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Research Article

Resilient heritage: Harnessing technology for sustainable conservation

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Abstract

Architecturally significant heritage buildings often struggle to meet modern energy efficiency standards. This study focuses enhancing the energy performance of the Polytechnic University of Tirana without compromising its historical integrity. Through detailed energy simulations using DesignBuilder software, the study evaluates the effectiveness of various double-glazing window configurations and internal shading systems. The results reveal that double-glazed units can lead to energy savings of up to 9.0%, particularly when using tinted, argon-filled glass. Shading devices, including fixed and automated internal louvres, provided additional savings between 4.3% and 7.8% by mitigating solar heat gain and improving thermal comfort. Also, the cost of each intervention is analyzed and savings per cost ratio ranging from €6,930 to €43,331 per 1% energy reduction is obtained. Notably, the economic analysis shows that simpler solutions, like air-filled double glazing and fixed louvres, offer a higher cost-efficiency. For the case study building, 16.53% energy savings may be obtained for a cost of €10,521 per 1% of reduction. The study's findings offer an example for future sustainable conservation projects, balancing historical preservation with energy efficiency. The results underscore the importance of targeted retrofitting in safeguarding cultural heritage while contributing to broader sustainability goals.

1. Introduction

In recent years, the intersection of heritage conservation and sustainability has garnered increasing attention, particularly in the context of retrofitting projects. The challenge lies in balancing the preservation of cultural significance with the need for energy efficiency, modern functionality and safety [1]. This balance is often complicated by the inherent conflict between invasive technologies that may compromise the integrity of heritage structures and the philosophy of minimal intervention that seeks to maintain authenticity and historical value. The discourse surrounding this balance is crucial as it reflects broader societal values regarding heritage and sustainability, emphasizing the need for innovative approaches that respect both cultural heritage and environmental imperatives.

The concept of minimal intervention in heritage conservation is rooted in the belief that alterations to historic structures should be as non-invasive as possible. This approach is supported by various scholars who argue that invasive technologies can detract from the authenticity and historical narrative of heritage buildings [2]. For instance, Guzman et al. highlight the importance of maintaining the original fabric of heritage sites, suggesting that any interventions should be

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reversible and should not obscure the original architectural features[3]. Conversely, the push for energy efficiency often necessitates the integration of modern technologies, which can include insulation, renewable energy systems, and advanced HVAC systems. These technologies, while beneficial for sustainability, can pose a threat to the historical integrity of the buildings if not implemented thoughtfully [4, 5].

Moreover, the integration of sustainability principles into heritage conservation practices has become increasingly relevant as climate change and energy efficiency concerns rise to the forefront of global discourse. Recent studies emphasize the necessity of adopting energy-efficient solutions in heritage buildings, as these structures often consume more energy than their modern counterparts due to outdated systems and materials [4, 6]. This need for energy efficiency is underscored by the growing recognition that heritage buildings can play a vital role in achieving sustainability goals, particularly when retrofitted to meet contemporary energy standards without compromising their cultural significance [7, 8].

The tension between invasive technologies and minimal intervention is further complicated by the diverse stakeholder interests involved in heritage conservation. Rosetti et al. argue that effective heritage management requires inclusive participation from all relevant stakeholders, including local communities, government entities, and conservation professionals [9]. This participatory approach not only enhances the sustainability of conservation efforts but also fosters a sense of ownership and responsibility among community members, which is essential for the long-term viability of heritage sites [10].

Furthermore, the application of modern technologies, such as Building Information Modeling (BIM), thermal analyses and 3D modelling, has emerged as a promising avenue for addressing the challenges of retrofitting heritage buildings. These technologies allow for detailed analysis and planning that can minimize the impact of interventions on the original structure while enhancing energy efficiency [11, 12]. For example, BIM can facilitate the creation of accurate digital models of heritage buildings, enabling conservationists to visualize potential changes and assess their implications before implementation [11, 13]. This approach aligns with the principles of minimal intervention, as it promotes informed decision-making that respects the historical context of the buildings.

1.1 Considered Case

The focus of this study is on two specific measures aimed at enhancing sustainability and energy efficiency in heritage buildings: the replacement of single-glazed windows with double-glazed units and the installation of shading devices. The replacement of single-glazed windows is critical as these units are often responsible for significant heat loss, contributing to higher energy consumption for heating and cooling. Studies indicate that upgrading to double-glazed windows can substantially improve thermal performance while maintaining the aesthetic integrity of heritage structures [14, 15]. However, the acceptability of such interventions is often influenced by the heritage values associated with the buildings, which may lead to resistance against complete window replacements [16, 17]. Ginks and Painter discuss the attitudes of conservation professionals towards slim double glazing, emphasizing its potential to improve energy efficiency without compromising the visual integrity of historic facades [18]. Furthermore, Wise et al. note that while residents value the functional aspects of windows, they also attach significant importance to their historical and aesthetic qualities, which can complicate retrofit decisions [16].

