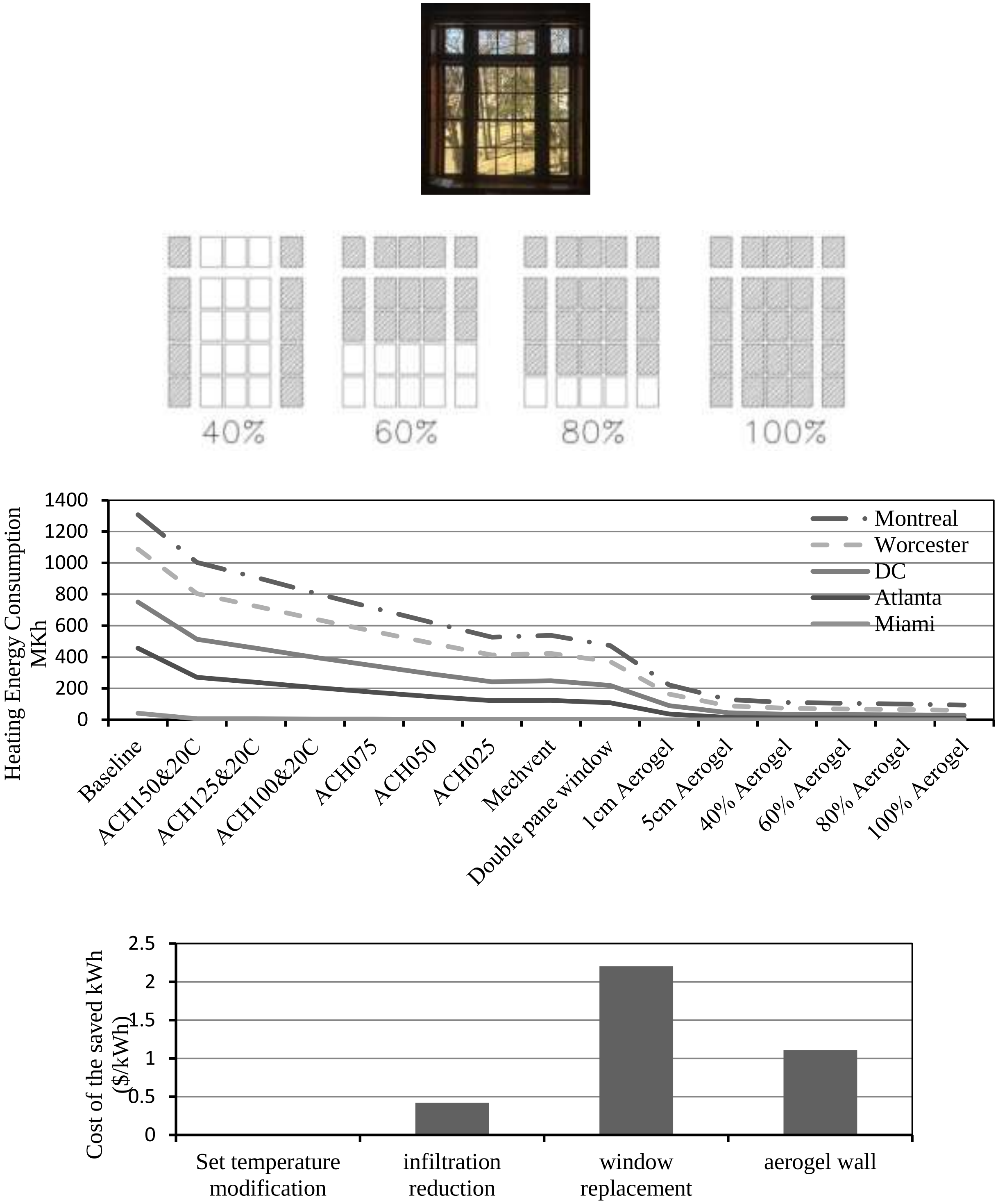

Figure 0 Existing windows in Kaven Hall; designed aerogel window configurations; heating energy consumption when the building is at different locations; Cost analysis of different ECMs.

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1. Introduction

In 2010, about 40% of the total primary energy was consumed in the building sector [1]. Therefore it has never been more compelling to reduce the energy use in buildings. Fortunately, many new buildings are currently equipped with energy saving features. However, most of the energy consumption occurs in existing buildings [2]. Thus, building retrofitting becomes critical to reduce their energy consumption.

The U.S. Department of Energy has funded more than 400 million dollar on building retrofitting projects in the last year, and different policies have also pushing the building retrofitting sector [3]. The building retrofitting provides secured benefit, including energy saving, reduced maintenance cost, improved occupant experience, and improved indoor environmental comfort.

This study reports an energy retrofit plan for an educational building located in a cold climate, Worcester (Massachusetts, U.S.) A level II energy audit was performed. Measurements of envelope transmissibility and indoor environment parameters were conducted in the building in accordance with ASHRAE and ISO standards. The building energy performance was analyzed using EnergyPlus, which allows detailed energy consumption analysis. Based on the results of the energy audit, several energy conservation measures (ECMs) were hence proposed to reduce the energy consumption. These included 1) modifying set-temperature for heating and cooling of the building, 2) reducing building infiltration, 3) replacing existing single pane windows with double pane windows, and 4) applying aerogel systems to the building envelope. These ECMs were evaluated in EnergyPlus.

The study of promising new insulation materials, such as aerogel, is among the focuses of this report. Aerogel is a good candidate for adding insulation from the interior because of its high R-value in thinner layers, nontoxic, low flammable, and air permeable properties. This study proposed two applications of aerogel: one is to apply aerogel blanket as additional insulation from the interior of the external wall; the other one is to replace the air-gap of double-pane windows with aerogel granules.

This report also presents a sensitivity test and a preliminary cost analysis in the discussion chapter. In order to investigate the feasibility of the retrofitting measures under different climates, simulations were repeated in various locations. A preliminary cost analysis was performed.

2. Background

The present chapter introduces the basic concepts of energy audit and building retrofit, and why we need to perform these activities. The chapter is a combination of background information and literature review.

2.1. Building Energy Use

In U.S., buildings consume about 40% of the gross domestic energy consumption (Figure 1). This consumption has increased from 34.0% in 1980 to 41.1% in 2010, together with the growing population and city expansion [1]. Related with energy consumption, buildings also emit tons of green house gas. In the building sector, the major sources of energy consumption are heating, cooling, and lighting load, as shown in Figure 2 [1].

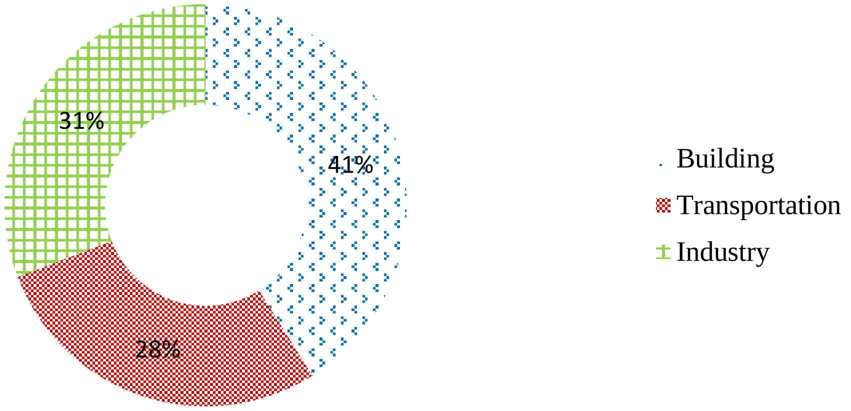

Figure 1 Eenergy consumption in different sectors in U.S

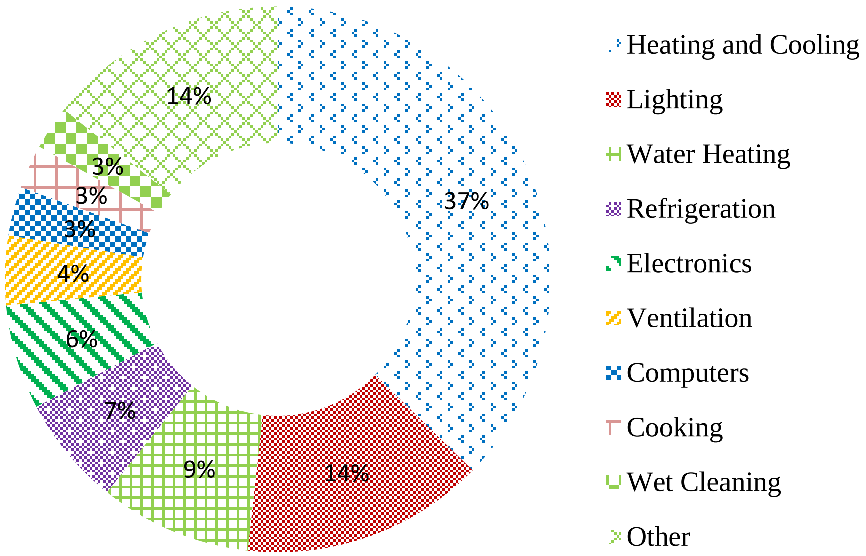

Figure 2 Building energy consumption in U.S.

Building energy consumption can be divided into two categories, residential buildings and commercial ones. The commercial sector takes up about 45% of the energy use. Within the commercial building sector, office space, retail space, and educational facilities consume about half of the total energy.

Lighting and heating loads are the two most prominent energy end-uses in commercial buildings, representing about 37% and 14% respectively [1]. In Northeast U.S., where the target building of this report is located, the heating load is even more substantial.

2.2. Building Energy Retrofit

Building retrofit is considered one of the most cost-effective ways of achieving sustainability [2]. Replacement rate of existing building is between 1.0% and 3.0% per year [2]. The United State Federal Government has put great financial support for existing building retrofitting, as shown by the fact that the in 2009, the Department of Energy funded 454 million for retrofit ramp-ups in energy efficiency [3]. Meanwhile the International Energy Agency has launched a series of Annex projects to promote energy efficiency of existing buildings.

The retrofitting of an existing building is a process of evaluating and implementing different retrofit techniques. There are several critical phases in a retrofitting program [2], as shown in Figure 3. The first phase is the project setup and the pre-retrofit survey. During this phase, the scope of the work and the project targets are defined, and the available financial and administrative resources are also realized.

The second phase is performing an energy audit of the building. This phase includes investigation of the historical energy consumptions, evaluation of building thermal properties and surveying the occupants' behaviors. Proposing a low cost or no cost energy conservation measure should also be included in this phase. From this step, one will understand the energy use and identify the energy waste of the building. One should also conduct a performance assessment by using building performance indicators and benchmark building energy use [2].

The third phase aims to identify different retrofitting options and propose an optimized energy saving plan. For each option, an energy modeling and an economic and risk analysis should be performed to quantify the related energy performance [2].

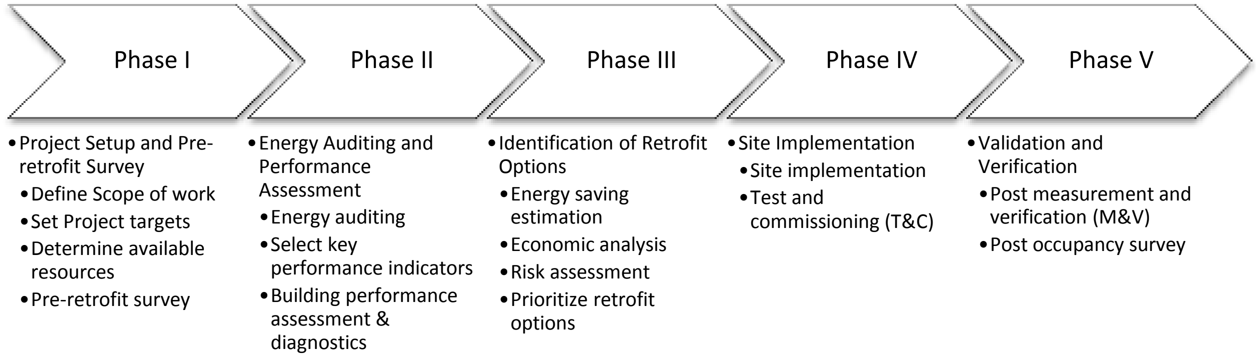

Figure 3 Typical phases in a retrofit project [2]

2.2.1. Building Energy Audit

Energy audit in buildings became popular in 1973 when the first energy crisis occurred [6]. As population and energy demand grow, the interest on energy audit increases. Energy audits are studies of energy use. They play a crucial role in building retrofitting projects.

There are three levels of energy audit: I) walk through assessment, II) energy survey and analysis, III) detailed energy analysis [7]. Different levels of energy audit are chosen according to the specific conditions of the building. Accuracy and budget requirements play decisive role in this decision making.

Level I analyze the energy bills and consist of a brief on-site survey of the building to provide a breakdown of potential low-cost/no-cost ECMs. Level II consists of a building survey and energy analysis, reparation of a cost analysis and rate on investment for feasible building improvements together with recommendations for potential cost effective capital improvements. Level III is an expanded assessment of selected building performance improvements which involves extensive data collection and a detailed energy and financial analysis to ensure long-term continuous improvement and operational cost savings [8].

2.2.2. Building Performance Assessment

During the life of a building, unexpected equipment malfunctions and envelope degradation occurs. This usually happens due to insufficient maintenance. Building performance degradation results in uncomfortable indoor thermal conditions and overall operation of the building. Building performance assessment and diagnostics are crucial parts of the sustainable building retrofit. They are used to benchmark energy use, identify system operational problems, and find energy conservation opportunities.

Recently, Richalet et al. summarized three approaches to evaluate building energy performance, computational-based, performance-based, and measurement-based approaches [9]. The computational-based approach relies on the input data collected from energy audit. The performance-based approach is based on historical energy bills. The measurement-based approach consists of in-situ measurements. Richalet et al. also stated that the measurement-based approach is the most powerful one because it presents the real behavior of a building [9]. The measurement-based method is the most time-consuming and presents the most reliable results.

