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Optimal Renovation Strategies for Education Buildings—A Novel BIM–BPM–BEM Framework

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Abstract: The aim of this paper is to propose a novel building information model (BIM)–building performance model (BPM)–building environmental model (BEM) framework to identify the most energy-efficient and cost-effective strategies for the renovation of existing education buildings to achieve the nearly zero-energy goal while minimizing the environmental impact. A case building, the University of Maryland's Architecture Building, was used to demonstrate the validity of the framework and a set of building performance indicators—including energy performance, environmental impacts, and occupant satisfaction—were used to evaluate renovation strategies. Additionally, this novel framework further demonstrated the interoperability among different digital tools and platforms. Lastly, following a detailed analysis and measurements, the case study results highlighted a particular energy profile as well as the retrofit needs of education buildings. Eight different renovation packages were analyzed with the top-ranking package indicating an energy saving of 62%, carbon emissions reduction of 84%, and long-term cost savings of 53%, albeit with a relatively high initial cost. The most preferable package ranked second in all categories, with a moderate initial cost.

Keywords: renovation; education buildings; building information model; building environmental model; building performance model; nearly zero energy

1. Introduction

1.1. Existing Energy Performance of Education Buildings

Education buildings have a unique energy profile that differs from that of a typical nonresidential building (refer to Figures 1 and 2). Based on the 2012 Commercial Building Energy Consumption Survey (CBECS) data, in education buildings, space heating accounts for 36% of the overall energy consumption (higher than in typical nonresidential buildings, at 25%), followed by cooling (11%) and computers (9%). The three major differences between a typical nonresidential building and education building are space heating, computing, and cooking. An education building has significantly less space heating and cooking energy demand, but it has a higher computing energy demand than that of nonresidential buildings. On average, the number of computers per floor area in education buildings increased by approximately 71% between 1999 and 2012, and education buildings have nearly twice as many computers per floor area than any commercial buildings [1]. Cooking in education buildings accounts for 7%, while in a typical commercial office building, the energy spent on cooking is close to 0%. The differences between education buildings and typical non-commercial buildings may be attributed to the former's unique operation schedule and varied user groups.

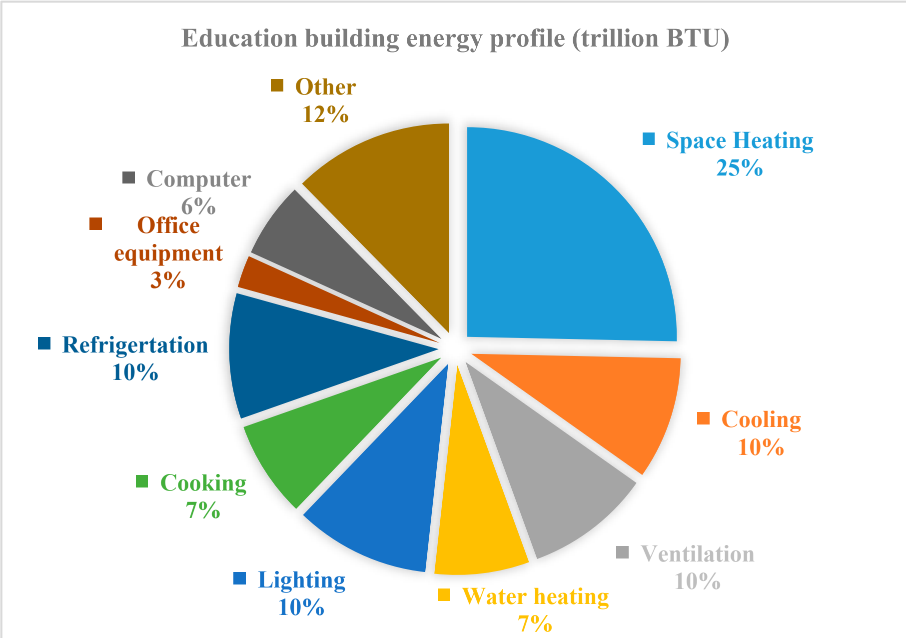

Figure 1. Energy consumption profile of an education building (by author based on CBECS 2012 data [1]).

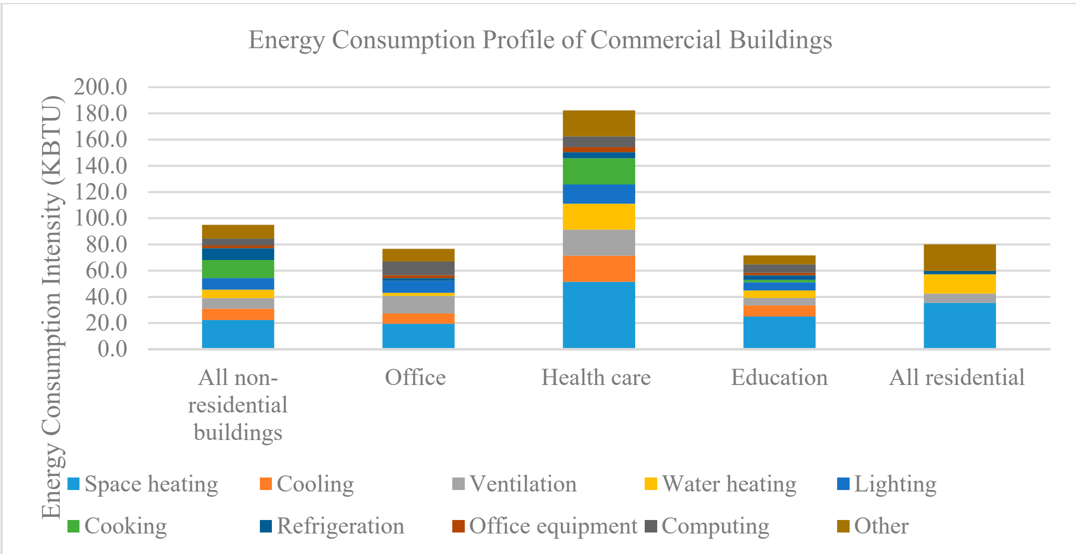

Figure 2. Energy consumption profile comparison (created by author based on CBECS 2012 data [1] and RECS 2015 data [2]).

Education buildings have longer operation hours than typical nonresidential buildings. Higher-ed buildings normally host evening classes, and K–12 schools often provide their facilities for the use of local community activities and meetings. Education buildings also have many varied user groups (of different ages and behaviors) since most classrooms are shared by different schools and departments and student levels. Within education buildings, higher-ed facilities differentiate themselves from K–12 buildings as well: K–12 buildings are normally closed during the summer and winter breaks while higher education facilities operate on a year-round schedule. Understanding the different operational characteristics of education buildings helped us to recognize the challenge of considerable uncertainty in employing a dynamic operational schedule to reduce energy consumption. Therefore, our renovation strategies shifted toward tightly controlling the categories and factors that would not be affected by an unpredictable schedule and user groups, such as the building envelope and systems.

1.2. Existing Research Condition of Education Buildings

Educational buildings in the United States account for approximately 14% of overall nonresidential floor areas. When major building systems and equipment reach the end of their service lifespan, among education buildings, 76.61% are 20 years or older and 38.30% are 50 years or older, with the latter group representing the approximate expected serviceable lifespan of buildings in general [1] (refer to Figure 3). Based on the 2012 Commercial Building Energy Consumption Survey data, education buildings are the second largest building type, with an average of approximately 2879 m^2 (31,000 ft^2) per building. The median energy performance of an education building is 0.41 kWh/m^2/yr (130.7 kBtu/sf/yr), and building owners spend an average $1.40 per m^2 ($1400 per ft^2) annually on utility bills. Moreover, 75% of education buildings have a performance of 0.57 kWh/m^2/yr (181.1 kBtu/ft^2/yr) or higher [1], which considerably exceeds the median level of a normal office building. The majority of education buildings require immediate renovation actions due to the buildings' age.