In addition, the installation of shading devices serves as an effective passive design strategy to mitigate solar heat gain, thereby improving indoor thermal comfort and reducing reliance on mechanical cooling systems. Shading devices can be designed to complement the architectural features of heritage buildings, ensuring that energy efficiency measures do not compromise their historical significance [19–21]. Nair et al. highlight that energy efficiency studies often focus on singular retrofit measures; however, a holistic approach is essential for the complex nature of historic buildings [15]. The integration of these two measures may represent a holistic approach to retrofitting heritage buildings, balancing the need for energy efficiency with the preservation of cultural heritage [22].

1.2 Challenges of Retrofitting Heritage Buildings

The challenges associated with retrofitting heritage buildings are multifaceted, primarily stemming from architectural and historical restrictions that often impede the implementation of energy efficiency measures. Heritage buildings, which embody significant cultural, aesthetic, and historical values, are subject to stringent regulations that prioritize their preservation over modernization [23]. This creates a tension between the need for improved energy performance and the imperative to maintain the building's original character and integrity. As noted by Nair et al., the unique construction techniques and materials used in these buildings often limit the applicability of conventional retrofitting solutions, such as external insulation or significant structural alterations, which may adversely affect their visual appearance [15].

Moreover, the reluctance of homeowners and conservation professionals to adopt invasive measures is compounded by concerns regarding the potential loss of heritage value. Sunikka Blank and Galvin highlight that aesthetic considerations and heritage values significantly influence retrofit decisions, with many homeowners prioritizing the preservation of their building's historical character over energy efficiency [24]. This sentiment is echoed in the findings of Wise et al., who emphasize that residents often view complete window replacements as unacceptable, favoring less invasive options like secondary glazing or internal shutters [16]. Such preferences reflect a broader trend in heritage conservation that seeks to balance energy efficiency with the preservation of cultural identity.

In this context, the adoption of double-glazing and shading devices emerges as a promising avenue for achieving energy efficiency while minimizing the impact on heritage values. Double-glazed windows, for instance, offer a significant improvement in thermal performance without necessitating the complete removal of original window frames, thereby preserving the building's historical façade [18]. Similarly, shading devices can be designed to complement the architectural features of heritage buildings, effectively reducing solar heat gain and enhancing indoor comfort without compromising the building's aesthetic appeal [25]. These less invasive solutions align with the principles of minimal intervention, allowing for the integration of modern energy efficiency measures while respecting the historical significance of the structures.

In summary, the complexities of retrofitting heritage buildings necessitate a careful consideration of both architectural integrity and energy performance. As the discourse on sustainable retrofitting evolves, it is imperative to explore innovative solutions that reconcile these often conflicting objectives. The integration of double-glazing and shading devices represents a viable path forward, enabling heritage buildings to meet contemporary energy efficiency standards while safeguarding their cultural heritage for future generations.

2. Building of Polytechnic University of Tirana

The Polytechnic University of Tirana, built in the 1940s, is a prominent example of Italian Rationalist architecture in Albania. Designed by Italian architect Gherardo Bosio, the building reflects the architectural vision of the fascist regime during the early 20th century. Bosio's design sought to combine functionality with modernist aesthetics, making the university a landmark in the urban fabric of Tirana [26].

The architectural significance of the building lies in its monumental scale and the use of modern construction techniques, such as reinforced concrete, while incorporating elements of traditional Albanian architecture. Its facade, characterized by symmetrical design and clean lines, blends modernist forms with classical proportions. Fig 1 shows the front view and ground floor plan of the building. The building, which now serves as the Polytechnic University's main campus, has been a vital part of Albania's educational and cultural history [27] .

As a heritage building, the Polytechnic University of Tirana presents unique challenges in retrofitting. The need to preserve its historical and cultural value conflicts with the necessity to improve energy efficiency. The building's original design, with single-glazed windows and minimal consideration for thermal performance, makes it an ideal candidate for sustainable interventions such as double glazing and shading devices. Balancing these retrofitting measures with the architectural integrity of the structure is critical to ensure its continued use and preservation as an educational institution and historical monument.