2.2.3. Energy Conservation Measures

The benefit of different ECMs should be evaluated prior to the implementation decisions. One or multiple energy retrofit measures have to be prioritized in this process [2]. The performance and effects of different ECMs are usually evaluated through energy modeling and simulations. There are many whole-building energy simulation tools available on the market, such as EnergyPlus, eQuest, DOE-2, ESP-r, BLAST, HVAC-SIM+, and BIM, etc. The calibration of the model is critical since buildings have their own features and only the calibrated models can be used to analyze and estimate the energy performance.

2.2.4. Retrofitting Technologies

In choosing the insulation material for retrofitting building envelope, there are many options from traditional materials to advanced ones. Jelle provided an extensive review of building insulation materials. In his paper, he divided these materials in three categories, traditional, advanced, and future materials [10].

Traditional insulation materials are usually filling materials. Their thermal conductivities range from 0.02 to 0.05 W/mK, and vary with temperature, mass density, and moisture content.

Advanced insulation materials show substantial increase in thermal resistance, and they more expansive than traditional ones as well. Unlike traditional materials, which offer the advantage of being able to be modified on site without loss of thermal resistance, advanced materials such as Vacuum insulation panels (VIPs) and aerogels are fragile and hard to modify on site. Careful installation is required to preserve their thermal performances.

Table 1 Properties of various insulation materials

		Thermal Conductivity (mW/mK)
Traditional	Mineral wool	30-40
	Expanded polystyrene	30-40
	Extruded polystyrene	30-40
	Cellulose	40-50
	Cork	40-50
	Polyurethane	20-30
Advanced	Vacuum insulation panels	3-4
	Gas-filled panels	4
	Aerogels	13-14

There are many buildings in northeast and mid-west that use bricks as load-bearing structure. Due to historical and aesthetic reasons, the retrofit of these load-bearing walls has to be targeted on the interior. There are many challenges and precautions need to be address for this kind of project, and moisture control is one of the most important one. Straube et al have done extensive research and proposed some moisture control principles. There are five conditions that must be met in order to have moisture problems in a building [11]: 1)A moisture source; 2) Means for this moisture to travel; 3) Driving force of the movement of moisture; 4) Material must be susceptible to moisture damage; 4) Moisture content must exceed the material’s safe moisture content level for a long time.

The moisture problem will not exist if any of these conditions do not present. However, in reality, only the elimination of the last one condition is practical as it is practically impossible to keep dry all the enclosure components. When the wetting and drying is controlled then the water does accumulate in the material, whenever the moisture content will be safety level [11].

An interior insulation retrofit of a masonry building requires a careful assessment of wetting mechanisms as well as the drying mechanisms. The renovation of a building enclosure has to be managed well to avoid freeze-thaw damages [11]. In cold climate, like New England, the freeze-thaw mechanism occurs very often. The added insulation on the interior reduces the temperature differences between the outside and inside surface of the load-bearing masonry walls. This results in the decrease in the drying capacity. In order to avoid condensation on the interior surface of the masonry wall, the airtight layer of the interior insulation should be provided, and this layer should not be zero or low vapor permanence which resists the potential for inward drying [11].

2.3. Other Retrofitting Projects

Many papers have been published about retrofitting projects. A summary of the ones considered during this project is provided below.

Vanoli et al. present a historical building energy retrofit project in Italy [12]. Their study showed that careful investigations of the existing building allowed the definition of a numerical model correspondent to the real building. Dynamic energy simulations were also tested with several solutions for the building energy optimization.

Xing et al. discussed zero carbon refurbishment in United Kingdom [13]. The authors established a hierarchical approach to achieve zero carbon refurbishment. A building refurbishment project was divided into three steps: 1) retrofit building fabrics; 2) energy efficient equipment; 3) micro energy generation.

Alajmi presented an energy audit project of an educational building in a hot summer climate [14]. Level 1 and 2 audits were conducted over the building. Building energy audit produced a list of ECMs, which were evaluated by building energy simulation software.

Escriva-Escriva et al. presented a new method for modeling the daily load profile of a group of air-conditioning systems in warm climate [15]. Instead of physically based load modelling, a different approach based on the simulation of a single HVAC system, a set of end-use electrical measurements, and a detailed walk-through and energy audit.

Many researches about different levels of energy audit were also considered. Rasul et al. used DesignBuilder to model the existing institutional buildings in Australia [16]. Their study proposed several ECMs which can save up to 41.87% of the energy without compromising occupancies thermal comfort. The model was then calibrated by measured data throughout the course of a year. Once the modeled prediction and collected data were in good agreement, the modeling and simulation of different energy conservation measures became valid.

As for computer-based energy simulation model, Kaplan and Canner recommended the allowable difference between the predicted and measure data to be 5% on a monthly basis and 15% on a daily basis for internal loads. The acceptable difference increases up to 15%-25% monthly and 25-35% daily for the simulation of HVAC systems. The annual simulation results should be with 10% of metered data [17].

3. **Energy Audit Methodology**

3.1 Exploring Kaven Hall

Sustainable building retrofit requires a systematic approach. As described in the previous chapter, the retrofit activities consist of varies stages. This project was carried out under the assumption that the retrofit decision had been made. The first step of retrofitting is to know the target building; this was done by performing a level II energy audit of Kaven Hall.

Comprehensive knowledge should be acquired before any retrofitting decision being made. Such knowledge includes the shape and location of the building. A building's floor plan, orientation, and location present the general idea of how the building interacts with its environment. The occupant schedule determines the use of the HVAC and lighting system. The activities inside the building affect thermal and cooling loads and electricity use.

An extensive study of the building envelope is also required. The building envelope is the skin of a building; it separates the indoor environment from the outside. Understanding the properties and functionality of the building envelope is essential to the understanding of the energy consumption of the building.

The indoor environment in Kaven Hall is largely conditioned from heating and cooling system. Thus, the knowledge of the existing HVAC system was also critical. The HVAC system consumes a large portion of the total energy, and its malfunction could also lead to substantial energy waste.

A building's lighting system also plays a big role in the overall energy consumption scheme. If a lighting system is not well designed, it could not only waste energy, but also decrease the productivity of the occupants.

Only when comprehensive knowledge of the building is acquired, the next process of the retrofitting options evaluations can be done.

3.1.1 Building Geometry and Organization Profile

Existing drawings showed incomplete information about the geometry of Kaven Hall. Floor plans were the only drawing available, and they revealed space rearrangements over the years. Up-to-date information was obtained through on-site measurements. The climate zone properties were determined using the ‘Guide to determining the climate region by county’ from Oak Ridge National Lab [5]. As shown in Figure 4, Kaven Hall is located in zone 5, having cold climate properties.

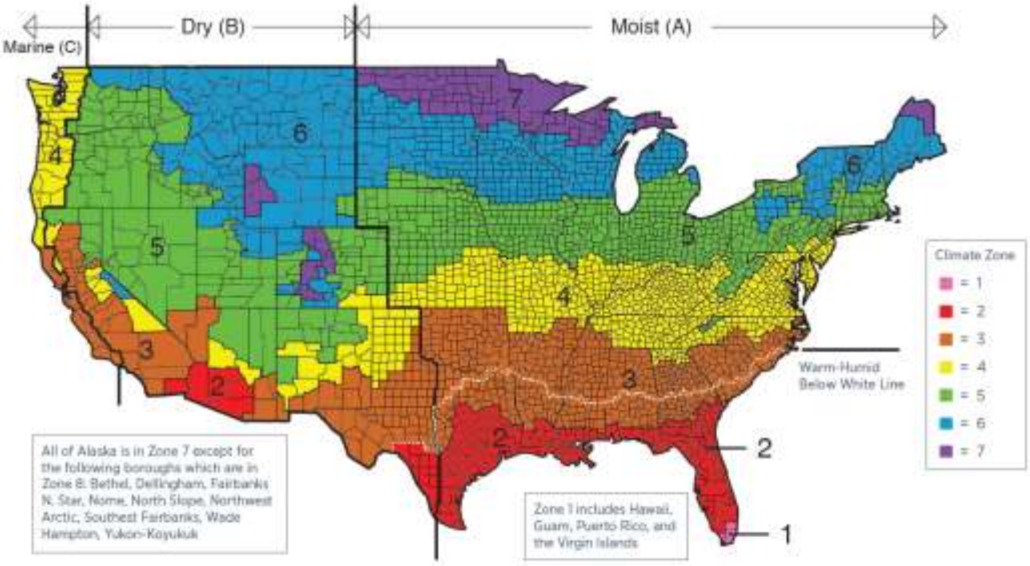

Figure 4 Zone divisions in U.S **[5]**

Human factors are important in an energy retrofitting project. Due to the lack of time and man power, a detailed occupant profile was not created. The occupant profile was hence simplified.

3.1.2 Building Envelope

In order to estimate the energy requirements and subsequent CO_2 emissions, it is important to determine the thermal transmittance values of the building envelope. The evaluation of the thermal transmittance can be conducted according to one of the following methods.

1) Calculating the transmittance in accordance with ISO 6946 with known stratigraphy of the structure;
2) Performing an endoscopy and core sampling of the structure to obtain the exact composition of the wall, then calculating the transmittance in accordance with ISO 6946;
3) Obtaining the thermal transmittance of the structure through documented archives.
4) Performing an in-situ measurement of the thermal transmittance in accordance with ISO 9869.

The first three approaches allow acquiring the knowledge of the exact composition of the external wall. In the case of the absence of detailed drawings, the building structure composition has to be obtained through on-site core sampling. After knowing the composition of the building structure, the thermal resistance of each component can be obtained published data. The total thermal resistance can then be calculated using the equation from ISO 6946 [18].

$$\boldsymbol{R_{TOT}} = \frac{1}{h_i} + \frac{s_1}{\lambda_1} + \left\{ l_{i+j} \left[\frac{(s_i/(l_i \cdot \lambda_i)) \cdot (s_j(l_j \cdot \lambda_j))}{(s_i/(l_i \cdot \lambda_i)) + (s_j(l_j \cdot \lambda_j))} \right] \right\} + \frac{s_2}{\lambda_2} + \frac{s_3}{\lambda_3} + \frac{1}{h_e} \tag{1}$$

Where h is the radiation/convection heat transfer factor (W/m^{2}K); λ thermal conductivity of a building component (W/mK); l is the thickness of the component (m).

The core sampling of the building structure requires professional equipment; it also induces unwanted disruptions of the building operation. The calculated value is also unreliable due the following reason:

- Construction not fully in compliance with the design;
- Material degradation;
- Alternation in environmental conditions, such as humidity changes;

In order to obtain a more reliable value of the thermal resistance of the load-bearing masonry wall in Kaven Hall, in-situ measurements using heat flux meter were carried out. The measurements were complied with the ISO 9869 [19].

The first step was the selection of the measurement site. The heat flux sensor was placed where heat transfers in one-dimensional perpendicular to the exterior surface. For temporary sensor installation, heat transfer sensor was mounted on the internal surface.

It was also necessary to put a layer of material over the entire area of the sensor to match the surface absorbance to the surrounding surface, and to create a smooth transition of air flows. In the case of Kaven Hall, where the internal wall surface has a smooth gypsum board finish, a masking tape was sufficient to create a smooth transition of air flows. The installation of the temperature sensors on exterior and interior surface followed the same rule.

On the exterior side, in addition to creating a smooth transition of air flows, it was also important to apply heat conductive material between the sensor and the surface. Such heat conductive materials include toothpaste and petroleum jelly such as Vaseline [19]. Air gaps greater than 0.5 mm between the sensors and surface can cause 2% to 10% of error because of the heat convection.

A typical configuration of the sensors consists of a heat flux sensor, which is usually positioned on the interior surface of the tested building element. Two or more temperature sensors were also attached to each side of the tested building element. The use of two or more temperature sensors decreased the error in case of elements not sufficiently uniform. Figure 5 shows the configuration of a typical sensor set up.

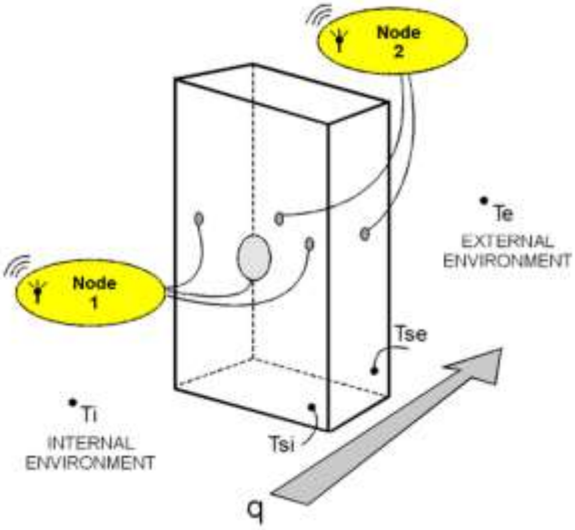

Figure 5 Installation of the heat flux meter **[20]**

In Figure 5, q is the heat flow rate density, which will be measured directly by the heat flux meter. In theory, the thermal transmittance (U) is usually evaluated as:

$$\boldsymbol{U = \frac{q}{T_i - T_e}} \tag{2}$$

where T_i and T_e are the internal and external environment temperature. The measurement procedure requires instantaneous values, evaluated at discrete instants of time over a sufficiently long period [20]. However, in practice it is easier and more reliable to measure the internal and external surface temperatures, which produce the thermal conductance of the building element. The thermal conductance can be evaluated as:

$$\boldsymbol{\Lambda = \frac{q}{T_{si} - T_{se}}} \tag{3}$$

where T_{si} and T_{se} are the internal and external surface temperatures. The thermal transmittance can then be derived from thermal conductance in accordance with ISO 6946 [18]:

$$\boldsymbol{U = \frac{1}{\frac{1}{h_i} + \frac{1}{\Lambda} + \frac{1}{h_e}}} \tag{4}$$

where h_i and h_e are the internal and external adduction coefficients. The sensibility of the sensor used in this report is 0.01 W/m^2, and the precision is greater than 5%.