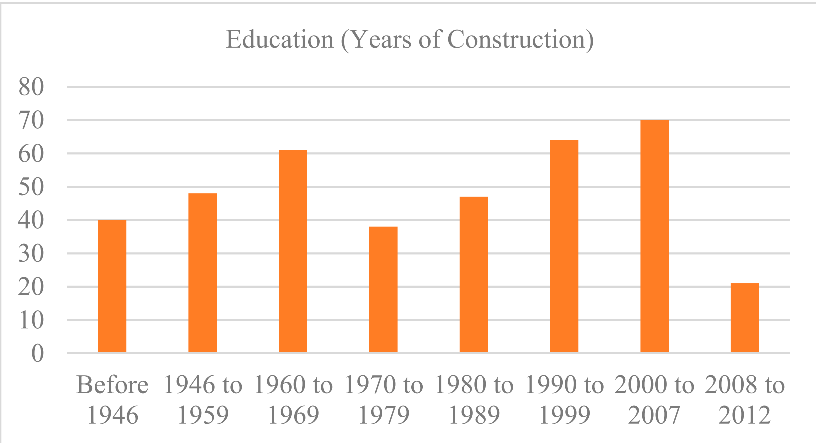

Figure 3. Age of education buildings (created by author based on CBECS 2012 data [1]).

In this section, several studies with a focus on education building energy renovation and retrofit are briefly reviewed. Favrizio et al. [3] proposed a method to diagnose energy performance, aimed at the integrated design of energy refurbishment of existing buildings. The research team used a method that combined heat flow measurement, infrared thermography, energy simulation, and situ investigation. A variety of renovation strategies were tested—such as the reduction of infiltration, replacement of windows, and increase of thermal insulation in the building façade—with results indicating the possibility to achieve high levels of energy saving, albeit with cost and construction constraints. Conversely, De Angelis et al. [4] evaluated the energy reduction potential through building envelope renovation and renewable energy production. Their results revealed that a maximum energy reduction of 37.3% could be achieved by improving thermal properties of the envelope together with effective natural ventilation. Niemelä et al. [5] demonstrated that the near zero-energy building target could be cost-effectively achieved in existing education buildings in Finland. They also found that the energy-saving potential of the HVAC system was significant compared to the building envelope. Dalla Mora et al. [6] studied an existing school building located in Italy, and several combinations of retrofit measures were applied to derive cost-effective solutions for renovation. Fonsca et al. [7] designed a renovation plan for the Department of Electrical and Computer Engineering building in University of Coimbra, Portugal, with the aim to achieve the nearly zero-energy goal using two primary technologies: LED lighting and photovoltaic panels. In contrast, Irulegi et al. [8] studied an education building in Spain; the research team proposed different renovation strategies for the winter and summer, and proved that the total energy-saving potential could reach as high as 62%.

1.3. The Research Gap in Existing Education Building Renovation Research

Overall, despite numerous studies conducted on education buildings, information on the energy consumption of this building type is still limited, in comparison to other commercial and residential buildings [3,9–15]. Furthermore, most reports focus on primary and secondary school buildings, with very limited studies concentrated on higher education buildings. The author conducted a literature review using academic research articles found on Web of Science (WOB) from 1970 to 2017, 182 articles were found related to energy retrofitting and renovation. Chen and Ma [16] studied the regulation influence on residential buildings' energy efficiency. Serraino and Lucchi [17] looked into the effectiveness of energy renovation strategies in public housing projects. Studies have also been conducted on energy refurbishment on historical building renovations [18–20]. Among the articles, 43% focus on residential building renovation and 35% on commercial buildings, with only 8% on education buildings. Furthermore, most reports focus on primary and secondary school buildings, with very limited studies concentrated on higher education buildings.

The second research gap is between energy efficiency improvement and environmental impact mitigation. While the majority of research articles focused on energy efficiency [20–23], there were a few papers that studied the balance between energy efficiency and environmental impact [20] examined European residential buildings and concluded that heating energy consumption was directly related to high emissions. Scheuer et al. [20] evaluated the life cycle energy and environmental performance (LCA) of a new building on the University of Michigan campus and concluded that the design of new buildings that integrate more sustainable technologies is a major step toward environmental impact reduction. At the same time, they pointed out that modeling challenges put great limitations on the application of the life cycle analysis since a detailed design evaluation was impossible with the building LCA data at that time [13]. Fifteen years after their research, LCA data experienced great development, which has enabled us to conduct evaluations not only in new buildings but also in existing buildings.

There is another trend emerging in the institutional environment that requires attention. Between 2012 and 2018, the number of net-zero energy (NZE)-verified buildings and NZE emerging buildings increased by over 700% [21]. ZNE-verified buildings are the buildings have achieved ZNE for at least one full year, with actual monitored performance data. ZNE emerging buildings are those have publicly stated a goal of reaching ZNE but have not yet demonstrated achievement of that goal. Education buildings (including K–12 schools) comprise the largest portion of NZE building projects, accounting for 37% (178) of all NZE buildings in the United States. Higher education (higher-ed) buildings represent 35% of all NZE education buildings [21]. There are four major drivers powering the rapid increase of general net-zero building development, particularly in the education building sectors. The first driver is energy-saving incentives and economic return that building owners can gain through setting high standards at the beginning of project planning. The second is "the recognition of increased market value through green building practice and attention to a label such as net-zero energy building" (European Union 2009). The third driver is the educational function, which is particularly valuable for institutional clients. A growing number of high-performance buildings, NZE buildings, and positive-energy buildings serve as living laboratories for higher education purposes. The final reason is that the education building sector offers national and regional forums to facilitate the transfer of the best designs and operational practices. Together, these four reasons explain why education buildings represent the largest growing portion of NZE projects and will continue to drive the growth of NZE in the education category. Despite such interest in NZE in the institutional sector, however, among the verified and certified NZE buildings worldwide, there is only one higher-ed building in existence and no renovation projects to date. Verified and tested methods and techniques for renovating existing buildings to achieve the net-zero goal are extremely limited. Consequently, the gap between the renovation needs of education buildings and verified strategies and techniques presents opportunities and challenges.

Energy-efficient building does not automatically translate to a satisfactory indoor environment and occupant satisfaction. Besides energy performance, other critical areas also need to be improved in aging education buildings, including thermal comfort, acoustic quality, daylight, and views. These performance indicators comprise the indoor environmental quality. Research indicates that an improved indoor quality can improve students' learning outcomes, and the detrimental effects of aging facilities can be reversed when schools are renovated [22–25]. In order to meet the energy target and occupants' preferences at the same time, a comprehensive performance matrix and baseline condition (based on existing building performance) for comparison are needed to evaluate the effectiveness of renovation strategies.

2. Case Project

2.1. Carbon-Neutral Goal of the University of Maryland

The University of Maryland is the flagship institution of the University System of Maryland (UMD) and the largest university in the state, with 12 schools and colleges across four campuses (College Park, Baltimore, Eastern Shore, and University of College). In 2018, the institution has more than 38,000 students, 9000 faculty and staff members, and more than 300 facilities on the College Park campus (the main campus, 1250 acres). The main campus is located in College Park, five miles north of the border of Washington, D.C. In 2007, the University of Maryland joined the Carbon Commitment, which committed to a carbon emissions reduction of 50% by 2020 and a 60% reduction by 2025, from 2005 levels [26] (From 2005 to 2015, UMD reduced carbon emissions by 27%, with a construction growth of 11%, and reduced energy consumption by 20% or more in select buildings [27]. The campus has set a goal to reduce the energy consumption of existing buildings by 20% by 2020 [26]. The average energy performance of buildings on the College Park campus was 0.34 kWh/m^2 (108 kBtu/ft^2) in 2017 [28] The general climate in Maryland is mild, with a mean annual temperature of 13 °C (56.65 °F), an average annual precipitation of 44.26 inches, and an annual humidity of 64%. Most of the academic year falls under the months of February through May, with the shoulder months being January and June through July.

On campus, 65.78% of the buildings are more than 25 years old and were not built to comply with the current building energy efficiency code; 30.66% of buildings are 55 years or older and approaching the end of their serviceable lifespan [29]. Renovation and retrofitting present a challenge as well as an opportunity. The energy consumption of the academic building stock varies significantly, from 0.063 kWh/m^2 (20 kBtu/ft^2) to 4.151 kWh/m^2 (1316 kBtu/ft^2). The highest energy use intensity was recorded in the engineering facility, where there are large laboratories and testing equipment. Most academic buildings are equipped with air conditioning units for heating and cooling, but some residential buildings do not have air conditioning systems. The campus has a central heating and cooling system powered by a power plant on site. Pipes connect multiple satellite central utility buildings (SCUBs) to campus buildings; a single SCUB can connect up to 17 buildings. These pipes provide both hot and chilled water for heating and cooling. In each individual building, there are also separate distributed air systems to provide a building-appropriate temperature and humidity level [29].