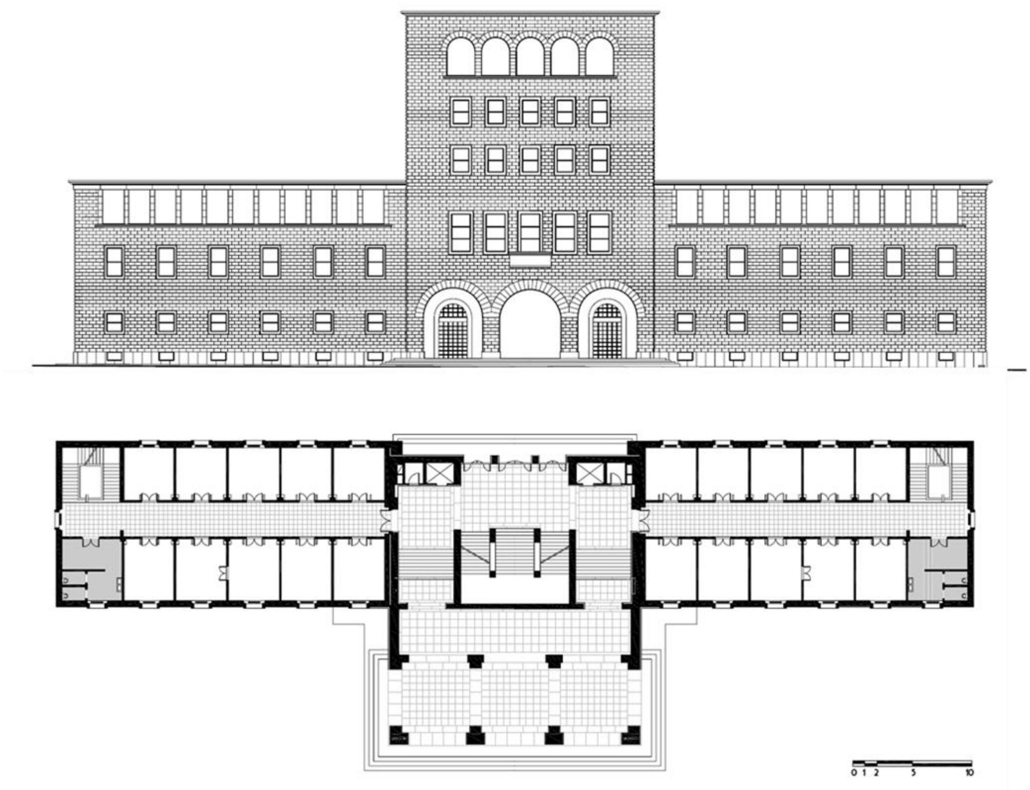

Fig. 1. Front view and the ground floor plan of the building

2.1 Physical Condition of The Building

The physical condition of the Polytechnic University of Tirana reflects its long history, with the building remaining structurally intact but showing signs of wear due to environmental factors and age. Constructed in the late 1930s and completed in the early 1940s, the building has survived significant historical events, including political changes and seismic activities, which have shaped Albania's architectural landscape. Despite these challenges, the structure remains a key part of Tirana's architectural heritage, though it now requires modernization to meet contemporary energy performance standards.

The architecture of the building is a mix of modernist design elements and traditional Albanian influences, characteristic of Gherardo Bosio's vision for the capital city's urban planning. The facade is largely intact, with its smooth, symmetrical lines and minimalist detailing remaining true to its original Rationalist style. The building features large windows and wide corridors, contributing to its overall sense of openness and connection with its surroundings [27].

However, the single-glazed windows, typical of the time, provide poor insulation, resulting in significant heat loss during winter and heat gain in summer. This lack of thermal efficiency is a primary area for improvement through retrofitting. While the building's exterior remains architecturally impressive, its energy performance lags far behind modern standards.

Structurally, the Polytechnic University of Tirana has proven resilient over the decades, with its reinforced concrete frame providing robust support against both time and environmental stresses. The building's masonry walls, reinforced concrete columns, and ceilings have helped it withstand seismic events, a common occurrence in the region. The structural system, which integrates brick walls with reinforced concrete elements, ensures that the building remains stable and retains its original form.

Nevertheless, the aging materials are beginning to show signs of deterioration, particularly in areas exposed to external weather conditions (Fig. 2). Cracks have appeared in some sections of the facade, and there is evidence of moisture infiltration, especially around the windows, which further contributes to energy inefficiency.

Fig. 2. Views from detoriated parts of the building

Retrofitting solutions such as replacing single-glazed windows with double-glazed units and installing shading devices will not only improve energy efficiency but also protect the building from further weathering, ensuring its preservation for future generations.