The windows were assessed using different methods. The overall thermal resistance of a window is a complex interaction of three mechanisms, conduction, convection, and long-wave radiation. National Fenestration Rating Council published a U-factor rating method for whole windows [4]. There is also center-of-glass U-factor rating method, which only takes into account the heat resistance of the glazing alone. The U-factor for the whole window usually has higher value than center-of-glass U-factor for most of the high energy-efficient windows. The total heat resistance of a window, including all its components, such as frame, glazing, divider, is calculated using the following equation:

$$\boldsymbol{U_t} = \frac{\left[\sum(\boldsymbol{U_f A_f}) + \sum(\boldsymbol{U_d A_d}) + \sum(\boldsymbol{U_e A_e}) + \sum(\boldsymbol{U_{de} A_{de}}) + \sum(\boldsymbol{U_c A_c})\right]}{\boldsymbol{A_{pf}}} \tag{5}$$

Where U_t is the total product U-factor, A_{pf} is the projected fenestration product area, U_f is the frame U-factor, A_f the Frame area, U_d is the divider U-factor, A_d is the divider area, U_e is the edge-of-glazing U-factor, A_e is the edge-of-glazing area, U_{de} is the edge-of-divider U-factor, A_{de} is the edge-of-divider area, U_c is the center-of-glazing U-factor, and A_c is the center-of-glazing area.

3.1.3 HVAC system

The evaluation of the HVAC system followed the steps below: 1) Identify and document equipment and controls; 2) Conduct a visual inspection of all systems; 3) Review operations and maintenance programs; 4) Evaluate HVAC controls; 5) Identify energy management opportunities.

The first step is to review all HVAC equipment. Information such as identification, ratings, fuel type, and age was gathered. The second step is performing a walk-through inspection of the existing HVAC system. This includes observing motors and belts, dampers, filters and fans, etc. The third step is to review the operation and maintenance program from the facility office of the school. The next step was to evaluate the HVAC controls in the building. The key was to understand what type of control systems exists in the building, and to what degree is the system automated. It is also important to know the target indoor thermal condition set in the equipment. The final step is to identify the energy management opportunities.

The target building, Kaven Hall, is part of the university campus. Building heat derives from steam from boilers at a central plant. Without a sub-meter at the building level, there is no practical way of measuring the energy use in this building. Because of limited amount of time and resources, the evaluation of the HVAC system was not carried out in detail.

3.1.4 Lighting System

The evaluation of the artificial lighting system was carried out in a building information model. First all the lighting fixtures were documented. Information included lamp data and position. All the lighting fixtures were recreated in the building information model, and the reflected ceiling plans were generated. The lighting fixture schedule was created to understand the energy use of the artificial lighting system in the building.

Daylight was studied using the lighting simulation software Radiance and DAYSIM. A simplified model is then created in Rhino, and the climate-based daylight analysis was performed with DIVA. Daylight studies were incorporated with the aerogel application study, which will be discussed later.

3.2. Energy Simulation

There are many programs readily available for building energy performance simulation. The core tools in the building energy field are the whole-building energy simulation programs. These programs provide users with key indicators of the building performance, such as energy consumption and demand, temperature, humidity, and costs.

D.B. Crawley et al. compare the feature of the 20 major building energy simulation programs: BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQuest, ESP-r, IDA ICE, IES<VE>, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRANSYS [21]. Each program has advantages and disadvantages. Ideally, for a whole building design from scratch, one should have a suit of energy simulation program to achieve the highest efficiency. However, in this project, where the focus is on evaluating the efficiency of various energy conservation measures, a single program could be selected. DesignBuilder with the engine of EnergyPlus was selected. EnergyPlus is a modular structured code based on most popular features and capabilities of BLAST and DOE-2.1E [21]. Loads are calculated by using a heat balance engine which is approved by ASHRAE standards. EnergyPlus is also capable of simulating daylight and HVAC systems.

DesignBuilder (DB) is one of the most comprehensive user interfaces for EnergyPlus (EP) dynamic thermal simulation engine. EP is tightly integrated into DB environment to generate detailed building energy performance data using real weather data. The simulation principle used by DB is the most detailed simulation with dynamic parameters and they include all energy supply and energy dispersion. EP, on the other hand, uses a modular program structure, which makes the calculation method easy to understand. The EP functions based on the heat balance principle, also known as Predictor-Corrector Method [22], and assumes that the room air is well stirred, providing an uniform temperature.

The principle behind is to predict the mechanical system load maintaining the designed temperature set point. DB models were structured in order of the building site, blocks, zones, and surface data. This structure sets up data globally in a model. Figure 6 shows the user interface of DesignBuilder.

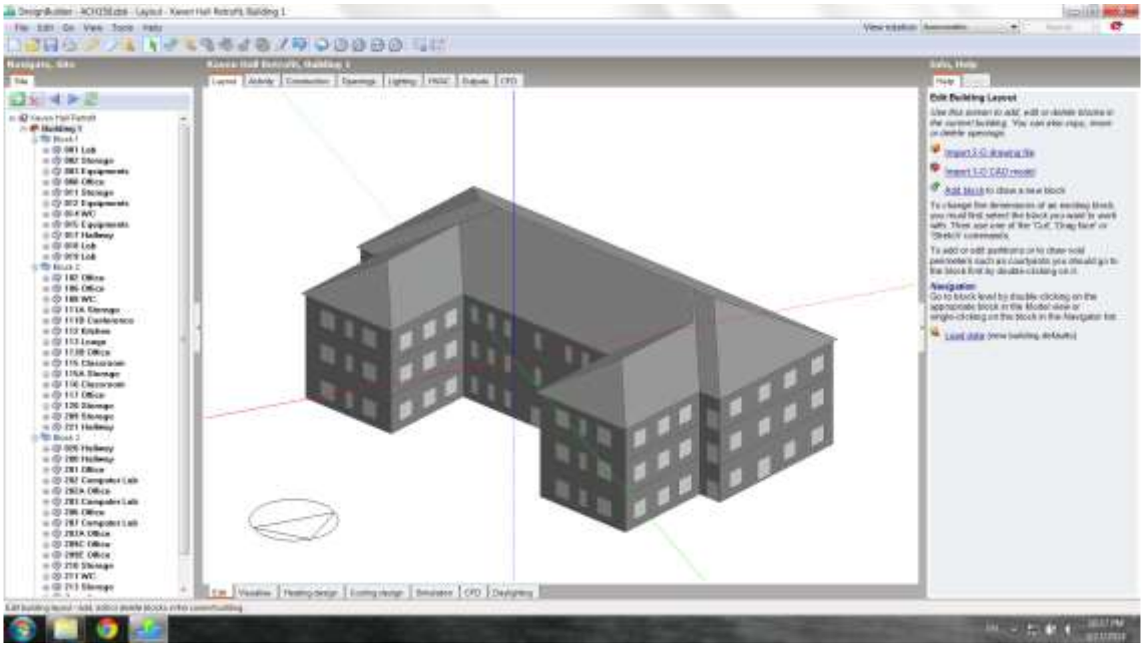

Figure 6 User interface of DesignBuilder

Several energy conservation measures (ECMs) are hence proposed to reduce the energy consumption. These include modifying set-temperature for heating and cooling of the building, reducing building infiltration, replacing existing single pane windows with double pane windows, and applying aerogel systems to the building envelope.

Changing set-temperature is categorized as a non-investment ECM, and it is the easiest and, usually, the first ECM that has been considered. DesignBuilder allows the users to change the set-temperature directly under the ‘activity’ tab.

Reducing building infiltration is considered one of the low-investment ECMs. Infiltrations are caused by air leakages through building envelopes, and, most of the time, the fenestration systems. DesignBuilder allows its users to change the building infiltration rate under the ‘construction’ tab. A schedule can be assigned to the infiltration rate. In this case, the schedule was always ‘on’.

Replacing the existing window system is also considered. The benefits associating with replacing all the windows include increased thermal resistance and reduced infiltration rate. DesignBuilder allows the users to change building opening units under the ‘opening’ tab. There are default window units that users can pick, and users can also setup a customized window.

Retrofitting the entire external walls is considered to further increase the thermal resistance of the building envelope. Retrofitting the external walls with aerogel blanket is considered. Aerogels are promising high performance material for building envelopes. Details about aerogels will be discussed in the next section.

All the EMCs were simulated incrementally. Each EMC was simulated on the basis of the previously simulated EMC. This approach shows directly the overall energy savings.

3.3 Aerogel Applications (Capstone Design)

Aerogels are one of the most promising high performance thermal insulation materials for building applications. Comparing to traditional thermal insulation material, aerogels show remarkable insulation characteristics with a thermal conductivity down to 13 mW/(mK) for commercial products [23]. Aerogel is nontoxic, low flammable, and air permeable, and provides a high R-value in thinner layers. It is a good candidate for interior installations.

3.3.1 Synthesis

Aerogels are dried gels with a very high porosity [24].

It was discovered in the early 1930s by Kistler [25]. Aerogels have a very low thermal conductivity, resulting from as well a low solid skeleton conductivity, low gaseous conductivity and a low radiative infrared transmission [23].

The synthesis of silica aerogels is usually divided into three general steps: gel preparation by sol-gel processes, aging of the gel in its mother solutions to prevent the gel to shrink during drying, and drying of the gel under special conditions to prevent gel structure to collapse. A simplified reaction for silica aerogels the most common type of aerogels for insulation purposes may be presented as [26]:

$$\boldsymbol{Si(OCH_3)_4 + 2H_2O \leftrightarrow SiO_2 + 4CH_3OH} \quad (6)$$

A detailed, comprehensive review on the synthesis of silica aerogels has been written recently by Dorcheh and Abbasi [27].

3.3.2 Thermal Conductivity

Due to its extraordinary small pore sizes and high porosity, the aerogel achieves its remarkable thermal properties. Aerogels have a very low thermal conductivity, resulting from a well-balanced relationship among 1) the low solid skeleton conductivity; 2) low gaseous conductivity, and 3) low radiative infrared transmission [28]. Such balanced relationships are hard to achieve because each factor is tightly coupled with each other, and, for example, a change in the skeleton conductivity will result in a change of the gaseous conductivity [23].

Although dense silica has relatively high thermal conductivity, silica aerogels have a small proportion of solid silica. Also, aerogels inner skeleton structure has many ‘dead-ends,’ resulting in an ineffective path for heat transfer [23].

Knudsen-effect explains the low gaseous conductivity in aerogels. Knudsen-effect expresses the gaseous conduction in a porous media as a function of the air pressure and the characteristic pore size. Silica aerogels feature low characteristic pore size and high porosity, and the gaseous conductivity is strongly influenced by ambient air pressure.

The radiant transfer of silica aerogels is dominant when the temperature is above 200 °C, but it is much less dominant at low temperatures [23]. Combining all three factors, the overall thermal conductivity of silica aerogels at atmospheric pressure is around 13 mW/(mK) and decreases even more at lower ambient pressure. Currently, silica aerogels are commercially available with a thermal conductivity between 13.1 and 13.6 mW/(m K) [23]. Figure 7 shows an aerogel sample.

Figure 7 Aerogel

3.3.3 Design of Aerogel Windows

The optical properties make the aerogel an interesting material to study when retrofitting a building fenestration system. Aerogel is one of the most promising materials in highly energy-efficient window systems. Products have appeared on the market, having aerogel in the interspace between the windows. This innovative solution provides not only low thermal conductivity, but also a high solar energy and daylight transmittance [29].

Granular silica aerogel windows have overall solar transmittance up to around 0.5. A monolith translucent silica aerogel window with a 10 mm thickness has a solar transmittance of up to 0.88 [30]. Researches have been conducted in the past decade on the development of highly insulating windows based on silica aerogels.

Two types of aerogel can be used in these high performance windows, monolith and granular. Monolith silica aerogels exist in a complete tile and have higher solar transmittance. However, there are still issues preventing cracking when drying the aerogel. Currently, the maximum size of a crack-free monolith silica aerogel is 0.58m x 0.58m [31]. Granular silica aerogels, on the other hand, do not have such issue. Silica aerogels exist in small granular. This application lowers the overall solar transmittance of the window. Figure 10 shows an installation of aerogel windows.

This report presents a study of granular aerogel in combination with regular clear double pane glasses in traditional double-hung windows. The study was divided into two parts: 1) energy analysis with different configurations; 2) daylight study with corresponding configurations.

The designs intent to preserve the original design of the window. As shown in Figure 8, the existing window has 25 individual glasses, each with a dimension of about 0.4m x 0.3m. The design proposed several alternative configuration by replacing some of the clear glasses with aerogel glasses. Figure 9 shows the four designs. Each design has different proportions of the aerogel glass. The first design replaces 40% of clear double-pane glasses with aerogel glasses. Similarly, the second, third, and fourth design have 60%, 80%, and 100% of glasses replaced by aerogel glasses respectively. Each design, apart the one that replaces all glasses with aerogel glasses, tries with preserve a clear view to the outdoor environment.

The energy analysis of these designs was carried out by changing the overall U-factor of the windows. The method for calculating the overall U-factor is adopted from National Fenestration Rating Council [4], and the calculated U-factors are shown in Table 2.