2.2. University of Maryland's Architecture Building

The general shape of UMD's Architecture Building consists of two different-sized rectangles that are located at a latitude of 38°59′3.73″ N and longitude of 76°56′51.57″ W. The two-story building occupies a total floor area of 6517 m^2 (70,150 ft^2), and the total conditioned area is 4355 m^2 (46,877 ft^2). The main façade is oriented toward the south and north (refer to Figure 4). The building is composed of classrooms, an auditorium with approximately 200 seats, offices, a library, conference rooms, two computer labs, and a gallery space. The building has a large atrium space in the center, with skylights and classrooms facing south and north. The majority of the offices are arranged on the second floor, around a shaded courtyard, so the orientation of the offices varies; most of the offices have a window and view. The original building was constructed in 1972, with several renovations and revisions performed after the initial construction. The gallery lighting system was replaced and upgraded in 1992, and the chiller was replaced in 1997. Major renovations occurred in 1998, where the computer rooms were renovated as well as the large auditorium space. In 2007, additional librarian offices were added to the library, and later in 2009, a visual resource center was also added to the library. As estimated by the university, to completely replace the existing building and meet the modern codes and standard, the total cost (including all soft costs) would be $36,391,731 ($518/ft^2) while renovating the existing building would cost approximately $26,565,950 ($379/ft^2) [28].

Figure 4. Existing School of Architecture Building.

3. Methodological Approach and Process

The research methodology was based on the proposed BIM–BEP–BEM framework. As mentioned earlier, BIM stands for the building information model, BPM represents the building performance model, and BEM is the building environment model (refer to Figure 5).

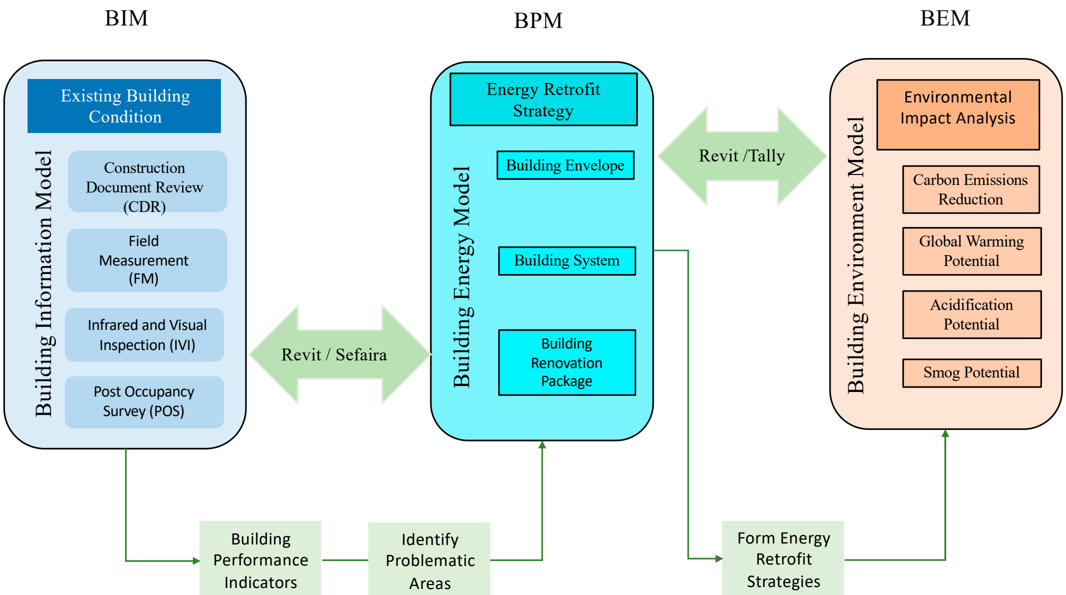

Figure 5. Research framework: building information model–building performance model–building environmental model (BIM–BPM–BEM).

The building information model (BIM) is a process involving the generation and management of digital representations of physical and functional characteristics of buildings. BIMs are files that can be extracted, exchanged, or networked to support decision-making regarding a building or other built asset [30]. BIM also introduces the opportunity to try out solutions in advance before building the structure on site: with a constructible model, the design solutions can be prototyped virtually [31,32]. BIM has been recognized as a suitable method for support planning, collaboration, and the design of new or existing buildings [33]. More practice-oriented publications often advocate the benefits of BIM as a maximization of efficiency and reduction in time effort [34]. BIM is also understood as a digital platform that enables interoperability and data exchange [35]. Oftentimes, BPM is described as a building energy model that focuses on energy performance. The process of expanding BIM into a building energy model has been extensively studied in the past several years with much success [36–38]. A building's environmental impact is generated through the entire building life cycle, from raw material extraction, construction, and operation to demolition. There are different approaches to quantify a building's impact, and life cycle assessment is one of the most commonly used and agreed-upon methods. There are a variety of tools that can be employed during the design and planning stage, such as Talley and the Athena Impact Estimator for buildings. However, the links between BIM, building energy performance, and environmental impact have not been fully established. Very recently, Barreca et al. [39] studied how to improve building information modeling by applying advanced 3D survey techniques, such as a 3D point cloud laser scanner and infrared thermos-graphic camera. Wong and Zhou [40] pointed out the limited research efforts regarding the management of environmental performance at the building renovation stage and the lack of a comprehensive BIM-based environmental sustainability simulation tool. Chong et al. [41] outlined the need for improved interoperability among BIM software and energy simulation tools, especially in renovation and refurbishment projects.

In this research project, based on original construction documents and on-site measurement, firstly, a virtual BIM model was constructed; the software chosen for this project was Autodesk Revit. Autodesk Revit is a BIM software developed by Autodesk; it also has 4D capability to track various building life cycle stages. Then, information and data from the BIM model were transferred to a building performance simulation program called Sefaira. Sefaira is a cloud-based software that simulates building energy performance and visualizes the daylight quality in spaces. Additionally, it has a plug-in tool in Autodesk Revit that can translate building information and data—such as the location, area, building system, materials, geometry, window configuration, and functional use—to an online platform. Alternative design options or a renovation package can be set up in the cloud and outputs—such as energy reduction, carbon emissions reduction, and cost—can be compared.

Sefaira uses EnergyPlus as the primary simulation engine. EnergyPlus was developed by the U.S. Department of Energy (DOE) as an open-source whole-building energy modeling engine [42]. EnergyPlus was built on the strength of both BLAST and DOE-w and includes simulation capacities such as heat balance load calculations; integrated loads, system and plant calculations in the same time step; and a user-configurable HVAC system description [43]. Sefaira's interface was developed with support from DOE to allow modelers to model heating, ventilation, cooling, lighting, water use, renewable energy generation, and other building energy flows using sub-hourly time-steps, modular systems, and plant integrated with heat balance-based zone simulation [44]. Furthermore, it allows the modeler to simulate thermal comfort and customize the operation schedule. Figure 6 illustrates the dashboard of an energy model for a case building on the Sefaira website.

Sefaira also accounts for occupant behavior in regression forms. For instance, the modeler can create and define different energy model profiles based on the set temperature (user preference) and operational schedule. In this research project, multiple BPM models were created in the cloud and the results compared, which are explained in the following sections. Finally, the material and building system information was extracted from the BIM model and translated into a BEM model. The software used for data transfer and to run an environmental impact analysis is Tally. Tally is the first software that has a direct plug-in in Autodesk Revit that allows the modeler and designers to run a whole building life cycle assessment of the environmental impact from different design solutions. The output from the environmental analysis includes acidification potential, eutrophication potential, global warming potential, ozone depletion potential, and smog formation potential. The following sections present different parts of the methodology applied in this case project.