2.2 Interventions

2.2.1 Double-Glazed Windows

The replacement of the existing single-glazed windows with double-glazed units was a key intervention aimed at improving the thermal insulation of the Polytechnic University of Tirana. Double-glazing offers a significant improvement over single-glazed windows by reducing heat transfer between the interior and exterior of the building, leading to lower energy consumption for both heating and cooling. Several types of double-glazing were tested in the simulation:

Standard Double-Glazed Units: The basic double-glazing configuration consisted of two panes of 6mm clear glass with a 13mm air gap between them. This air gap acts as a buffer to slow down heat transfer through the window, reducing heat loss in winter and heat gain in summer.

Argon-Filled Double-Glazing: In this configuration, the air gap was filled with argon gas, which has a lower thermal conductivity than air. The argon-filled gap enhances the insulation properties of the window, providing better energy performance. This reduces the need for heating in winter and cooling in summer, making the building more energy-efficient.

Tinted Double-Glazing: Tinted glass was introduced in some scenarios to further reduce solar heat gain during the warmer months. The tinting reduces the amount of sunlight entering the building, particularly on south-facing facades, without compromising the availability of natural light. This solution was particularly useful for minimizing overheating and reducing cooling loads.

Double-Glazing with Internal Louvres: Some configurations included internal louvres integrated between the two glass panes. These louvres were fixed in certain cases, while in others, they were adjustable and activated based on the intensity of solar radiation. This feature provided additional control over solar gain, allowing for dynamic adjustments to optimize energy efficiency and occupant comfort.

Each type of double-glazing was evaluated in terms of its ability to reduce heat transfer and improve indoor thermal conditions, with the argon-filled and tinted variants showing the highest potential for energy savings.

2.2.2 Shading Devices

The second major intervention involved the installation of shading devices on the building's facades to manage solar heat gain and improve the building's energy performance during the warmer months. Shading devices can significantly reduce the amount of direct sunlight entering a building, thus reducing the cooling load, while also preventing glare and maintaining visual comfort for occupants. The types of shading devices tested in the simulation included:

Fixed Louvres: These are permanent shading elements attached to the exterior of the building. Fixed louvres were positioned at angles optimized to block high-angle summer sunlight while still allowing lower-angle winter sunlight to penetrate the building. This intervention helps in maintaining natural daylighting while reducing the cooling demand during hot months.

Automated Louvres: Unlike fixed louvres, automated louvres can be adjusted dynamically based on real-time solar radiation. The simulation tested several activation thresholds, where the louvres would tilt to block sunlight once a certain level of solar radiation was reached (e.g., 120 W/m^2, 400 W/m^2, or 600 W/m^2). This dynamic control allows for greater flexibility, maximizing energy savings while minimizing artificial lighting requirements during times of lower solar intensity.

External Blinds: Blinds were another shading option modeled in the simulation. These are flexible shading devices that can be manually or automatically adjusted. External blinds were used for their ability to block solar radiation while still permitting some visibility and ventilation. Automated blinds, which respond to changing sunlight conditions, provided the highest efficiency by adapting to the building's orientation and local solar patterns throughout the day.

Brise Soleil: This is a horizontal shading structure placed above windows to block direct sunlight during peak hours. It was particularly effective for south-facing windows in preventing solar gain during midday while still allowing daylight in the mornings and late afternoons. The fixed nature of Brise Soleil offers a simple yet efficient way to reduce cooling needs.

The combination of these shading devices helped mitigate the impact of solar radiation on the building's thermal comfort and energy usage. Dynamic shading devices, like automated louvres, showed the most potential for energy savings due to their adaptability to changing weather conditions, while fixed solutions provided consistent protection against overheating

3. Analyses

DesignBuilder software was used to model the building of Polytechnic University of Tirana and perform detailed energy simulations to assess the impact of retrofitting interventions. DesignBuilder is a powerful tool for energy analysis that allows users to create 3D models of buildings and evaluate their thermal performance under various conditions [28]. It integrates several advanced modules for simulating heating, cooling, lighting, ventilation, and renewable energy systems, making it ideal for retrofitting studies.

The first step in the simulation process was creating an accurate digital model of the building. Using DesignBuilder, the architectural and structural features of the university were modeled based on detailed drawings and data collected from site surveys. This included defining the dimensions, materials, and construction techniques used in the building. The original windows, for instance, were modeled as single-glazed units, and the surrounding brick and concrete elements were included to reflect the building's thermal properties.

For accurate energy simulations, the model also incorporated the local climate data of Tirana, including temperature fluctuations, solar radiation, and wind patterns. Occupancy schedules were defined to reflect the typical use of the building, with specific data on internal heat gains from equipment and lighting. This baseline model was used to simulate the building's current energy consumption, providing a reference point for evaluating the effects of the retrofitting measures.

Once the baseline model was established, two key retrofitting interventions were tested with several different installations: the replacement of single-glazed windows with double-glazed units and the installation of shading devices (such as louvers or blinds) on the building's facade.