Table 2 U-factor of each window design

% aerogel content	U-factor
0% aerogel	1.51 (W/m^{2}K)
40% aerogel	1.14 (W/m^{2}K)
60% aerogel	0.86 (W/m^{2}K)
80% aerogel	0.58 (W/m^{2}K)
100% aerogel	0.30 (W/m^{2}K)

Figure 8 Existing windows installed in Kaven Hall

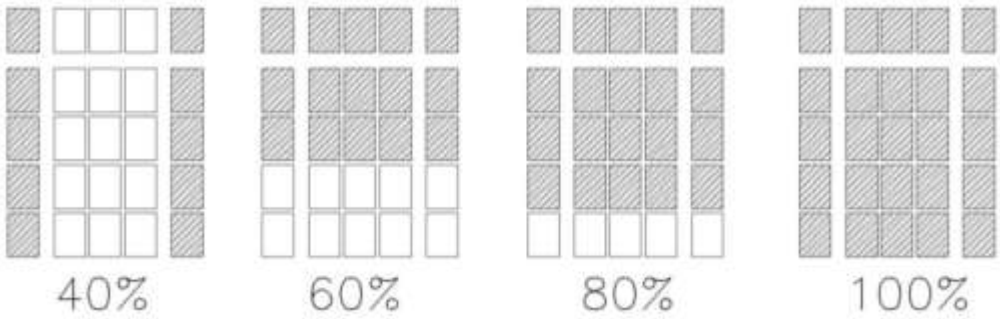

Figure 9 designed aerogel window configurations

The daylight analysis was performed with DIVA for Rhino. DIVA stands for Design Iterate Validate Adapt and is an environmental analysis plugin for the Rhinoceros 3D modeling program [32] [33]. DIVA performs a daylight analysis with the engine of Radiance and DAYSIM [32]. A model was built in Rhino, and four rooms at four corners were established to cover the daylight conditions in all orientations. Analysis grids were constructed 0.8 m off the floor and 0.45m apart from each other. The user interface of Rhino and DIVA is shown in Figure 11.

Figure 10 example of translucent aerogel insulation as a high performance thermal insulation solution for daylighting **[31]**

The following material property values were used for the simulation: the wall reflection factor is 0.5; the ceiling reflection factor is 0.8; the floor reflection factor is 0.2; the window frame reflection factor is 0.4; the single clear solar transmittance is 0.88; the double clear transmittance factor is 0.65; the double panel with aerogel transmittance factor is 0.3. The assigned values were approximated and do not reflect the real material properties. Parameters were kept the same in all simulations.

Table 3 Reflection and transmittance factor of different building components

Building components	Reflection/transmittance factor
Wall	0.50
Ceiling	0.80
Floor	0.20
Window frame	0.40
Single Clear	0.88
Double Clear	0.65
Double panel with aerogel	0.30

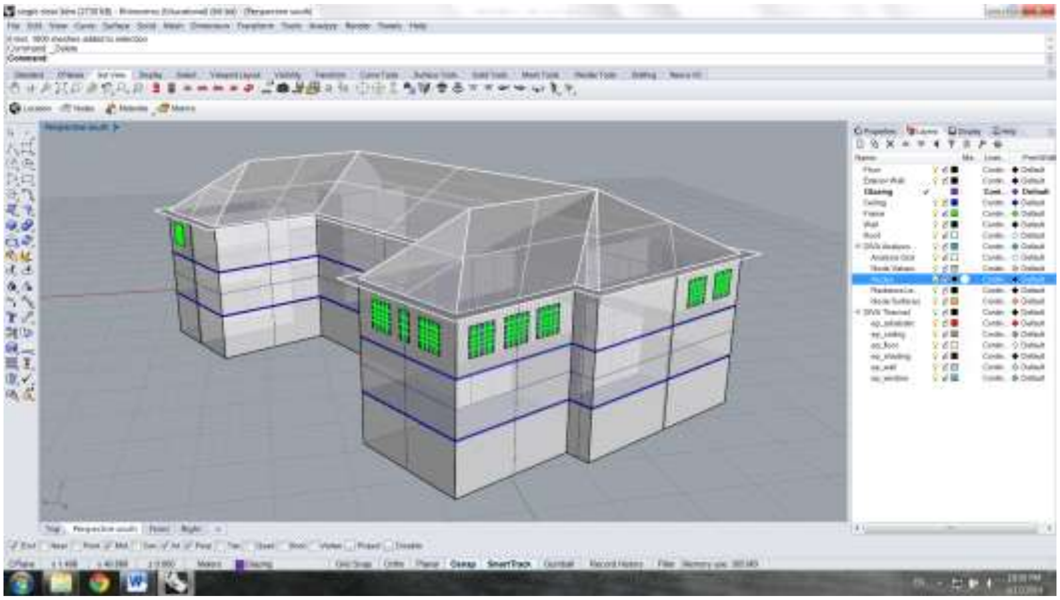

Figure 11 User interface of DIVA for Rhino when performing daylight analysis

3.4 Economic Analysis

The final retrofit outcome is largely driven by the capital investment from the clients. The economic analysis of a building retrofit project compares different ECMs on the economic base and presents filtered retrofit measures that are both energy-efficient and cost-effective.

There are different economic analysis methods. General project evaluation methods can be applied to the economic feasibility of a single retrofit measure, and life cycle cost method, levelized cost of energy and other advance analysis methods can be used to evaluate multiple retrofit alternatives. When evaluating a single ECM, net present value (NPV), internal rate of return (IRR), overall rate of return (ORR), benefit-cost ratio (BCR), discounted payback period (DPP), and simple payback period (SPP), etc., can be used. Remer and Nieto identified that NPV is the most typical technique for optimal building economic assessment among 25 techniques [34]. The NPV method finds the difference between the benefit and cost, and all amounts are discounted for their time value. Following is a formula for NPV:

$$NPV_{A1:A2} = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+d)^t}$$

Where $NPV_{A1:A2}$ is Net Benefit for alternative A1 as compared with alternative A2, B_t is benefit in year t, C_t is costs in year t.

4. **Results**

This chapter discusses the results from the energy audit, energy simulations, and daylight simulations. This chapter divided into two sections, building energy performance and the evaluation of ECMs. The building energy performance section summarizes the results from energy audit.

4.1 Building Energy Performance

4.1.1 Building Geometry and Occupant Profile

The building under study is Kaven Hall, an educational building of Worcester Polytechnic Institute in Massachusetts. Kaven Hall is located at the southwest corner of the Salisbury Street and Boynton Street. It was built in 1954, and it is now served as the home of the Civil and Environmental Engineering Department. The entire building is made of steel skeletons and masonry bricks. It features three floors and an attic with a total 3623 square meters (39,000 square foot) floor area. The building has three stories, and each story is about 4 meters high, which brings the building to a total height of around 18 meters.

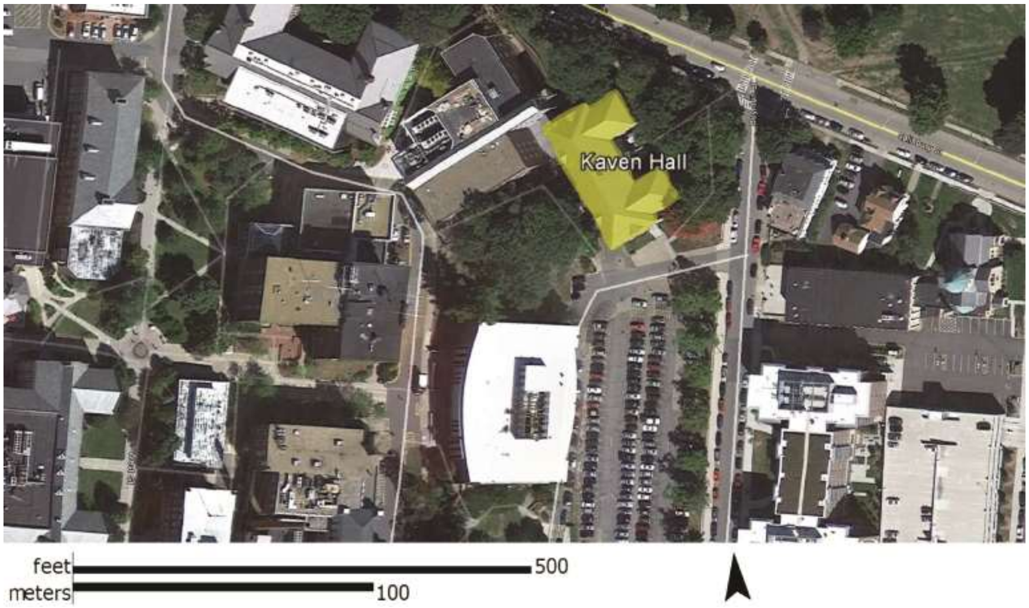

Figure 12 Location and surroundings of the Kaven Hall (in yellow)

Kaven Hall was named for Moses Kaven, a WPI alumnus who was the vice president of the United Show Machinery Co, and a generous benefactor. Looking down from the sky, Kaven Hall has a shape of a 'C', which stands for civil engineering. Figure 13 throughFigure **15** show the elevations of the building.

Figure 13 Southwest elevation

Figure 14 Northeast elevation

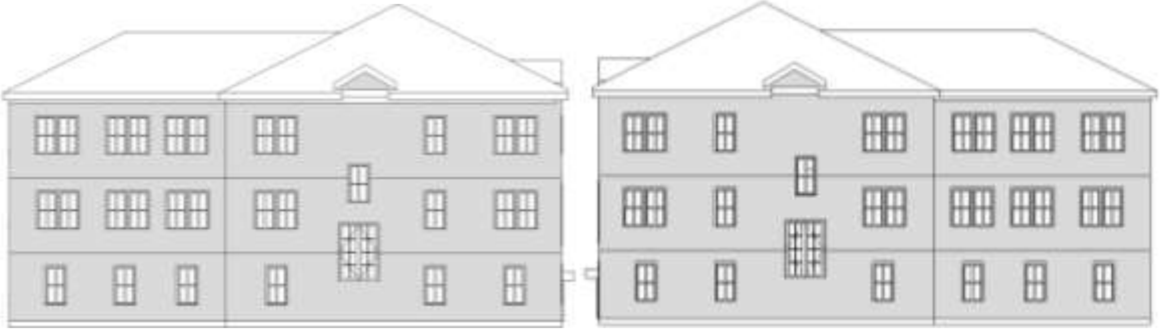

Figure 15 Northwest and southeast elevation

Kaven Hall is entirely made of bricks, and the exterior wall thickness varies from 56 cm at the bottom to 38 cm at the top part of the building. Diferrent parts of the wall have different thickness due to the specific condition at the time of construction. The building oriented 26 degree from north to west on the longer side. The building runs 46 meters long and 26 meter wide and has a center corridor connecting one end to the other. It also extends to the northwestern and southeastern wings of the building. The corridor has thick wall, which also work as structural support. Rooms with different functionality are located on both side of the corridor. Figure 16 shows the plans of the building.

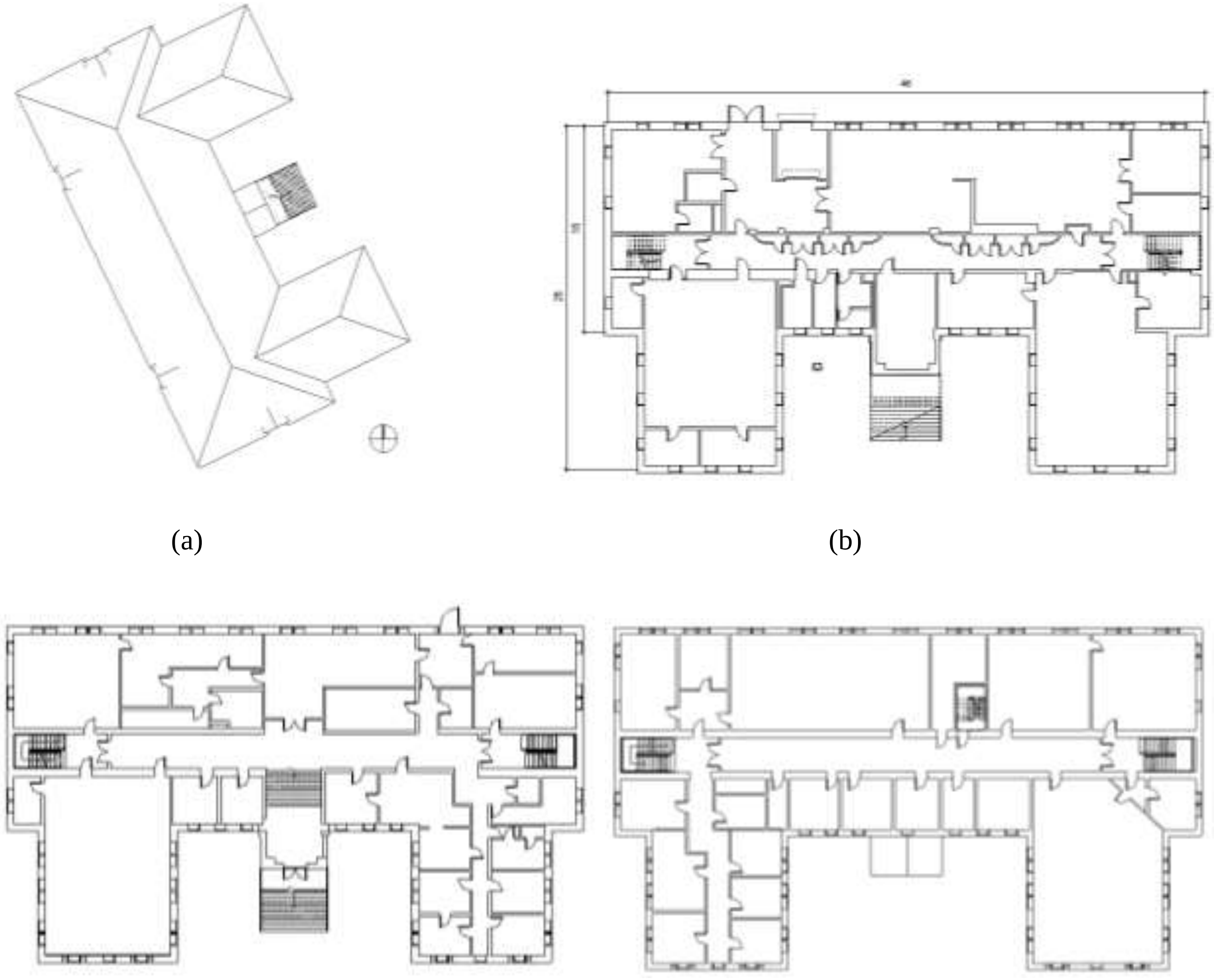
(a) (b) (c) (d)

Figure 16 Site plan (a), basement (b), first(c) and second (d) floor plan of Kaven Hall

The building serves as an educational building with different functionality. Figure 17 shows plan organizations. Space in Kaven Hall can be categorized as Hallway, Conference room, Classroom, Lab, Equipment room, Loading Zone, Officie, Storage, WC, Kitchen, and Student Lounge.