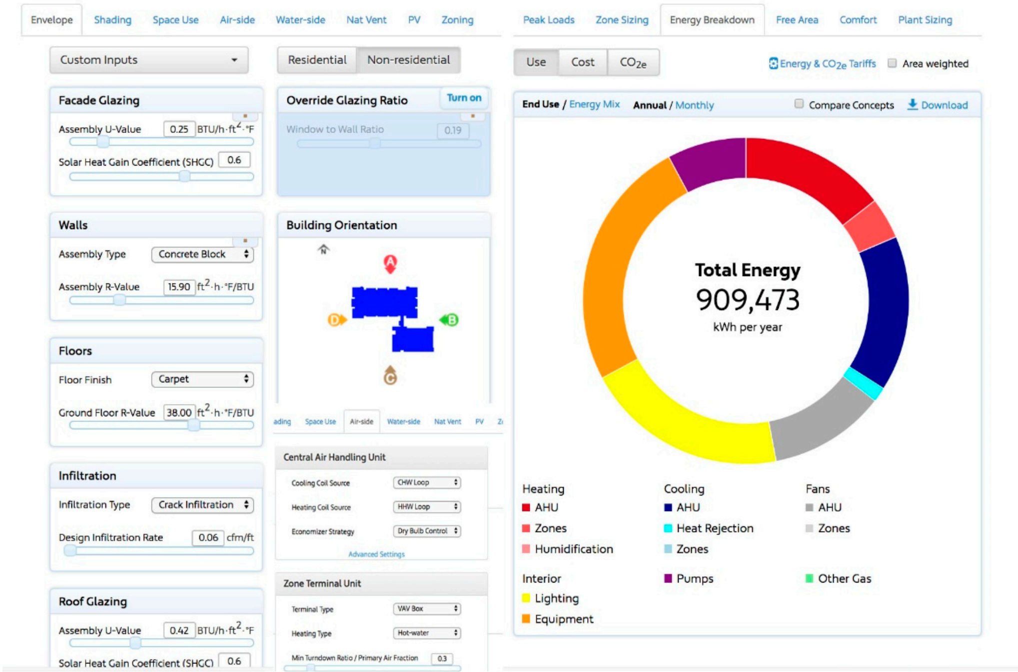

Figure 6. Sefaira online dashboard.

3.1. Building Information Model (BIM)

The BIM stage in this research comprises four components: the construction document review (CDR), field measurement (FM), infrared and visual inspection (IVI), post-occupancy survey (POS), and BIM model building. There are three primary purposes of the BIM stage: (1) to generate an overall assessment of the existing building's (UMD's Architecture Building) conditions; (2) identify problematic areas and potential improvement opportunities according to alignments and discrepancies within CDR, FM, IVI, and POS; (3) and set up a BIM model based on information from IVI, POS, FM, and CDR and then prepare for data extraction to the BPM and BEM models.

3.1.1. Construction Document Review (CDR)

Exterior Envelope of the Architecture Building

The original exterior wall is composed of composite brick veneer with two tiers of CMU (concrete masonry unit) backup and no insulation or air space in between (with an overall dimension of 305 mm (12 inches), which provides a very limited R-value for the exterior walls, estimated at 10.8 W/m^2 K (1.90 Btu/h·ft^2·°F). The existing wall construction does not meet the current code requirement: an R-value of 13 for the exterior wall [45]. The exterior brick units are in fairly good condition; there are only a few areas in which minor damage to the mortar can be seen. The original roof is made of concrete with 1-inch insulation board and composition roofing over it (refer to Figure 7). Based on the original construction of the roofing system, the estimated R-value is 28.3 W/m^2 K (5.0 Btu/h·ft^2·°F). There were no recordings indicating that the original roof had been replaced, and the composition roofing only has a warranty of 20 years. However, we cannot assume that the roofing has not been replaced sometime between 1972 and 2018. The current campus-wide standard for roof insulation is R-30 (ASHRAE 2016). The existing windows are the original units composed of single-pane uninsulated glass with painted steel frames. Most current windows units are not operable, with a U-value of approximately 7.3 W/m^2 K (1.29 Btu/h·ft^2·°F). The windows account for around 40% of the total vertical surface area. The existing doors generally have hollow metal frames. The current R-value of the window and door units also does not meet current energy efficiency standards. In general, the existing building exterior requires complete to moderate repair and maintenance, considering the age of the building. The primary problem is that the existing building envelope standard falls quite below the current building energy code requirements. However, with the appropriate retrofit, there is large potential for energy reduction with minimal costs.

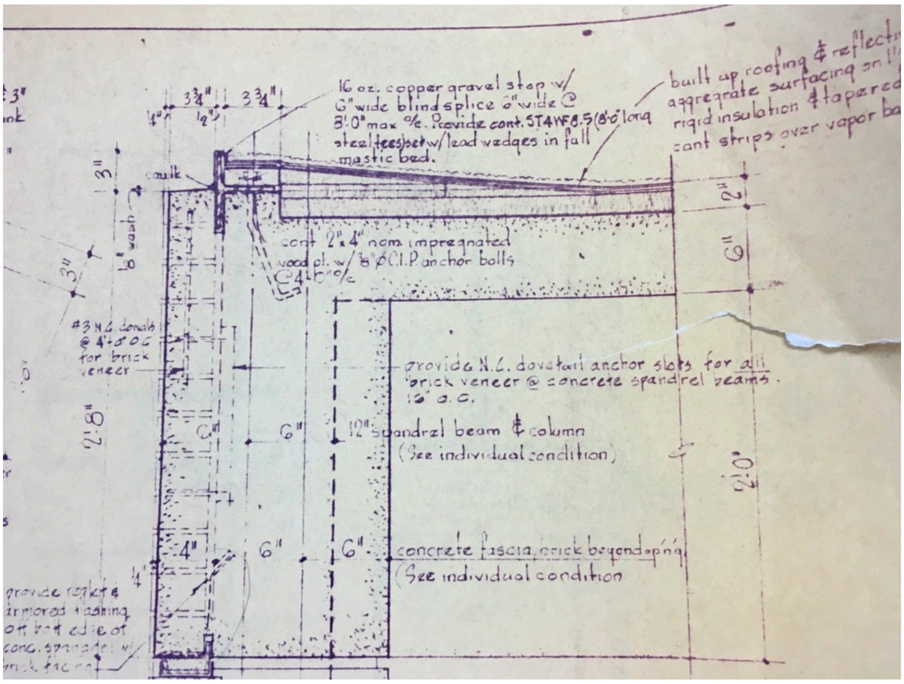

Figure 7. Original construction documents illustrating the roof assemblies.

Architecture Building System

The heating for the building is supplied by satellite central utility plants: hot water is pumped into the building, and the centralized climate control system in the building controls the indoor temperature in the winter by supplying the hot water. In the basement, there are seven air handling units that supply cool air to 16 different zones within the building. The annual energy consumption between 2015 and 2017 was, on average, 148 kWh/m^2 (47.13 kBtu/ft^2). The general lighting is composed of fluorescent lamps and some LED lighting in one computer room. There is no ventilation system; air renewal is executed through the opening of windows and doors and natural infiltration. The existing building, in general, has sufficient daylight due the large skylights on the roof and large exterior windows.

3.1.2. Infrared and Visual Inspection (IVI)

An infrared thermograph camera, FLIR One, was used to identify the major thermal bridge, heat loss, and air infiltration in the Architecture Building's envelopes (walls, roofs). The infrared inspection around the windows' frame indicated the potential for air leakage and infiltration. Outdoor images revealed a maximum of an 8 °C (46 °F) difference between different sides of buildings, which could be caused by insufficient insulation. Indoor images clearly illustrated that the thermal leaking happened primarily where the ceilings and walls connected [3] (refer to Figure 8).

Figure 8. Infrared images of interior and exterior conditions.

3.1.3. Field measurement (FM)—Indoor Environmental Quality

One of the major obstacles to an affordable energy retrofit is the fact that most older, existing buildings are not metered, making it difficult to identify which categories could gain the most from an energy retrofit. Under such conditions, different renovation strategy indicators, other than energy consumption, could be beneficial for the design team to identify problematic areas. In this study, the combination of a field auditing index and post-occupancy satisfaction index were used as building performance indicators. The energy retrofit packages not only measured an energy consumption reduction but also the users' preferences. Since summer 2017, four filed measurements have been conducted to measure every room in the Architecture Building: 6 July and 4 September 2017 and 23 January and 4 June 2018. The temperature, humidity, CO_2 levels, acoustic levels, and lighting levels were recorded. The five sets of data were normalized; Section 4.1 illustrates the results of the datasets. Overall, thermal comfort and acoustic level (speech privacy) were the top two problematic areas based on field auditing. The equipment used for this project included the Supco IAQ55 indoor air quality/temperature/humidity CO_2 tester, Graniger light meter, and RISEPRO digital sound level meter.