The single-glazed windows were replaced with various double-glazed configurations within the simulation. Each configuration was tested to analyze its impact on heat transfer, overall energy consumption for heating and cooling, and indoor thermal comfort. The goal was to quantify the reduction in heat loss during the winter and heat gain during the summer, which would directly reduce the building's reliance on mechanical heating and cooling systems.

To assess the effectiveness of shading devices, several types of external shading were modeled, including fixed and adjustable louvers. These devices were designed to block excessive solar radiation during the hot summer months, reducing the cooling load on the building. The simulation calculated the effects of shading on both direct solar heat gain and daylighting, ensuring that the reduction in energy consumption for cooling did not negatively affect the natural lighting inside the building. Different shading angles and materials were tested to optimize the balance between minimizing glare and maximizing energy savings. The simulations provided detailed insights into how each retrofitting measure affected heating, cooling, and lighting energy consumption, as well as the thermal comfort levels within the building.

3.1 Considered Intervention Cases

Various retrofitting interventions for improving the energy efficiency of the Polytechnic University of Tirana are explored. These interventions primarily focus on upgrading the windows from single-glazed to double-glazed units and implementing shading strategies to control solar heat gain. The following cases outline the specific types of double-glazing configurations and shading devices considered.

List of Considered Cases:

- Case 1: Clear Double Glass with Air Gap: This configuration involves replacing the single-glazed windows with clear double glass that has an air-filled gap between the panes to improve insulation and reduce heat transfer.
- Case 2: Tinted Double Glass with Air Gap: In this case, tinted glass is used in combination with an air gap to minimize solar heat gain, while still allowing daylight to penetrate the interior.
- Case 3: Clear Double Glass with Argon Gap: The air gap is replaced with argon gas in this configuration to enhance the insulating properties, reducing heat loss and improving energy efficiency.
- Case 4: Tinted Double Glass with Argon Gap: This combination includes both tinted glass and an argon-filled gap, providing superior insulation and solar control to minimize energy consumption for cooling.
- Case 5: Clear Double Glass with Air Gap and Internal Louvres Always On: In this scenario, internal louvres are added between the glass panes and remain permanently fixed to block direct sunlight, reducing cooling loads.
- Case 6: Clear Double Glass with Air Gap and Internal Louvres Activated at 120 W/m²: The internal louvres are set to activate when solar radiation exceeds 120 W/m², dynamically responding to changing sunlight levels to optimize thermal comfort.
- Case 7: Clear Double Glass with Air Gap and Internal Louvres Activated at 400 W/m²: The louvres in this case activate when solar radiation exceeds 400 W/m², allowing more natural light in before shading begins to reduce solar heat gain.
- Case 8: Clear Double Glass with Air Gap and Internal Louvres Activated at 600 W/m²: This configuration sets the louvres to activate at 600 W/m², offering the maximum amount of daylight before solar shading is applied.
- Case 9: Shading Devices for Inner Courtyard Facade: To address the potential greenhouse effect caused by glazing on the inner courtyard, inner shade louvres are proposed. These louvres will block direct sunlight and reduce heat gain, while preserving the building's historical appearance.

3.2 Current State of The Building

To assess the current energy performance of the Polytechnic University of Tirana, an initial simulation of the building's existing conditions was conducted, referred as Case 0. This baseline model was essential for understanding the energy consumption patterns before implementing any retrofitting measures. The simulation considered the building's single-glazed windows, lack of shading devices, and typical heating, cooling, and lighting demands.

The results of the base case simulation revealed the following key insights:

High Energy Use for Heating and Cooling: Due to the presence of single-glazed windows, the building exhibited significant heat loss in the winter and heat gain in the summer, resulting in a high demand for both heating and cooling. The lack of proper insulation in the windows led to inefficient thermal performance, with the building requiring considerable energy to maintain comfortable indoor temperatures.

Poor Solar Control: Without any shading devices, the building was highly susceptible to solar heat gain, especially in the warmer months. This led to overheating in interior spaces and increased cooling loads. The lack of solar control measures also contributed to glare issues, negatively impacting occupant comfort.

Energy Use Intensity (EUI): The Energy Use Intensity (EUI) for the base case was calculated based on heating, cooling, and lighting energy consumption. The results indicated that a large proportion of the building's total energy usage (about 45%) was dedicated to maintaining thermal comfort through heating and cooling, highlighting the inefficiency of the current building envelope (Fig 3).