Figure 17 First floor usages (up left), second floor usages (up right),

and third floor usages (lower left)

4.1.2 Building Envelope

The measurement of the thermal properties of the external wall required 5 days in order to average out the error. In Figure 19, the trends of the external and internal wall temperature were reported. The surface temperature of the wall and the ambient air temperature were measured. The external temperature trend was maximum at 10 °C and lowest at around -5 °C during the time of measurement. The indoor temperature was meanly around 17 °C, with a stable value due to the great thermal inertia of the building. A large indoor and outdoor temperature difference was achieved to minimize the possible error during the measurements.

Figure 18 set up of the heat flux meter and temperature sensors

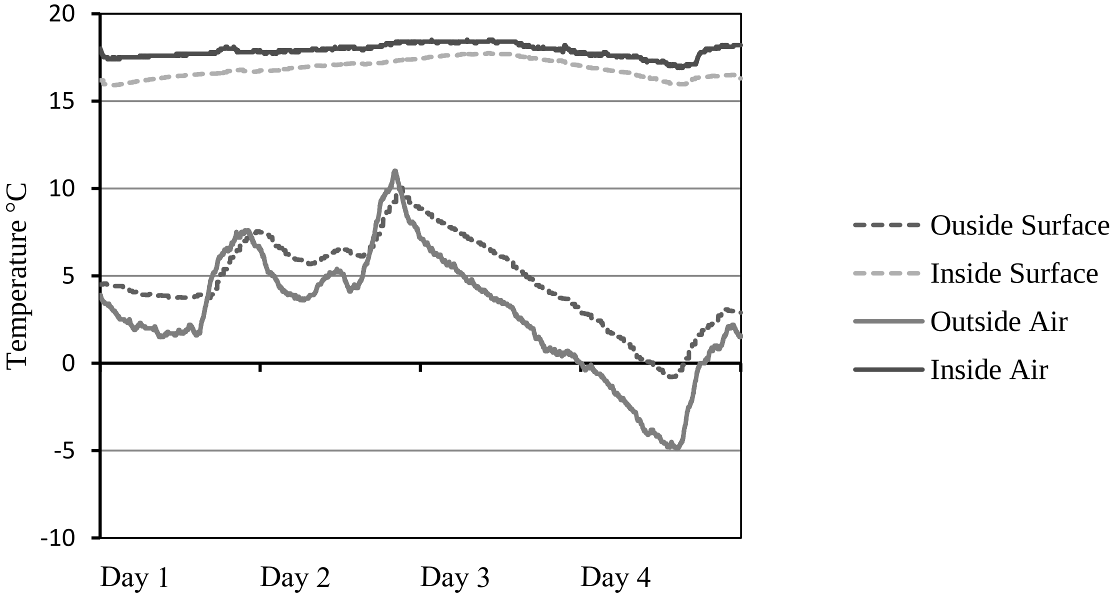

Figure 19 Indoor and outdoor temperature trends

Figure 20 shows the value of the thermal conductance measured by the heat flux meter. The measured thermal conductance was consistent with the temperature changing rate measured by the temperature sensor. Figure 21 shows the surface temperature difference of the wall. According the ISO 6946, the surface to surface thermal transmittance can be calculated by dividing the sum of the overall heat flux by the sum of the surface to surface temperature difference.

The surface to surface thermal transmittance of wall is:

$$\Lambda = \frac{q}{T_{si} - T_{se}} = \frac{\sum_{i=1}^{n} q_i}{\sum_{i=1}^{n}(Tsi_i - Tse_i)} = \frac{5506.41}{2384.16} = 2.31\, W/m^2K$$

According to ISO 6946, the overall U-value of the wall, with air film, is:

$$U = \frac{1}{R_i + \frac{1}{\Lambda} + \mathrm{R_e}} = \frac{1}{0.13 + \frac{1}{2.31} + 0.04} = 1.65\, W/m^2K$$

The overall thermal resistance of a building component can be calculated using the equation [18]

$$\boldsymbol{R_{TOT}} = \frac{\boldsymbol{1}}{\boldsymbol{h_i}} + \frac{\boldsymbol{s_1}}{\boldsymbol{\lambda_1}} + \left\{\boldsymbol{l_{i+j}}\left[\frac{(\boldsymbol{s_i}/(\boldsymbol{l_i}\cdot\boldsymbol{\lambda_i}))\cdot(\boldsymbol{s_j}(\boldsymbol{l_j}\cdot\boldsymbol{\lambda_j}))}{(\boldsymbol{s_i}/(\boldsymbol{l_i}\cdot\boldsymbol{\lambda_i}))+(\boldsymbol{s_j}(\boldsymbol{l_j}\cdot\boldsymbol{\lambda_j}))}\right]\right\} + \frac{\boldsymbol{s_2}}{\boldsymbol{\lambda_2}} + \frac{\boldsymbol{s_3}}{\boldsymbol{\lambda_3}} + \frac{\boldsymbol{1}}{\boldsymbol{h_e}} \tag{7}$$

The calculation provided a thermal transmittance value equal to 1.33 W/m^2K, which is about 24% lower than the measured value. It was expected that the measured U-value to be higher than the calculated U-value.. After almost 60 years of usage, several factors could potentially contribute to the higher thermal conductivity. Such factors include material degradation and wetted surface.

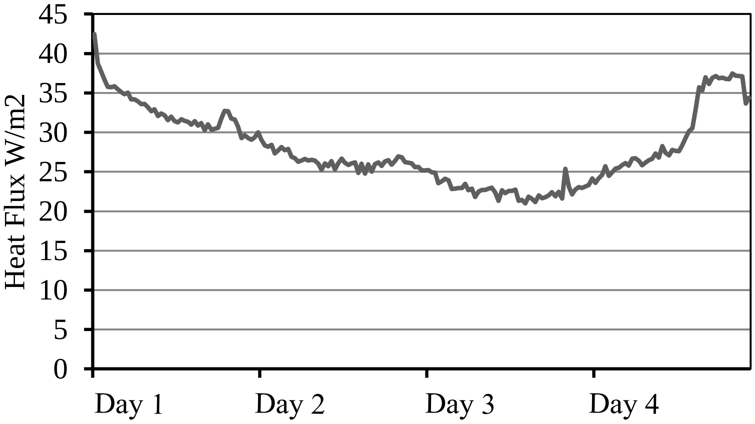

Figure 20 measurement and trend of the heat flux

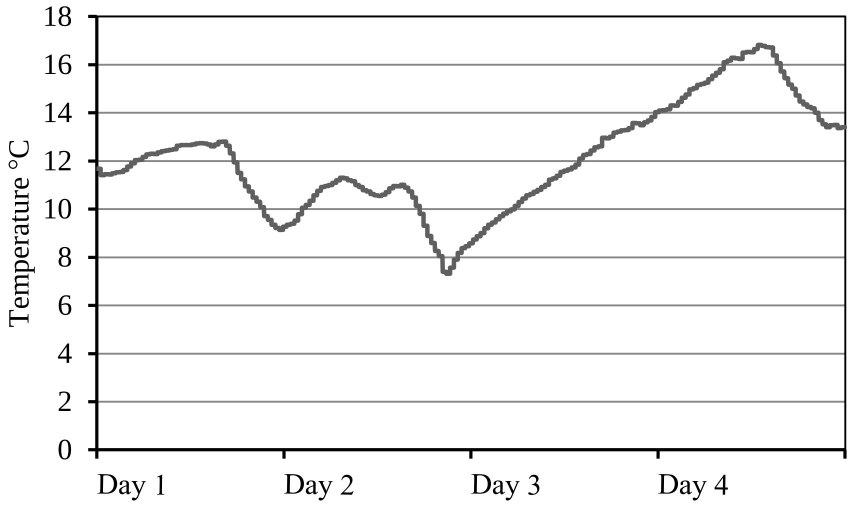

Figure 21 surface temperature difference of the external wall

4.1.3 Building HVAC System

The fuel source of Kaven Hall was natural gas. The building was heated through the medium of steam and was distributed through radiators in each room. The boiler was not located inside the building, and the steam is delivered 100 meters away from school's power plant. A detailed energy analysis required at least five years of energy consumption records. Because there were no sub-meters installed for Kaven Hall, historical analysis became challenging.

The cooling system inside Kaven Hall consists of two types: through-the-window units and split units. The through-the-window cooling unit had capacity about 18000 Btu/h and an energy efficiency rating of 9.0. If one unit operates for 500 hours a year at 18000 Btu/h, the actual power consumption is at about 250 W. There were totally 22 through-window units. The other type was split-unit system. This type of system was used for large lecture room or computer lab. There are three separate split-unit systems serving a total of 405 square meters. Table 4 through 6 summarize the HVAC system of Kaven Hall.

Table 4 Kaven Hall building envelope

Characteristic	Area (m^2)
Gross Floor Area	3772
Conditioned Floor Area	2793
Total door Area	257.7

Total Exterior Glass Area	435.6
Total Exterior Wall Area	1435
Total Roof Area	1212
Insulation Type	1” Air Spacing
Metering	None

Table 5 General information about the heating system

Characteristic	Description
Area Served	2703 m^2
Location of Units	Each room excluding bathrooms
System Type	Single Zone
Maintenance	Average
Control	Space thermostat

Table 6 General information about the cooling system

Characteristic	Description
Area Served	1658 m^2
System Type	Single Zone
Maintenance	Average
Control	Space thermostat

4.1.4 Building Lighting System

The lighting study of Kaven can be firstly separated into two sections, artificial and day-lighting. All of the lamps inside the building were ceiling mounted fluorescent lamp. They existed in forms like pendant and recessed.

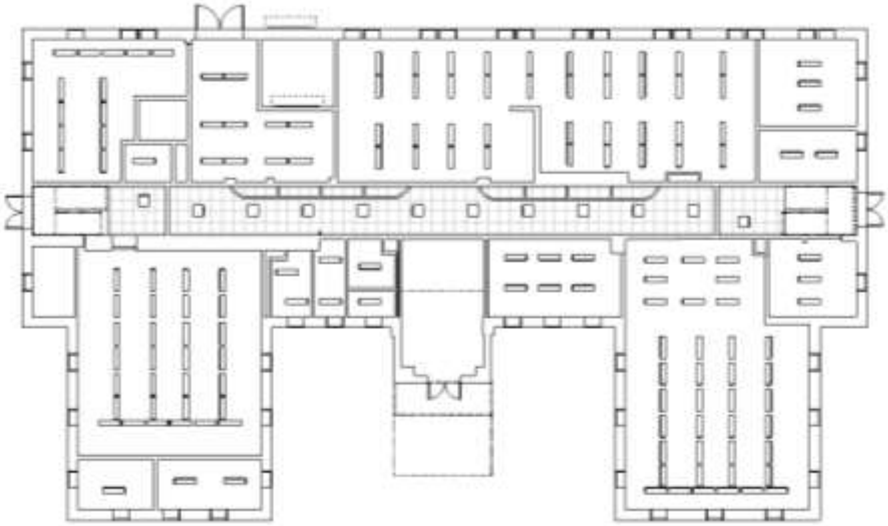

Figure 22 Lighting fixture layout of the first floor

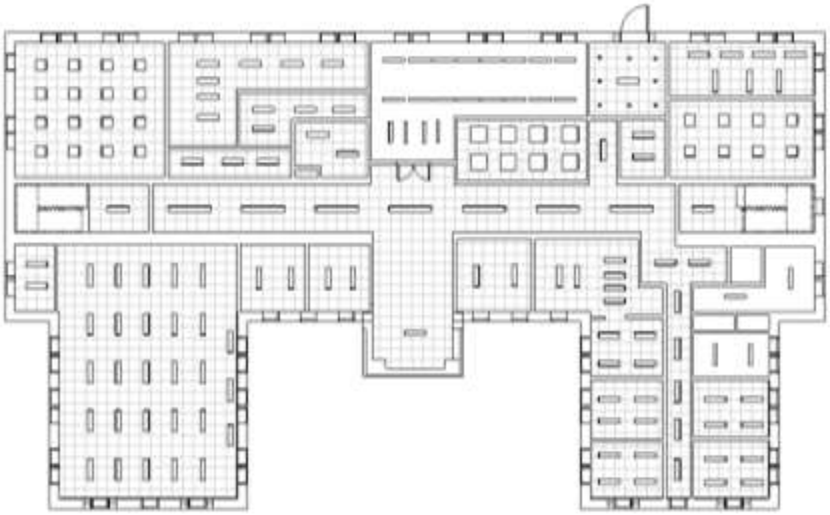

Figure 23 Lighting fixture layout of the second floor

Figure 24 Lighting fixture layout of the third floor

Almost the entire building uses linear fluorescent lamp with different size and length. Table 7 lists all lamps in the building. The total calculated power from artificial lighting is 13.4 kW. Table 8 listed the calculated lighting energy density on each floor. The overall artificial lighting consumption was moderate.