3.1.4. Post-Occupancy Survey (POS)

In order to further understand the overall space quality and problematic areas in the existing building, as well as common dissatisfaction points of the indoor environmental quality, a post-occupancy survey, the Indoor Environmental Quality Survey, was conducted online between September 2017 and March 2018. The online survey was sent out to all UMD School of Architecture students, faculty, and staff. A total of 85 responses were received, equaling a total response rate of approximately 24%, which is consistent with the response rates of 10% to 50% for online surveys. The only personal information asked for was the participants' age. Among those who responded, 40% were between the ages 16–22, 37.1% were between 23–36, and 8.6% were 56 and above (refer to Table 1).

Table 1. The demographics of survey participants.

Age Range	Participation Percentage
16–22 years old	40%
23–36 years old	37.1%
37–45 years old	5.7%
46–55 years old	8.6%
56 years and above	8.6%

The survey comprised thirteen questions based on the users' time spent in the Architecture Building during February 2018. Eleven of these questions asked the participants to rank their satisfaction level for light, noise, temperature, and acoustics, from very dissatisfied (1) to very satisfied (7), seen below in Table 2. The analysis was done based on these numerical responses, and it omitted the two questions that did not ask for any rankings.

Table 2. Rating system for the Indoor Environmental Quality Survey.

Very Dissatisfied	1	2	3	4	5	6	7	Very Satisfied

3.1.5. BIM Model Building and Identification of Problematic Areas

The BIM model was constructed based on original construction documents from the Architecture Building's library as well as documents recording different versions of renovations from the facility management archive library; the research team also conducted field measurements to verify critical dimensions and several unidentified areas that were not indicated in the architectural drawings. The author constructed a three-dimensional virtual model (refer to Figure 9) using Autodesk Revit and manually input all related material properties that were not part of the default Revit template [46]. All information related to physical characters and conditions of the existing buildings were embedded in the three-dimensional objects. The Revit model was then prepared and set up to simulate the energy performance of different renovation techniques and packages, which are explained in the next BPM stage in the following Section 3.2.

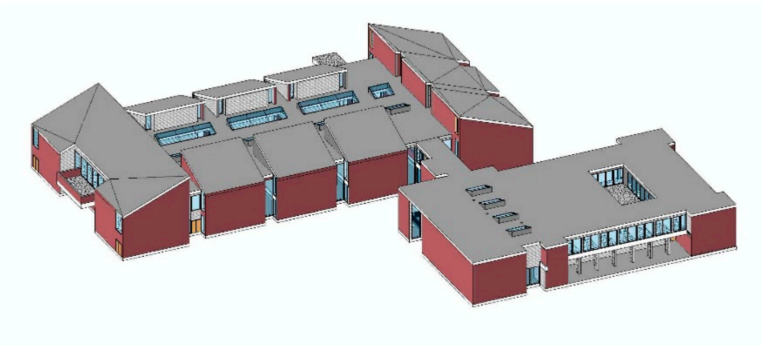

Figure 9. BIM model of the Architecture Building.

From the results of FM, POS, IVI, and CDR, two primary problematics areas were identified (a detailed explanation is included in Section 4, findings): sound transmission and overheating. These two problematic areas were then used as a guiding principle, together with the energy reduction goal, to evaluate the effectiveness of varied renovation strategies.

3.2. Building Performance Model (BPM)

In this research project, there was limited control regarding the building's embodied energy since a large portion of it was already spent in the initial construction of the existing building. Accordingly, the author focused on the existing and future operational energy performance of the building. The BPM is composed of three steps: (1) identify and simulate building envelope retrofit techniques; (2) identify and simulate building system retrofit techniques; and (3) identify and simulate the building retrofit package based on results from 1 and 2. The metric used to measure and compare the techniques and packages were total energy reduction (%), total CO_2 emissions reduction related to energy (%), cost saving per year (%), initial construction cost (low to high), and construction feasibility (low to high). The primary purposes during the BPM stage were to create a ranking of the proposed renovation packages from energy-saving and cost-optimized perspectives. The Sefaira system was used to carry out the simulation. The construction and maintenance cost information was provided by the Facility Management Office of the University of Maryland.

3.2.1. Energy retrofit Techniques—Envelope and Lighting System

To tackle the two primary problematic areas, a focus on retrofit techniques resulted in exterior envelope upgrades and an interior partition retrofit. In the existing building, the exterior wall and partition walls were either made of CMU block or cast-in-place concrete without thermal and acoustic insulation. Renovation techniques identified for the building envelope and lighting system were:

(1) T1: Substitution of present window with low-emissive units (with U-value of 0.25 w/m^2 k)
(2) T2: Application of additional thermal insulation to the roof slab (R-50)
(3) T3: Application of additional thermal insulation for the exterior walls (add additional 3-inch panels of expanded polystyrene insulation, R-38)
(4) T4: Application of additional thermal insulation and acoustic insulation for the interior walls (add additional 2-inch panels of expanded polystyrene insulation, R-10)
(5) T5: Replace all existing windows with double glazing window units
(6) T6: Reduce air infiltration by using air-tight windows (air infiltration rate, 0.3 $L/s{\cdot}m^2$, 0.06 cfm/ft^2)
(7) T7: Replace all existing lights with LED lighting
(8) T8: Application of phase-change material (PCM) wall board on the inside face of exterior wall

Based on the available records, there were no major upgrades/renovations done to the building envelope; therefore, improving the exterior wall and roof insulation were considered first as well as enhancing the window energy performance. Roof insulation can be increased to R-50 by adding additional panels of expanded polystyrene [3] (10-inch thickness). The overall achievable annual saving is around 250,671 kWh, and it implies avoided CO_2 equivalent emissions of about 22%, compared to the existing building. The cost of this renovation technique, including demolition and roof surface repair, is around $33,230 to $64,839, based on a unit cost of $10.25/$ft^2$ to $20/$ft^2$ [47]. In the first year of installation, a saving can be realized. The existing building has a minimal R-value for the exterior wall; adding additional insulation board on the inner face of the exterior wall could increase the R-value to R-38. The retrofit of the exterior wall alone could produce an energy saving of approximately 290,635 kWh and a CO_2 emissions reduction of roughly 21%. Insulation could also be applied to the surface of the interior wall with insulating plaster, which could provide acoustic insulation. With 2-inch thermal plaster, it potentially adds an additional R-10 insulation, which represents a considerable reduction of heat transmittance through the rooms and prevents sound transmission. Meanwhile, thermal insulation also provides extra sound protection. For instance, acoustic batts insulation and other composite materials can absorb the sound transmission through vibrations within the wall cavity [48,49]. The total energy saving is around 3%, with the CO_2 emissions reduction around 8%. Another practical envelope retrofit technique includes replacing the existing glass with low emissivity (Low-E) glazing or replacing all single-pane glass with double-pane glass. The latter results in a 19% CO_2 emissions reduction and 11% energy consumption reduction.

Most buildings on campus were built in the late 1960s and early 1970s, and the air infiltration rate varied from 3.0×10^{-4} to 3.0×10^{-4} $m^3/s{\cdot}m^2$ $(pa)^{0.65}$ (2.1 to 4.9 cfm/ft^2 (inches of water). Additionally, 15% to 45% of the overall air leakage could be attributed to flow through the intake and exhaust system openings [50–52]. Based on ANSI/ASHRAE standard 62.1-2016, the minimal requirement for an office space and auditorium seating area is 0.06 cfm/ft^2 and 0.12 cfm/ft^2 for a library [46]. A reduction in air infiltration through the façade presents the most obvious gain in heat-related energy consumption, with a reduction of approximately 27%. As heating accounts for 44% of the overall energy consumption, reducing the air infiltration by tightening the building envelope may be the most efficient energy-saving technique, equivalent to a saving of $29,643. However, other impacts of this solution should be further studied such as indoor air quality.