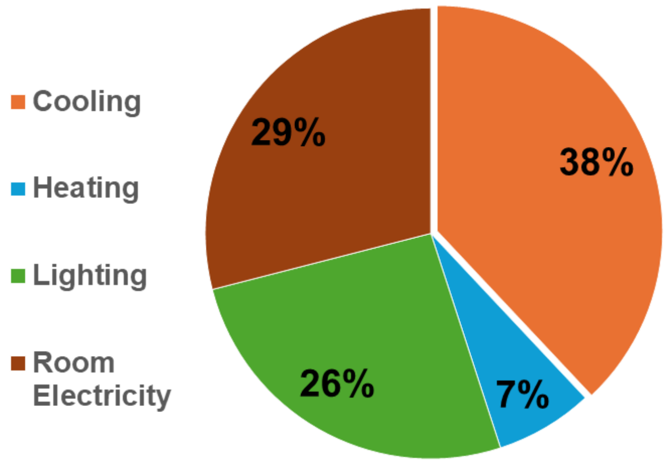

Fig. 3. The Energy Use Intensity (EUI) breakdown for the Polytechnic University

The Base Case serves as a critical reference point for evaluating the effectiveness of retrofitting interventions. By comparing the base case energy consumption to the results after implementing the proposed retrofits, the potential energy savings and efficiency improvements can be quantified.

3.3 Simulation Parameters

The relevance of the energy simulations conducted for the Polytechnic University of Tirana depends heavily on defined parameters. These parameters selected to ensure that the energy performance of the building was modeled under realistic and representative conditions. The key simulation parameters used in the study were as follows:

3.3.1 Building Location and Climate Data

Location: The Polytechnic University of Tirana is situated in Tirana, Albania, a region characterized by a Mediterranean climate with hot summers and mild, wet winters. Local weather data, including temperature, humidity, wind speeds, and solar radiation, were incorporated into the simulation.

Climate data source: The climate data used for the simulations was based on historical weather records for Tirana. This information was essential for accurately modeling heating and cooling loads across the different seasons.

3.3.2 Building Envelope

Existing windows: The base case modeled the original single-glazed windows, which were poor insulators, allowing significant heat loss and gain. This baseline was compared to various double-glazing configurations tested in the simulation.

Wall and roof insulation: The simulation assumed the existing wall and roof structures without additional insulation. This contributed to the building's high energy consumption for heating and cooling, providing a clear contrast when compared to the improved performance after retrofitting interventions.

3.3.3 Occupancy Patterns

The building was modeled with typical occupancy schedules for educational institutions, which assumed the building was primarily occupied during the day. The energy simulations accounted for variations in internal heat gains from occupants, equipment, and lighting based on these schedules.

Occupant heat gain: Human body heat contributed to the overall internal heat gains, impacting cooling requirements during the warmer months. This factor was considered in all cases.

3.3.4 Internal Loads

Lighting: The lighting system was modeled with a power density of 5 W/m^2 for typical spaces like classrooms, offices, and corridors, with specific target illumination levels (e.g., 300 lux for classrooms).

Equipment and appliances: The internal heat gains from equipment such as computers, laboratory devices, and other electronic systems were included, based on typical usage patterns for a university setting.

3.3.5 HVAC System Settings

Heating and cooling setpoints: The simulations used a heating setpoint of 22°C and a cooling setpoint of 24°C. These setpoints reflected the desired indoor comfort levels during the winter and summer seasons.

Heating Setback: A setback temperature of 5°C was modeled for unoccupied hours, reducing energy consumption when the building was not in use.

System efficiency: The Coefficient of Performance (CoP) for the heating system was set at 0.83, while the cooling system’s CoP was set at 2.5, representing typical values for the existing mechanical systems.

3.3.6 Solar Radiation and Daylighting

Solar gain: The simulation took into account solar radiation effects on the building's windows and facades. Solar gain was a critical factor in determining the cooling load during the summer months and the potential benefits of shading devices.

Daylighting: Natural daylighting levels were considered to evaluate how shading devices might impact the need for artificial lighting, especially when fixed or automated louvres were introduced.

3.3.7 Air Infiltration

The infiltration rate, which quantifies how much outside air enters the building due to gaps in the envelope, was factored into the simulations. Higher infiltration rates in the base case contributed to heat loss in winter and increased cooling needs in summer, further justifying the retrofitting measures aimed at improving the building’s air-tightness through new glazing.

3.3.8 Simulation Timeframe

The simulations covered an entire year, with seasonal variations in energy consumption assessed. Monthly energy usage for heating, cooling, and lighting was calculated to identify peak loads and understand how retrofitting interventions impacted energy efficiency throughout the year.

4. Analysis Results

The thermal analysis of the first and second floors of the existing building reveals significant differences in heat distribution. Figure 4a illustrates the thermal distribution without any interventions, showcasing noticeable temperature variations across the floors. In contrast, Figure 4b, depicting the scenario with interventions, demonstrates a much more uniform thermal distribution. This improvement indicates enhanced heat comfort, as the interventions effectively balance temperature differences, creating a more comfortable indoor environment.