Table 7 Energy consumption of the lighting system

Type /Length	Count	Watt	Efficacy (lm/w)	Luminous Flux	Color Temp	Lamp	Lamp /Fixture	# of Lamp	Total Watt
2’	70	28	65	910	3500	T-8	2	140	1960
3’	32	18	65	1170	3500	T-8	3	96	1728
4’	117	32	65	2080	3500	T-8	1	234	7488
4’	14	56	97	2080	3500	T-12	1	14	784
8’	14	60	75	3900	4000	T-12	1	14	840
Spiral	35	18	52	936	3500	T-2	1	35	630
Total	**282**		70(avg.)					**533**	**13430**

Table 8 Energy density of the lighting system in three floors

	Energy Density (W/m^2)
Level 1	15.9
Level 2	15.5

Level 3	13.7

Natural light inside Kaven Hall is generally adequate. There are about 150 square meters of the area of glazing on each floor. However, this number does not reflect the actual situation. In fact, there are through-window air conditioning units, partitions and ivy on the external surface that blocked the transparent area. Drastic improvements of daylighting require re-sizing the glazing systems, and installing light shelves.

4.2 Energy Conservation Measures

4.2.1 Energy characterization and historical energy request

The calibration of the energy model requires detailed historical data of the energy consumption of Kaven Hall. The only available historical data from the university's facility office is the total natural gas consumption among the 23 buildings on campus for the past five years. No separate electric meter or natural gas meter on Kaven Hall was available. The average natural gas consumption on campus was obtained dividing the total natural gas consumption by the total floor areas of the 23 buildings on campus. Because the natural gas is the solely source dedicated to the heating service of the campus, Table 9 shows the average heating consumption of the entire campus.

Table 9 Average heating energy consumptions for the past five years among 23 buildings on campus

Year	kWh	kWh/m^2
2008-2009	24975901	256
2009-2010	24521289	251
2010-2011	24142172	247
2011-2012	23834184	244
Average	24368394	**249**

Model validation is a critical task to make that all the sub-systems are properly modeling and reflecting close to real-life conditions for the purpose of estimating the energy saving of retrofitting measures. Due to short period of time and lack of installed thermometers in the building, the validation of the base model was based on logical assumptions.

Most of the 23 buildings on campus were built around the same time, using similar materials and construction techniques, and the average heating consumption of 249 kWh/m2/year was used in this study as a benchmark.

Table 10 Physical characteristics of the base model building

Characteristic	Description for base model
Location	Central Massachusetts, USA (Latitude 42.27°N and longitude -71.9°
Type of building & shape	Three stories plus attic, University Academic Building, *C*-shape
Total height	Approximately 18m
Gross floor area	3930 m^2 (ceramic tiles and synthetic carpet)
External wall	Brick 350 mm, Gypsum board 25 mm, (U)=1.68 W/m^2K
Roof	Asphalt shingles 75 mm, wood board 60 mm, U=2.56 W/m^2K
Glazing	Single pane, clear/no shading (U)=5.8 W/m^2K, total solar transmission (SHGC)=0.82, lighting transmission = 0.881
Number of occupants	Approximately 400
Heating system	Steam radiator, 24/7 Nov.-April
Cooling system	Separated air-cooled
Ventilation	Natural ventilation, minimum fresh air 0.1 L/s/person, infiltration rate 1.5 ACH
Lighting	14 W/m^2

Table 11 Physical characteristics of the each building zones

	Area [m2]	Density [people/m^2]	Heating Set-point (Set-back) °C	Cooling Set-point (Set-back) °C	Equipment Gain [W/m^2]
Office	550.6	0.07	23.5 (22.0)	25.0(35.0)	25
Lab	703.1	0.03	23.5 (22.0)	25.0(35.0)	5
Computer Lab	265.0	0.15	23.5 (22.0)	25.0(35.0)	25
Classroom	392.7	0.2	23.5 (22.0)	25.0(35.0)	5
Hallway	559.4	0.1	23.5 (22.0)	N/A	0
Kitchen	26.9	0.02	23.5 (22.0)	N/A	60
Lounge	70.1	0.2	23.5 (22.0)	N/A	0
Storage	196.7	0.01	N/A	N/A	0
Attic	1019.9	0.02	N/A	N/A	2
WC	104.1	0.1	23.5(22.0)	N/A	1.6

4.2.2 Evaluation of various energy retrofitting actions

The energy breakdown for the modeled building is shown in Figure 25. The largest amount of energy is consumed by the heating system (74%), followed by office appliances (11%) and lighting (10%). Office appliances consume the second highest energy because there were several labs and computer rooms, many small and large printers and copy machines. The heating was on 24/7 from November to April. The natural ventilation (doors being opened constantly with peaks occur at every 50 minutes (class schedule) and windows being opened by individual due to lack of fresh air), high infiltration rate (several severe gaps and cracks at fenestration systems), and poor envelopment in terms of thermal properties make the heating energy consumption high. Information on heating and cooling system was collected from design data, equipment tags, as well as the information provided by the school’s facility office.

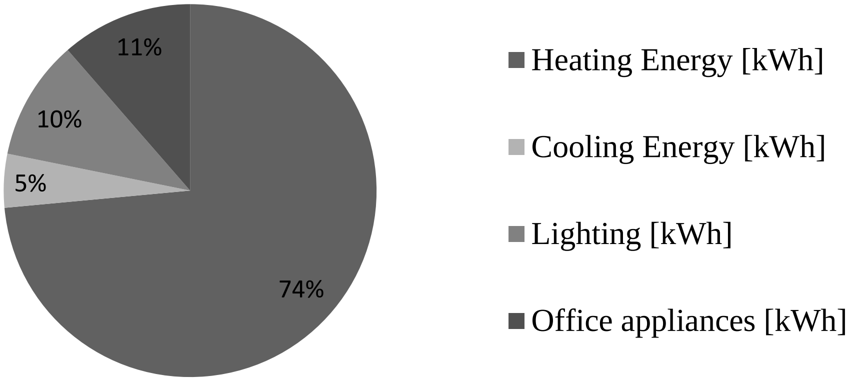

Figure 25 Building energy consumption breakdown

4.2.2.1 Change of the indoor temperature set-points

The impact of indoor temperature settings on energy use is analyzed. According to the school's facility office, the set-temperature of the indoor heating air mean temperatures is 23°C. During the summer, the mean air temperature of independent window air conditioning units is 25°C. This temperature setting is used in the based model.

Appropriate temperature monitoring system can be installed to adjust the temperature at a more accurate level. Thermostats should be installed in each zone and temperature dial of the radiator can be adjusted accordingly. According to ASHRAE Standard 55-2013 [35] and to the EN15251,

a) In winter time, from November to the end of April, an indoor temperature equal to 20°C saves the heating energy consumption from 1090 MWh to 803 MWh, roughly 20% of reduction;
b) In summer time, when the set-point temperature increased from 25 to 26 °C, the cooling energy consumption decreased from 69 MWh to 52 MWh, 25% of reduction.

4.2.2.2 Reduction of the infiltrations due to bad fenestration conditions

The second retrofitting measure is to reduce the building infiltration rate. Windows are surely the building systems over which the retrofit has to focus. The existing windows are in bad conservation state. Some are deformed, and several two-three centimeter gaps in the window have been reported which created significant air draft. Regarding the energy analysis of the DesignBuilder, the infiltration reduction from 1.5 ach to 0.25 ach, the energy was saved by 47%.

In summer time, the situation is opposite. Shown by the dynamic energy analysis, the cooling energy consumption increased while the building becomes more airtight. However, the increase is marginal comparing the reduction of the heating energy consumptions. Overall, the total energy consumption, including heating and cooling, decreased by more than 50% by increasing the building airtightness from ach1.5 to ach 0.25.

However, according to the newest ASHRAE standards, a minimal air change rate of the 0.5 was required to achieve a healthy indoor environment. Additional mechanical ventilation units were desired to increase the air change rate from 0.25 to 0.5. To minimize additional heat loss, mechanical ventilation system would be equipped with heat recovery function to use the waste heat to pre-heat the air coming in. High efficient central ventilation system requires addition renovating inside the building, and localized window ventilation unit would be easy to install. The heat recovery rate of the localized window ventilation unit is 45% according the current industry level, which is about 40% less efficient than the central ventilation system on the market.

Shown by the dynamic energy simulation, the implementation of the mechanical ventilation slightly increased the heating energy consumption. During the summer time, the cooling consumption decreased due to constant air exchange between the indoor and outdoor.

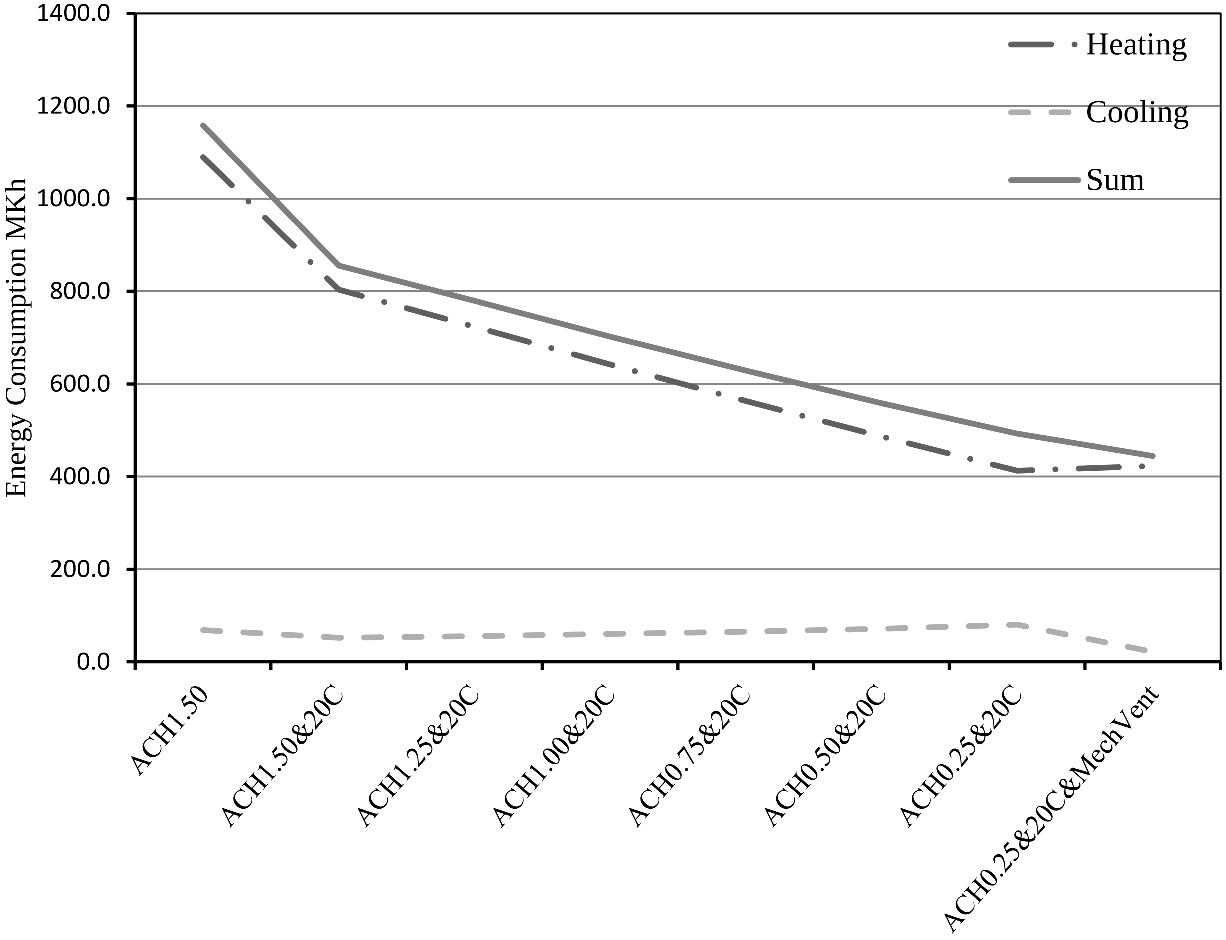

Figure 26 heating and cooling energy density under various energy retrofitting actions

4.2.2.3 Replacement of the present fenestration and adoption of double glazing system

Using more energy efficient windows can be beneficial in both reducing the energy use and improving the door comfort levels. Energy efficient windows usually feature low U-factor, low emissivity, and high air tightness. Nowadays, window system with multiple glazing is used.

Double-glazing is defined as two panes of glass with a layer of air or noble gas filling the gap in between. Triple-glazing instead would have three panes of glass with two layers of air or noble gas in between [16]. The main advantage of using multiple glazing systems is the increased insulation. Well-made double glazing, when properly installed, can reduce cooling and heating costs by as much as 10%. Depending on the amount of glass used in the building, the costs savings can be even more [36].

Transparent building components affect both the thermal dispersion for transmission and the achievable solar heat gains. Using more energy efficient windows (low U-factor, low emissivity glazing, air tight) can be beneficial in both reducing the energy use, and improving the indoor comfort levels.

For existing building, the U-factor is about 5.8 W/m^{2}K. The total solar transmission is 0.82.

In the simulations, the glazing system was tested with low emissivity double glazed and triple glazed windows. The first simulation used two 3 mm low emissivity (e2=0.1) clear glazing with 13 mm air gap filled with argon gas. The achieved thermal properties with this type of glazing showed great advantages. The U-factor is around 1.5 W/m^{2}K and solar heat gain coefficient around 0.6. The second simulation used glazing that features three 3 mm low emissivity (e2=e5=0.1) clear glasses with 13 mm argon gas fill in the gaps. The achieved U-factor decreased to 0.78 W/m2K, and the solar heat gain coefficient reduced to 0.47.

Simulations showed that well-made and well-fitted double glazing offers reduction of heating energy consumption by about 18%, as shown in Figure 27. The heating energy saving, changing from single pane to double pane low-e, was 12.3%.

4.2.2.4 Increase of the thermal insulations of the walls

Another energy retrofit action is to improve the thermal insulations of the vertical walls, by placing aerogel blanket on the inner side of the exterior wall. The target wall R-value for deep energy retrofit projects is usually 5.3 m^{2}K/W [37].

In order to preserve the exterior appearance of the building, the retrofitting actions have to be taken from the interior. Multiple aerogel blanket with total thickness of 5cm was considered in this study in order for the vertical wall to achieve high insulation value while also minimize the reduced floor area due to the increased thickness of the walls. Aerogel blanket also works as vapor barrier.