Two other techniques that were compared include replacing existing T4 and T8 lighting fixtures with LED lights and adding phase-change materials in the exterior wall. Lighting accounts for 9% of the overall energy consumption; installing LED lights could save approximately 282,375 kWh, 12% compared to the baseline. Additionally, phase-change materials (PCM) could be added into the wallboard to increase insulation [53]. Below, Figure 9 and Table 3 presents a comparison of different techniques. Overall, T6 and T8 generate the largest energy consumption reduction and CO_2 emissions reduction, with T4 following as the third most effective technique.

Table 3. Building envelope retrofit techniques: a comparison of energy saving, cost saving, and CO_2 emissions reductions.

Technique (Envelope)	Overall Energy Reduction (%)	CO_2 Reduction (%)	Cost Saving (Per Year %)	Peak Cooling Reduction (%)	Peak Heating Reduction (%)	Initial Cost	Construction Feasibility	NPV in 5 Years
T1	11%	19%	7%	4%	5%	High ($40–55/ft^2)	High	Neutral
T2	13%	22%	9%	7%	7%	Moderate ($0.6–1.2/ft^2)	High	+
T3	12%	21%	7%	4%	5%	Moderate ($0.6–1.2/ft^2)	Moderate	Neutral
T4	13%	23%	8%	5%	5%	Moderate ($0.6–1.2/ft^2)	Moderate	Neutral
T5	11%	19%	7%	4%	5%	High ($400–1500/window)	High	-
T6	16%	27%	10%	6%	6%	Low ($0.2/ft^2)	Moderate	+
T7	12%	16%	10%	7%	7%	Moderate ($70–250/fixture)	High	+
T8	15%	28%	9%	5%	5%	-	Low	-

In terms of cost, T6 is the most cost-effective (saving) in comparison to other techniques, with T8 following in second (refer to Table 3). T2 and T7 are the most effective in reducing the peak heating and cooling loads (refer to Figure 10). In terms of the initial construction cost, T6 has the lowest cost while T5 has the highest cost; T8 is difficult to predict due to the lack of enough data, and the remaining techniques share similar per-unit costs. When observing the construction feasibility, T7 represents the most practical strategy whereas T8 is the least feasible, due to the accessibility of phase-change materials (refer to Table 3).

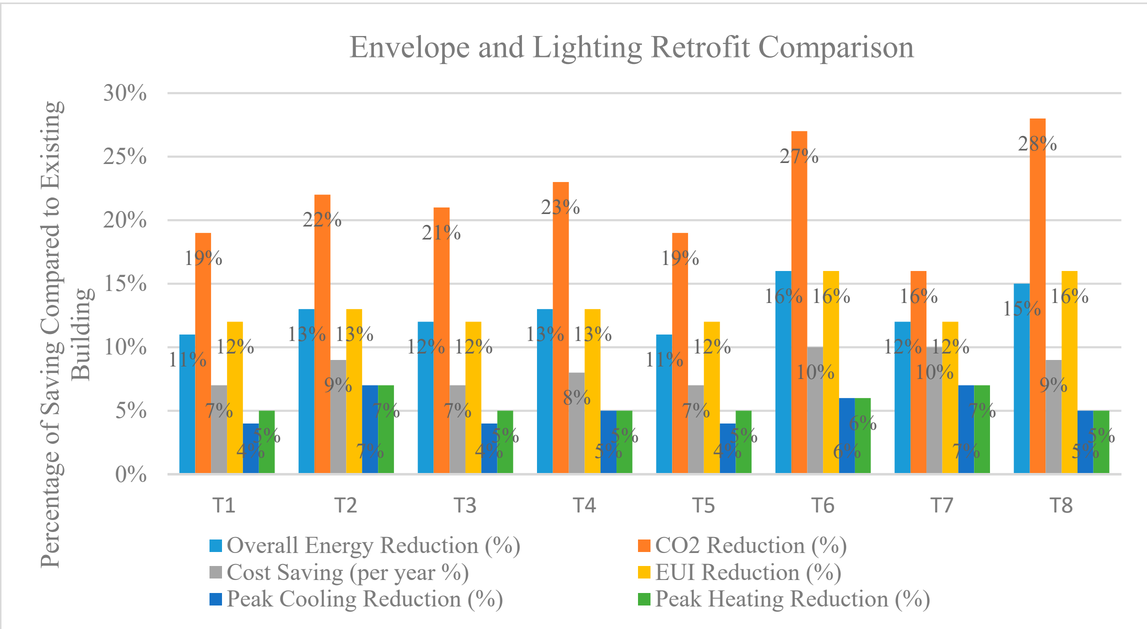

Figure 10. Envelope and lighting retrofit comparison.

3.2.2. Energy Retrofit Techniques—Building System

Renovation techniques identified for the building system included the following:

(1) HVAC1: VAV with rooftop package unit
(2) HVAC 2: VAV with central plant
(3) HVAC 3: DOAS System (Package Terminal AC)
(4) HVAC 4: DOAS System (Split System)

(5) HVAC 5: DOAS System (Fan Coil Units and Central Plant)
(6) HVAC 6: DOAS System (Water Source Heat Pump Fan Coils)
(7) HVAC 7: DOAS System (Active Chill Beams)
(8) HVAC 8: DOAS System (Passive Chill Beams)

Table 4 below presents a comparison of the different techniques. Compared to a conventional variable air volume VAV system, a dedicated outdoor air system (DOAS) can provide better ventilation and humidity control, thus creating enhanced indoor air quality. However, because the DOAS system requires a separate system for outside air, the VAV system is more cost-effective and offers lower maintenance requirements. Among the eight different options, HVAC 1 and 2 produce the highest energy-saving and CO_2 emissions reduction potential, with a relatively low cost (refer to Table 4).

Table 4. Comparison of building system retrofit techniques.

Retrofit Techniques (HVAC)	Total Energy Reduction (%)	CO_2 Emissions Reduction (%)	Cost Saving (Per Year %)	Initial Cost
HVAC1 (VAV)	53%	70%	45%	low
HVAC2 (VAV)	57%	86%	44%	low
HVAC3 (DOAS)	18%	44%	6%	moderate
HVAC4 (DOAS)	18%	44%	6%	moderate
HVAC5 (DOAS)	35%	97%	6%	moderate to high
HVAC6 (DOAS)	26%	79%	1%	moderate to high
HVAC7 (DOAS)	5%	12%	2%	moderate to high
HVAC8 (DOAS)	26%	49%	15%	moderate to high

3.2.3. Retrofit Strategy Package Setup

Based on the results from the building envelope and building system retrofit techniques, six different packages were proposed according to their energy-saving potential, carbon emissions reduction potential, construction feasibility, and initial cost (refer to Table 5). A simulated final site energy use intensity was also provided.

Table 5. Comparison of building retrofit packages for achieving the nearly zero-energy goal.

	Building Envelope Techniques								HAVC	Initial Construction Cost	Final Energy Use Intensity (EUI) kWh/m^2
Retrofit Package	T1	T2	T3	T4	T5	T6	T7	T8			With PV Panel Installed on Roof
P1		x	x	x		x			HVAC 2	Low	0.082 kWh/m^2
P2	x	x	x	x		x			HVAC 2	Moderate	0.088 kWh/m^2
P3	x			x	x	x	x		HVAC 2	Moderate	0.082 kWh/m^2
P4	x	x	x	x	x	x			HVAC 2	High	0.088 kWh/m^2
P5	x	x	x	x	x	x	x		HVAC 2	High	0.078 kWh/m^2
P6		x		x		x			HVAC 2	Low	0.088 kWh/m^2
P7			x	x		x	x		HVAC 5	Moderate	0.196 kWh/m^2
P8	x	x	x	x	x	x	x	x	HVAC 8	High	0.23 kWh/m^2

3.3. Building Environment Model (BEM)

In stage three, different retrofit packages were investigated and compared to further understand their environmental impact. Life-cycle assessment (LCA) is a process whereby the material and energy flows of a system are quantified and evaluated. Given the complexities of the interactions between the built and natural environments, LCA represents a comprehensive approach to examining the environmental impacts of an entire building [46]. The five environmental impact indicators selected for this study were global warming potential, ozone depletion potential, acidification potential, eutrophication potential, and smog formation potential. The LCA conducted in this project is based on

ISO standards for life cycle assessment 14040 (principles and framework) and ISO 14044 (requirements and guidelines) in accordance with EPA, SETAC guidelines [54,55].