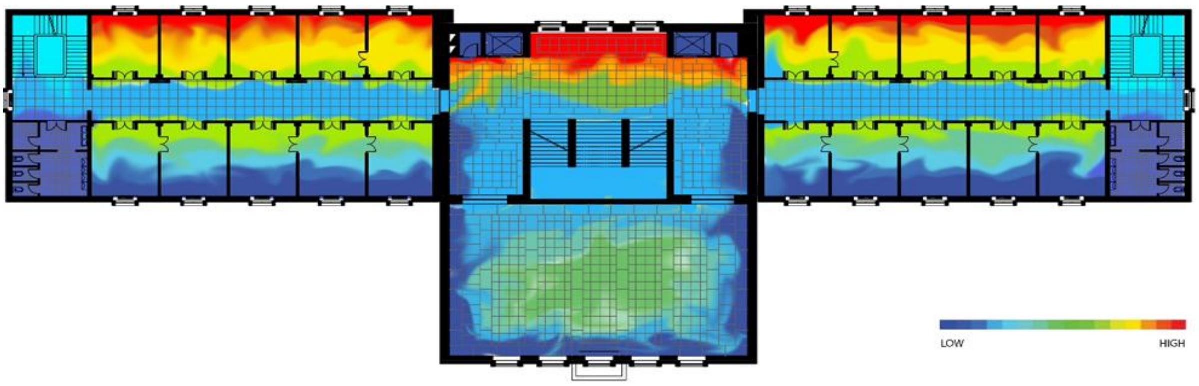

Fig. 4.(a) Thermal analysis of the first and second floor of the existing building without interventions by DesignBuilder

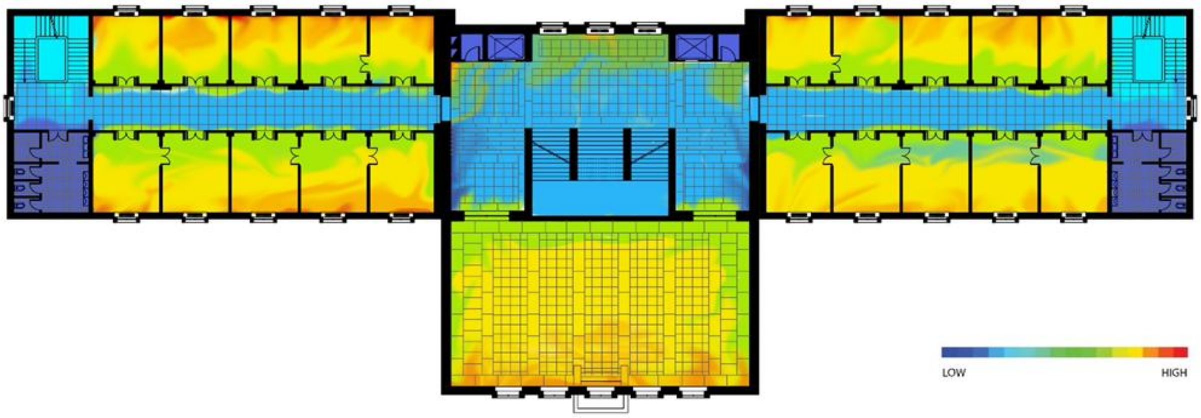

Fig. 4.(b) Thermal analysis of the first and second floor of the existing building after combined interventions of Case 4 and 9 by DesignBuilder

The results of the energy analysis for the base case (Case 0) and various retrofit interventions (Cases 1–9) are summarized in Figure 5. The analysis focuses on the building's annual energy consumption for lighting, heating, and cooling, as well as the potential energy savings achieved through different retrofitting measures.

As shown in Fig. 5, the lighting energy use remains constant at 32.5 % across all cases, reflecting the fact that the lighting system was not altered in any of the retrofit scenarios. The energy demand for heating shows a noticeable reduction in several cases compared to the base case (Case 0), where the heating load is 7.7%. Cases 1 and 3, which involve the use of clear double-glazing with air and argon gaps, result in the most significant reductions, with heating demands dropping to 5.5% and 5.8%, respectively. This improvement is due to the better insulating properties of double-glazed windows, which reduce heat loss during the winter months.

Cooling energy consumption is highly sensitive to the interventions, with significant variations across the cases. In the base case, cooling energy is 49.8%, which is the highest among all scenarios. Cases 2 and 4, which incorporate tinted double-glazing with air and argon gaps, show the largest reductions in cooling demand, reaching 43.0%. The use of internal louvres in Cases 5 to 9 also positively impacts cooling energy, but with varying effectiveness depending on the solar radiation thresholds for louvre activation. For example, Case 9 (internal louvres activated at 600 W/m^2) results in a cooling demand of 43.4%.