The aerogel blanket application induces a strong reduction of the wall thermal transmittance, from 2.2 W/m^2K to $0.25W/m^2K$.

Two dynamic energy simulations were carried out. First, a 1 cm standard aerogel blanket was used between the existing brick and plaster board. In the second simulation, 5 aerogel blankets with total thickness of 5 cm were used.

Simulations showed that implementing aerogel reduced the heating energy consumption of the building, in particular when implementing 5 cm of aerogel.

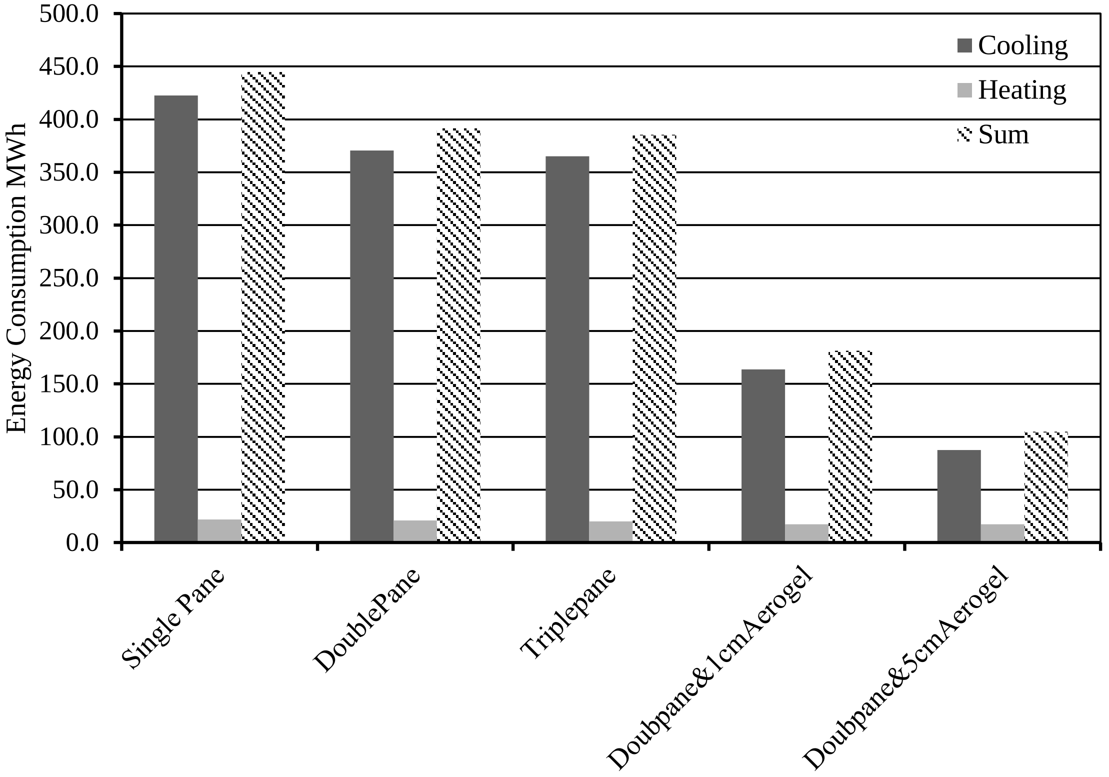

Figure 27 heating and cooling energy consumption under various fenestration and wall retrofitting actions

4.2.3 Analysis of aerogel window applications (Capstone Design)

Instead of having argon-filled gap between the double pane window, windows with aerogel filling the gap increase the thermal resistance. This application drastically decreases the U-factor of the window, but it also decreases the visual transmissivity.

The index considered in this report was the Useful Daylight Index (UDI), which represents the percentage of time in which the daylight level is useful for the occupants. It is commonly divided into three intervals: values which are lower than 100 lux, between 100 and 2000 lux, and greater than 2000 lux during the occupied time. In this case, the occupied time was 24 hours a day, and 365 days a year. Values lower than 100 lux are considered ‘too little’ daylight, while values greater than 2000lux are considered ‘too much.’ The upper threshold is also one of the indicators to detect times when visual discomfort might occur. When luminance values are between 100 and 2000 lux, it is considered useful daylight. UDI allows analyzing whether a space is under-lit or over-lit, and the overall distribution of the ‘well day-lit’ space.

The following figures show the UDI (100-2000 lux) under the current and proposed retrofit scenario. Zone 1 to 4 was labeled in the Figure 28. Zone 1 is a room at the east corner; zone 2 is a room at the south corner; zone 3 is a room at the north corner; zone 4 is a room at west corner of the building.

UDI is a dynamic daylight indices, which indicates that UDI takes into account the location and climate condition during the daylight simulation. For example, in zone 1, with single clear windows, 34.8% of the year the average useful daylight in the space is between 100-2000 lux (There are total 4458 hours of daylight in Worcester, MA during a year. Out of total 8760 hours a year, Worcester has daylight for 51% of the time during a year), as shown in Table 12.

The ‘total’ in Table 12 indicates the overall daylight performance in four zones. The introduction of 40% aerogel does not significantly reduce the daylight performance, while the 60%, 80%, and 100% largely lower the daylight performance.

Table 12 Mean Useful Daylight Illumination 100-2000 Lux (%)

	Zone 1	Zone 2	Zone 3	Zone 4	**Total**
Single Clear	34.8	33.8	35.5	40.7	144.7
Double Clear	37.3	36.0	35.0	40.6	148.8
40% Aerogel	38.2	36.5	33.4	39.0	147.1
60% Aerogel	37.9	35.9	32.1	36.1	142.0
80% Aerogel	37.4	35.3	30.5	34.0	137.2
100% Aerogel	36.2	34.4	28.6	30.9	130.1

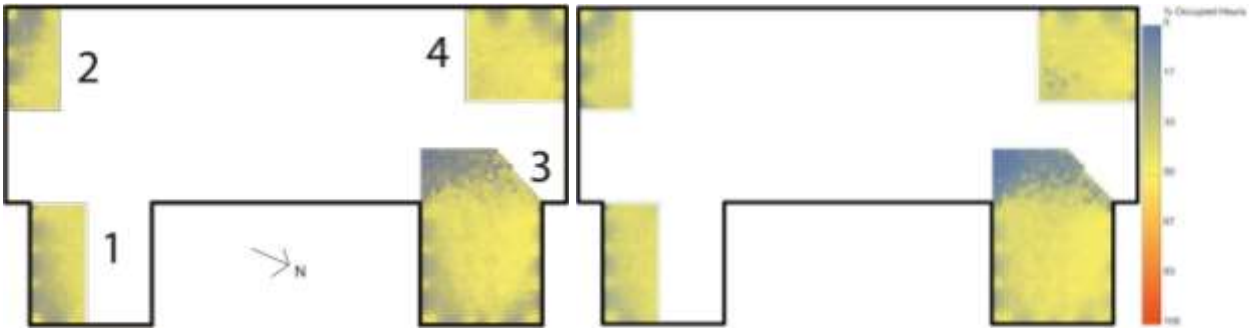

Figure 28 useful daylight index when using single pane windows (left) and double pane windows (right)

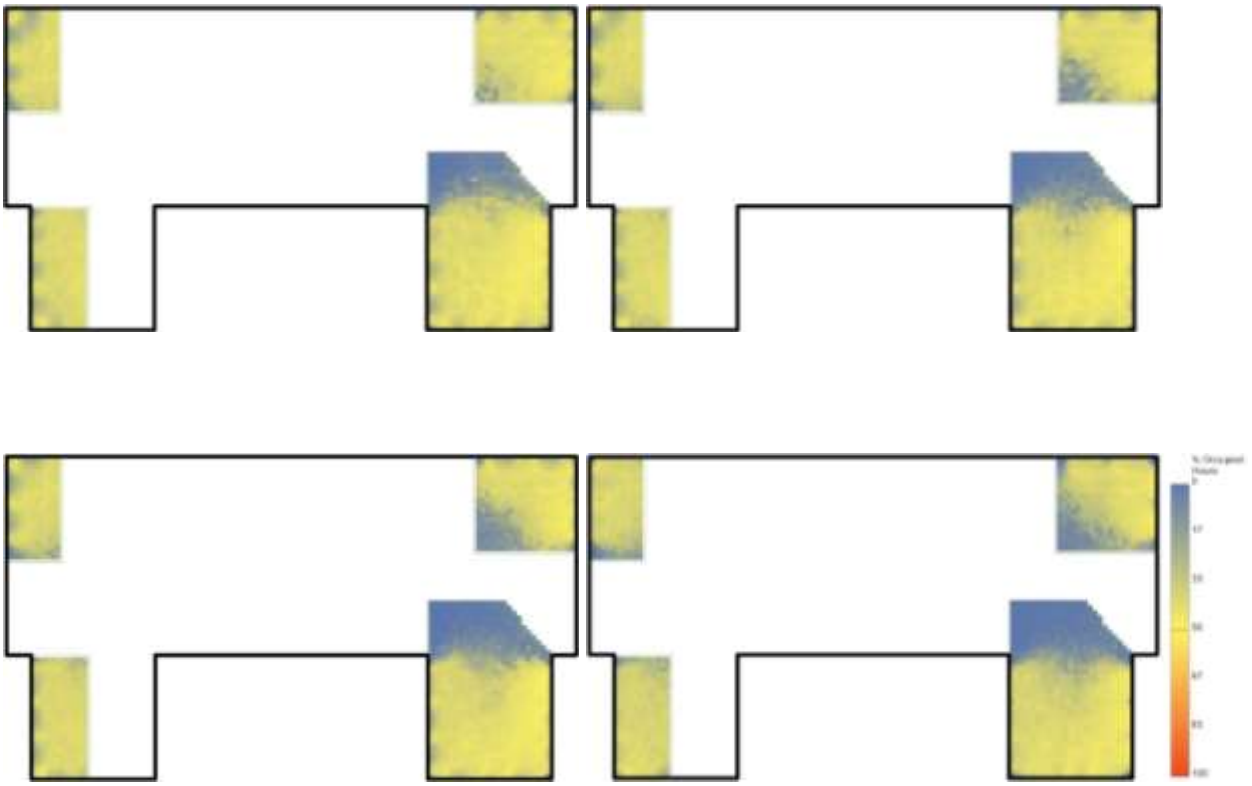

Figure 29 useful daylight index when using windows with 40% (upper left), 60% (upper right), 80% (lower left), 100% (lower right) aerogel coverage

The energy performance of the aerogel glazing was hence simulated. The R-value of the four different combination of aerogel windows was calculated. With 40% of aerogel proportion, the U-factor is 1.14 W/m^{2}K; With 60% of aerogel proportion, the overall U-factor is 0.86 W/m^{2}K; With 80% of aerogel proportion, the overall U-factor is 0.58 W/m^{2}K; With 100% of aerogel proportion, the overall U-factor is 0.30 W/m^{2}K.

As shown by the simulations in Figure 30, the heating energy consumption decreased with the increasing of the aerogel proportion of the windows. The energy consumption decreased in a linear relation with the proportion of the aerogel.

The cooling energy consumption kept almost stable with the increasing proportion of the aerogel. Although a large proportion of the aerogel decreased the U-factor of the window, keeping the unwanted heat inside during the summer time, the decrease solar transmissibility decreased as well, which limited the solar heat gain during the summer time. Simulations showed that the increased thermal resistance offsets the decreased solar heat gain and leaves the cooling consumptions at a stable condition.

The energy saving was larger at 40% aerogel than other configurations. The choice has to be made about which configuration to use. Energy performance and daylight performance are conflicting with each other, the higher the energy performances, the lower the daylight performances. Considering both performances, the design with 40% aerogel should be selected. The energy simulations showed a linear relationship between the amount of aerogel and the total energy savings. The daylight simulation showed non-linear relationship between the amount of aerogel and UDI. The overall trend of UDI is decreasing with increasing amount of aerogel, but the decrease is generally small. Finally, a 40% aerogel window configuration was selected because it reduces energy consumption, while does not significantly reduce the daylight availability.

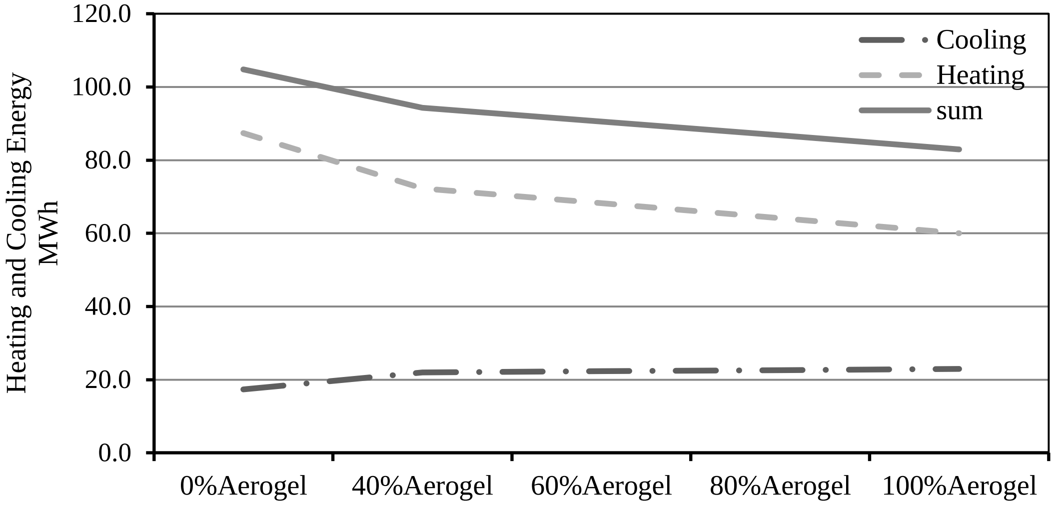

Figure 30 Heating and cooling density under various aerogel applications

5. **Discussion**

5.1. Climate influences on retrofitting

In order to investigate the feasibility of the previous retrofitting measures under different climates, simulations were repeated for various locations. These simulations tested how sensitive was the Kaven Hall energy performance under various climate conditions.