The tool used for analysis was Tally. Tally is the only application to conduct a lifecycle assessment that is fully integrated in the Autodesk Revit model. It analyzes environmental impact during the whole building life cycle, from raw material extraction to demolition. Tally uses the GabB Life Cycle Inventory (LCI) database, which is one of the leading databases used by life cycle analysis practitioners [56,57]. First, the renovation packages were constructed in Revit as design options. The model created in BIM included all necessary data of building assemblies and systems, such as windows, doors, walls, columns and floors, and the HVAC system, among others. Afterward, the materials and constructed data were translated from the Revit model through Tally to be mapped with LCI data. The plug-in tool Tally allows researchers to map BIM objects with the GaBi LCI database to run an analysis of the environmental impact of different renovation packages. Detailed results and an explanation are presented in Section 4 below.

4. Findings

4.1. Existing Condition and Problematic Areas

Based on field measurement (FM) results, several problematic areas were identified. (1) The acoustic quality represented the largest problematic area. The preferable noise level is 30 dBA for an open-plan class and 44–48 dBA for a closed office. On the ground floor, 67% of rooms had a noise level above 55 dBA, and 40% of rooms in the entire building had a noise level above the recommended level. (2) The second problematic area was thermal comfort—particularly temperature—where 30% of the spaces had a temperature outside of the acceptable range, based on ASHRAE 90.1 (20 °C to 23.6 °C). Moreover, those spaces became overheated in the winter, spring, and summer. None of the spaces had a humidity level outside of the recommended range. (3) The third problematic area was the lighting level, which was unevenly distributed across the building. Less than 8% of the rooms fell below the recommended light level range, of 300–500 lux. Furthermore, 18% of the rooms were overlit, with a median lux level of 500 lux (refer to Figure 11).

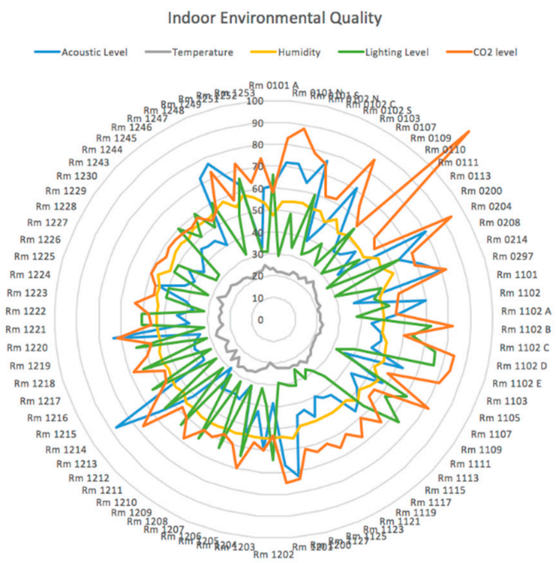

Figure 11. Field measurement results.

The POS results indicate that people were least satisfied with the speech privacy, thermal comfort, and window view, and they were most satisfied with the cleanliness and maintenance, amount of light, air quality, and visual comfort. Furthermore, 55% of the occupants were dissatisfied with the speech privacy in their workspace, 38% were unhappy with their access to a window view, and 37% were displeased with the thermal comfort (refer to Figure 12).

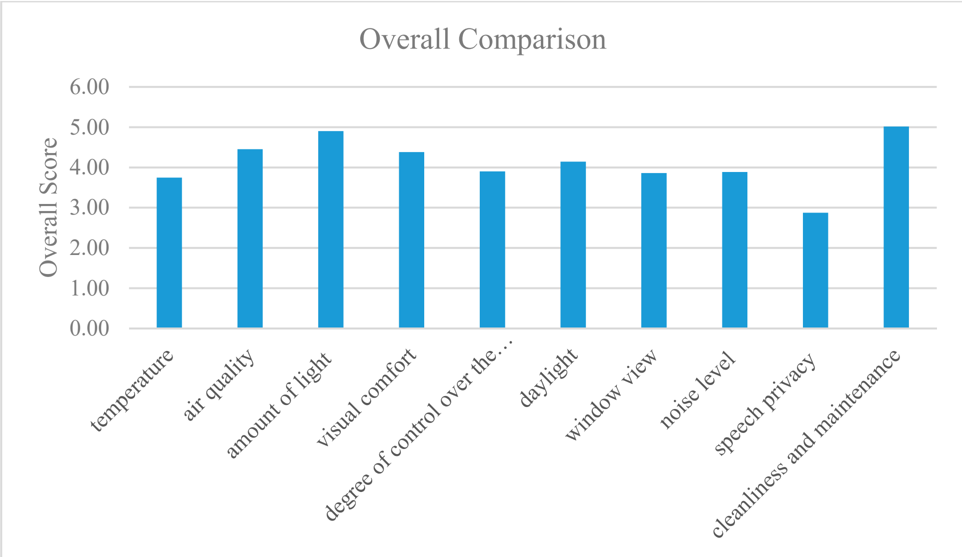

Figure 12. Post-occupancy survey (POS) results.

In general, the POS results indicate high-level alignment with FM data. *Acoustic quality improvement* and *overheating mitigation* were identified as the top two primary focuses to improve the indoor environmental quality and user satisfaction. There were certain areas that revealed large discrepancies between POS and FM (refer to Figure 13): air quality, window view, and visual comfort. Although FM indicates that the air quality and window view meet the design criteria, many users expressed their dissatisfaction through the survey. Further in-depth individual interviews could help to identify the causes of these discrepancies.

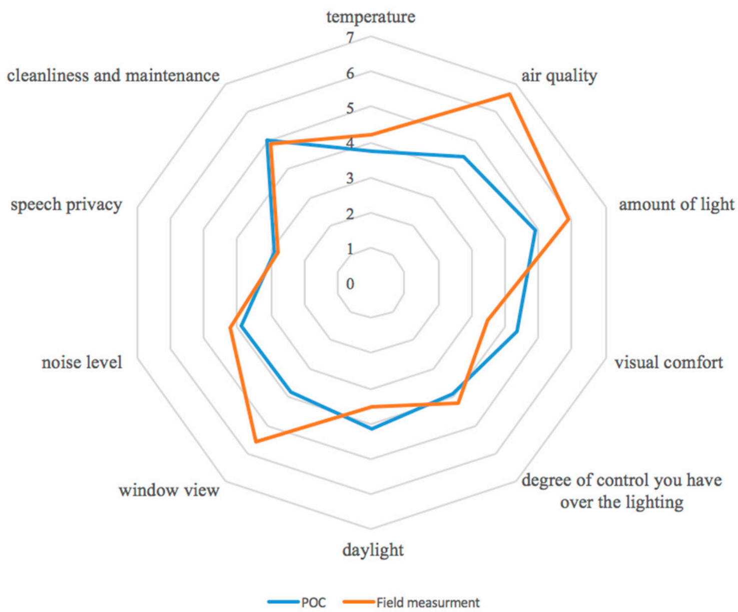

Figure 13. Problematic areas in existing building.

4.2. Building Energy Saving due to Retrofit Packages

Among eight different packages, P4 and P5 produce large energy-saving benefits with a relatively high initial construction cost. Alternatively, P1 and P6 produce considerably high energy-saving benefits with a relatively low cost. P2 and P3 produce the same results as P1 and P6 but with a moderate initial cost. Lastly, P7 and P8 produce less energy and cost saving compared to the other packages (refer to Figure 14).

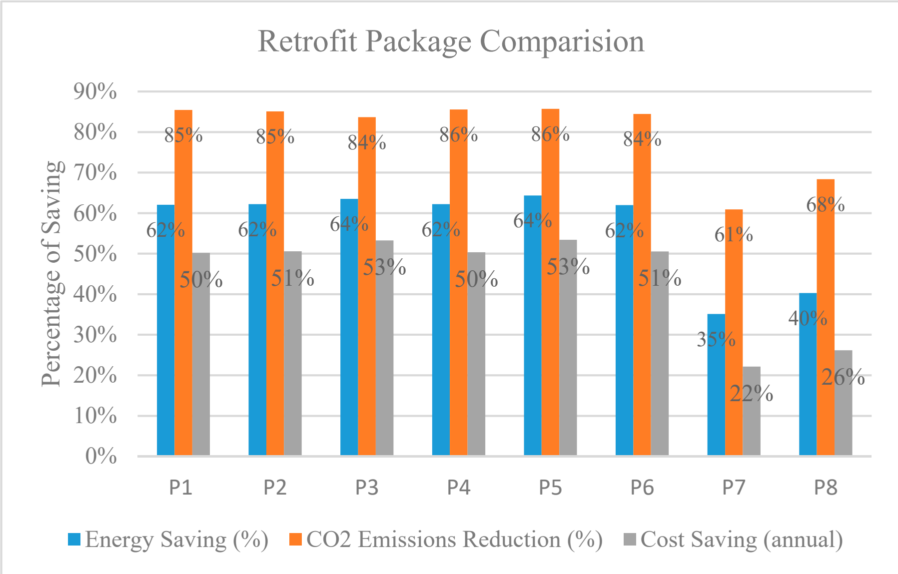

Figure 14. Renovation packages: comparison of energy, CO_2 emissions reduction, and cost saving.

4.3. Building Environmental Impact from Retrofit Packages

Among the eight retrofit packages, the best-performing package with the least environmental impact is P3 and P5. P4 has the highest environmental impact potential in all categories, thus also having the potential to create the most damage in the long term. P1 represents the second most negative package, with a higher potential impact in all environmental categories than the rest of the options. The third least favorable package is P6, which has much higher ozone depletion potential and slightly higher eutrophication potential (refer to Figure 15).

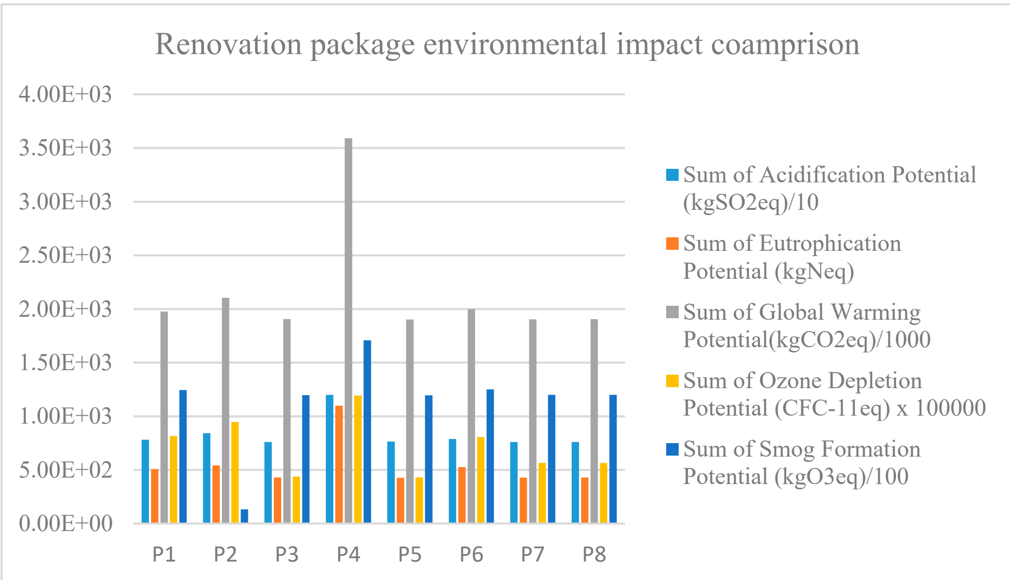

Figure 15. Renovation package environmental impact comparison.

Below, Table 6 ranks the different renovation packages based on their potential to achieve the nearly NZE goal while minimizing the environmental impact and considering the initial cost and construction feasibility. P3 presents the optimal solution, considering all performance indicators; P5 offers an alternative solution if the budget is sufficient. Conversely, P1 could potentially achieve the nearly NZE goal with a low cost and high construction feasibility; however, the long-term environmental impact would be of great concern.

Table 6. Overall renovation package comparison.

Retrofit Package	Energy Saving (%)	CO_2 Reduction (%)	Cost Saving (yr)	Initial Cost	Construction Feasibility	Ranking of Achieving Nearly NZE (Refer to Table 5)	Ranking of Lowest Environmental Impact (Refer to Figure 14)	Improvement in Speech Privacy	Improvement in Thermal Comfort
P1	62%	85%	50%	Low	High	2	7	Yes	Yes
P2	62%	85%	51%	Moderate	High	3	5	Yes	Yes
P3	64%	84%	53%	Moderate	Moderate	2	2	Yes	Yes
P4	62%	86%	50%	High	Moderate	3	8	Yes	Yes
P5	64%	86%	53%	High	Moderate	1	1	Yes	Yes
P6	62%	84%	51%	Low	High	4	6	Yes	Yes
P7	35%	61%	22%	Moderate	High	5	3	Yes	Yes
P8	40%	68%	26%	High	Low	6	4	Yes	Yes

5. Conclusions

This paper presented a novel BIM–BPM–BEM framework tailored toward education building renovation. It aimed to select suitable renovation strategies that take into account all performance indicators: an energy consumption reduction, CO_2 emissions reduction, environmental impact reduction, and indoor quality improvement. A variety of renovation techniques were identified, and multiple retrofit packages were compiled with four primary goals: (1) to optimize the energy demand reduction to contribute to UMD's overall carbon neutrality goal; (2) improve speech privacy by adding additional acoustic insulation; (3) improve thermal comfort by mitigating overheating problems, and; (4) minimize the long-term environmental impact. Firstly, the data derived from field measurements was cross-referenced with a post-occupancy survey and infrared thermography scan to create an accurate building profile and BIM model. Then, the BIM model was clearly defined in order to be translated to the BPM stage, where it simulated the energy performance of different renovation packages. The environmental impacts of eight proposed renovation packages were then compared in the BEM stage. Finally, the BPM and BEM results and cost indicators were analyzed together to determine the optimal renovation solution for the existing building. The data used for the environmental impact analysis and energy simulation was derived directly from the BIM model to ensure the data interoperability.

This research fills the current gap between energy efficiency improvement and environmental impact mitigation. The results from the BPM and BEM analyses revealed that the energy and cost-saving benefits do not always align with the environmental impact reduction potential. For instance, renovation packages 2 and 4 produced high cost savings as well as energy and CO_2 reductions; however, they also produced the largest environmental impact potential in all five indicators studied. Awareness of the asymmetrical benefits between energy saving and environmental impact could encourage design teams and decision-makers to examine balanced solutions for building renovations. Energy, indoor environmental quality, and long-term environmental impacts should be integrated and used together in a building performance evaluation matrix. To this extend, package 3 presents the optimal solution, considering all performance indicators.

The proposed framework could potentially be applied to large-scale projects, such as campus district renovation or neighborhood renovation. Studying the energy consumption reduction on a large scale is a relatively new focus area: the first published study on energy retrofit on the district level was found in 2008 by [58]. Since then, several large-scale studies have been published, such as Moscow's residential district renovation impact on energy and emissions [59]. Easy-to-use evaluation and analysis frameworks and tools help to promote the adoption of large-scale energy renovation planning and implementation.

Another important insight resulting from this study was the importance of interoperability among different software in facilitating data translation and transformation. Advanced digital technologies and platforms—such as BIM (Autodesk Revit), BPM (Sefaira), and BEM (Tally)—make it possible for decision-makers to examine all performance indicators within the same framework and form decisions with a holistic understanding of all the advantages and disadvantages of the proposed renovation strategies.

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Nomenclature

BIM	Building Information Model
BPM	Building Performance Model
BEM	Building Environment Model
DOE	Department of Energy
CDR	Construction Document Review
IVI	Infrared and Visual Inspection
POS	Post-Occupancy Survey
FM	Field Measurement
LCI	Life Cycle Inventory
NZE	Net-Zero Energy

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