Such theoretical investigations have limited use in real world practices. Because during the simulations, all the parameters in the energy model were kept the same except the location, and, in a real world, buildings would have been built with different methods and materials.

According the climate zone divisions from Oak Ridge National Laboratory, five locations were chosen from five climate zones [5]. All five locations were chosen from the east half of North America, having the same moisture air conditions. Results showed that the effect of climate conditions varies among different ECMs; cooling and heating energy consumptions showed expected changes with the changing locations.

The cooling energy consumption consumptions varied as expected, the lower the latitude, the higher the cooling energy consumption. Miami, being the south-most city on the list, has the highest overall cooling consumption.

As shown in Figure 31, the slope of the lines indicates the sensitivity of that retrofitting action to the climate conditions. For the same ECM, the slope change means that the ECM is sensitive to climate conditions. For example, changing set-temperature has more impact on cooling energy consumption when the building is located in Miami than when the building is located in Worcester or Montreal.

Some ECMs are more climate sensitive than others. The introduction of the aerogel in the windows has more impact on the cooling energy consumption when the building is in Miami. The increasing air tightness of the building has a reverse impact when the building is in Miami, where increasing building air tightness decreases the cooling energy consumption in summer time. Other retrofitting actions were less sensitive to the climate. The introduction of the mechanical ventilation system has almost the same impact on cooling energy consumptions in all five locations.

During the winter time, the situation was similar but opposite. The heating energy sensitivity of the retrofitting actions increased as the location was moving north. The increasing building air tightness had a greater impact on the heating energy consumptions when the building was in the Northern area, as shown in Figure 32.

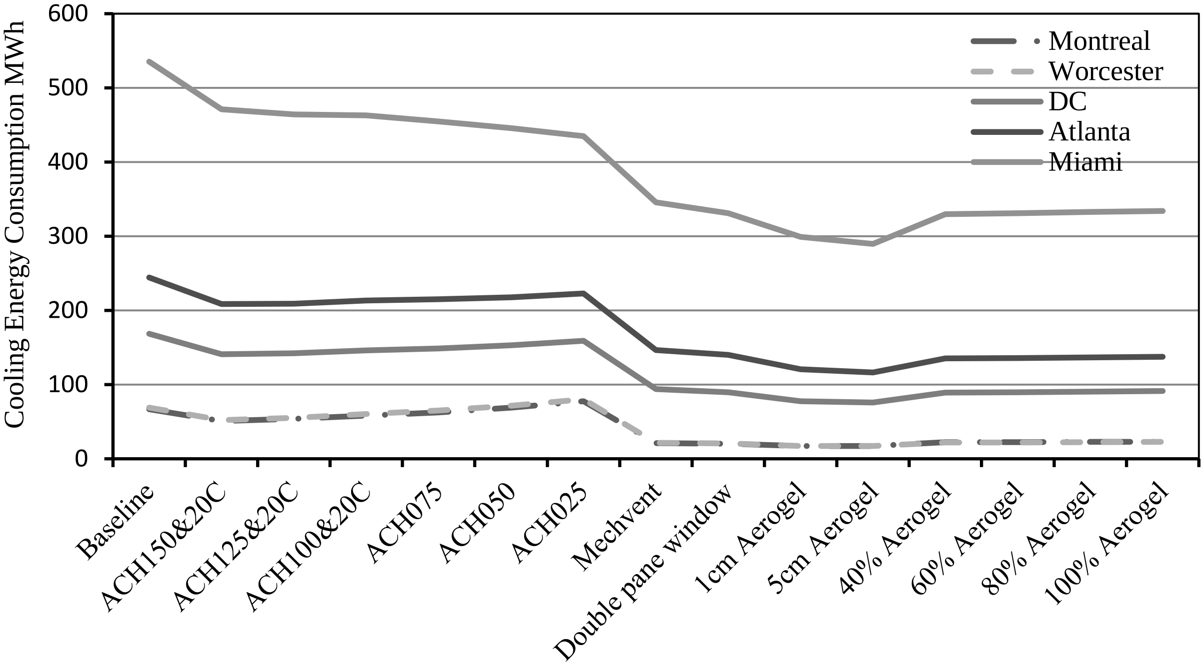

Figure 31 Cooling energy consumption when the building is at Montreal, CA, Worcester, MA, Washing DC, Atlanta, GA, and Miami, FL.

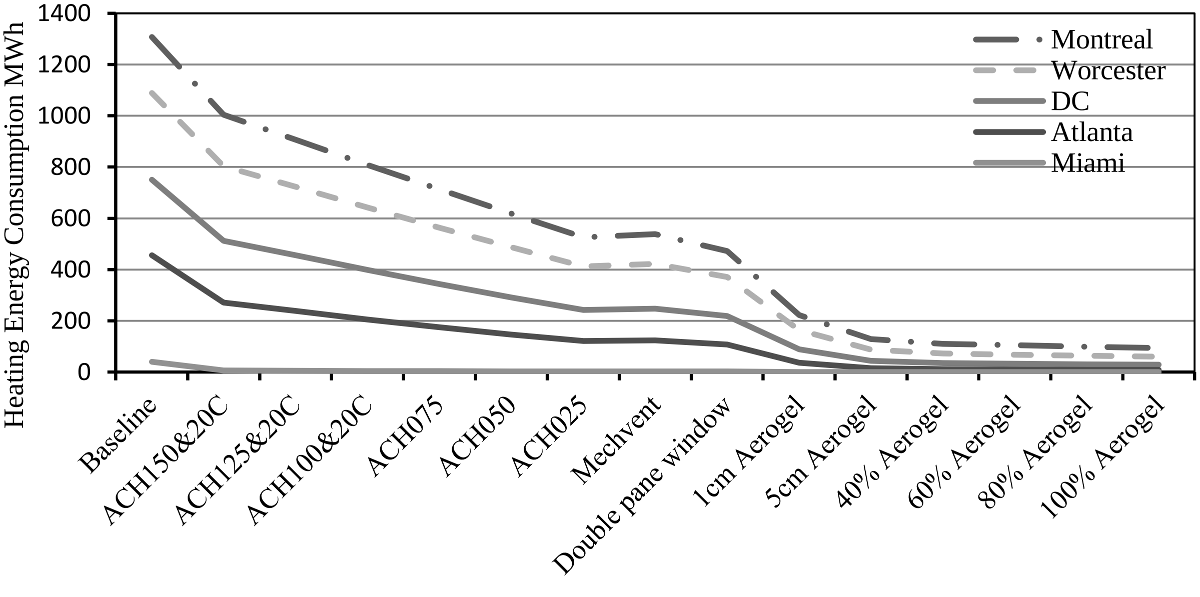

Figure 32 Heating energy consumption when the building is at Montreal, CA, Worcester, MA, Washing DC, Atlanta, GA, and Miami, FL.

5.2 Preliminary Cost Analysis

Affordability is a key aspect of high performance building insulations system, because it helps ensure large-scale deployment of the systems.

The first retrofitting action is modifying the set-temperature of the heating and cooling system during the winter and summer. This action does not require capital investments. Adjustable dials were already installed in each room. However, it is hard to achieve the ideal temperature since occupants' preferred temperature varies.

The second action is to reduce the infiltration rate of the building. The replacements of glass anchor block and ruined frame and sheath are required. The whole retrofit action has estimated cost of 350$/m2, according to RS Means construction cost [38]. The total window surface of the building is about 435.6 m2. The total cost of this retrofit action is about $152460. Due to the time constraint, the cost of reducing the infiltration was estimated at a preliminary basis. Windows vary in conditions and so does the cost of fixing each window. A more accurate cost estimate would require inspections to every window.

The next retrofit action is to replace the windows. The acts of the installation of new windows eliminates the need of reducing the infiltration rate, since newly properly installed windows are fairly airtight. The cost of replacing the entire window system includes 1) removing the existing window, 2) purchase of the new windows, and 3) installing of the new windows. In Massachusetts, the labor cost of removing and installing windows is $3.37 and $15.68 respectively.

Another retrofitting action is the installation of aerogel blanket on the interior side of the external walls. There have been many researches focusing on the installation and cost estimation of aerogel. Fraunhofer Institute in U.S. has performed a cost analysis of installing aerogel blanket on the interior [37]. Their aerogel blanket cost was based on the current cost of commercially available aerogel in the U.S. market and short-term cost reduction predictions. In the United States, the cost of an aerogel blanket with R-4 per 10 mm will be between $2.50 and $3.00/ft2 in the near future (considering coming improvement in the production method and production volume increase) [37]. This evaluation used a price level of $2.75/ft2, which might be slightly lower from the current U.S. market prices. Studies from Fraunhofer Institute showed that the installation of thin aerogel blanket cost much less than the installation of thick aerogel blanket. The price of labor cost went up as the thickness of the aerogel blanket increases. The cost of installing 3cm of aerogel blanket is 1.5-2 times more expensive than retrofit with fiber and foam insulation when achieving the same R-value.

The past natural gas bill from school's facility office indicates that the price of natural gas is approximately $0.034 per kWh. The natural gas usage goes entirely to the heating of the campus buildings, and this price is used to estimate the total money saved by heating energy reduction. The price of electrical bill for commercial buildings in Massachusetts is around $0.15 per kWh, and this price is used to estimate the money saved by cooling energy reduction.

Table 13 summarized the cost of each ECM. Modifying the set-temperature is the most cost effective. Infiltration rate reduction is followed as the second most cost effective ECM. Reducing the infiltration rate decreases the heating energy demand but increases the cooling energy demand in the summer time. Although the increase in cooling energy demand is small comparing to the heating energy demand, the price for electricity is higher than that of natural gases.

Table 13 also included the calculated discounted payback time (DPP) and net present value (NPV). DPP indicates the time when the investments and the returns balance with each other, taking the discount rate of 6% into account. It is usually reasonable to invest in the one with low DPP. NPV is another critical index. Usually the positive value of NPV indicates that the respective project was worth investing.

Figure 33 shows the cost of each saved kWh for each ECM. The cost of each saved kWh is another indicator of whether the ECM was worth investing. Without considering the price of electricity and natural gas, this method focuses on the cost of saving energy. The prices of electricity and natural gas are different, and they may offset the difference between the energy savings in heating and cooling periods.

Table 13 Retrofit actions singularly analyzed: results of the technical-economical study

Action	Cost ($)	Heating demand saving (kWh)	Cooling demand saving (kWh)	Heating savings ($)	Cooling savings ($)	Total savings ($)	DPP (yrs.)	NPV ($)
Set-temperature modification	0	285851	16677	9662	2642	12304	0	205071
Infiltration reduction	152460	390696	-28128	13206	-4457	8749	>30	-59675
Window replacement	223520	42109	59473	1423.3	9424	1959	18	103071
Aerogel wall	317574	283158	3537	9570.7	560	10131	>30	-148722

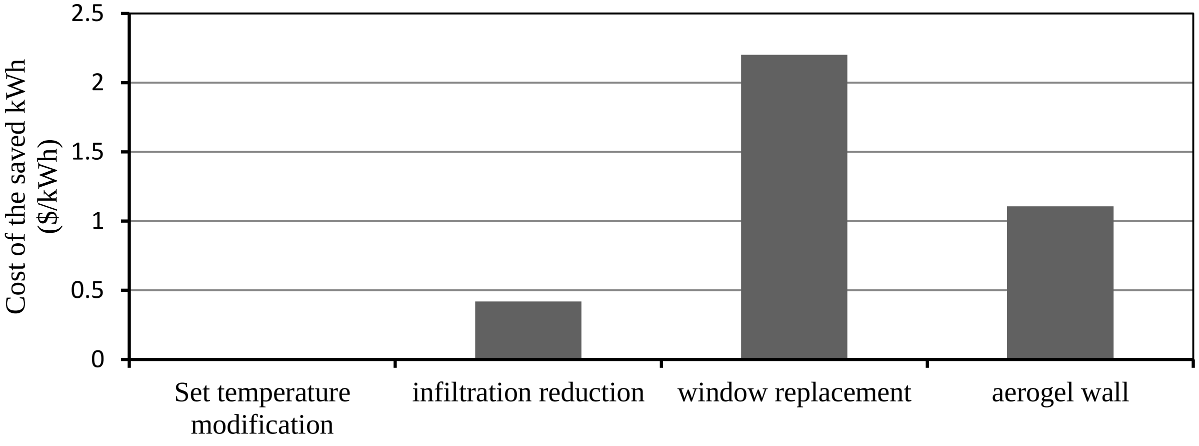

Figure 33 Cost of the saved kWh under various retrofit action

Set temperature modification and infiltration rate reduction were categorized as no cost and low cost energy retrofit measures. Consequently, it is reasonable to take the advantage of implementing these retrofit actions since they have very low payback time.

Glazing system replacement and adding aerogel blankets as insulation are retrofitting actions that require considerable amount of capital investments. The replacement of glazing system has less payback time and higher net present value than aerogel blanket installation. It is more reasonable to choose window replacement rather than aerogel blanket installation.

Energy retrofit is an unavoidable option for Kaven Hall, and, as an educational building, Kaven Hall should take the leading role of sustainability. The installation of all the proposed retrofitting actions is highly beneficial in the terms of energy savings. Retrofitted Kaven Hall can be served as a research target for further investigations of energy saving validation.

6. Conclusions

Energy retrofitting is becoming an unavoidable option for existing buildings worldwide. This study considered an educational building located in a cold climate (Massachusetts, U.S) built in 1956. The focus of the retrofitting strategies was on the building envelope system. The building is not in an ideal shape and is far below the current energy standard. An energy retrofit is inevitable for Kaven Hall. Evaluations of various energy conservation measures on the building envelope system showed that energy saving of 90% can be achieved.

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