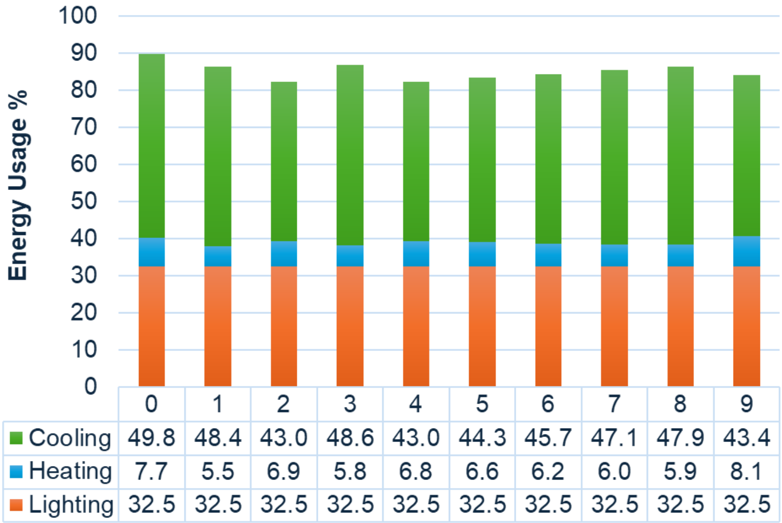

Fig. 5. The comparison of Cooling, Heating, and Lighting Energy Use Intensity (EUI) between the considered cases

The energy savings potential of each intervention is illustrated in Fig. 6. Case 4 (tinted double glass with argon gap) achieves the highest overall energy savings of 9.0%. Case 2 (tinted double glass with air gap) follows closely with an energy saving of 8.9%. Other notable cases include Case 1 (clear double glass with air gap), which achieves 3.8% energy savings, and Case 9, which uses internal louvres and saves 7.53%.

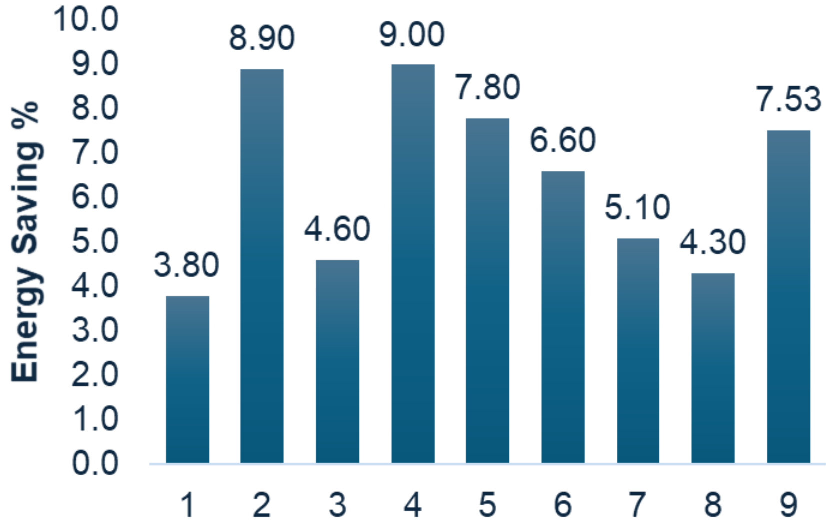

Fig. 6. The comparison of total energy saving for the considered intervention cases

The results demonstrate that upgrading to double-glazed windows with tinted glass and argon filling is the most effective intervention for reducing energy consumption, particularly for cooling. Meanwhile, integrating shading devices like louvres offers additional energy savings by reducing solar heat gain and cooling loads.

4.1. Economic Analysis

The economic analysis of the different retrofitting interventions focuses on the estimated costs, the percentage of energy savings relative to the base case, and the cost-effectiveness of each solution. Table 1 summarizes the results of this analysis, detailing the initial investment costs for each intervention, the percentage of energy savings achieved, and the cost per 1% energy saving.

The interventions vary significantly in terms of initial costs. Case 1, which involves the installation of double-glazing windows with 6mm clear glass and 13mm air gap, has the lowest estimated cost at €44,975 while achieving 3.80% energy savings. On the other hand, Case 8, which uses clear double glass with air gap and internal louvres activated at 600 W/m^2 solar radiation, has the highest estimated cost at €186,325, but results in only 4.30% energy savings.

Table 1. Estimated cost and effectiveness of the considered interventions

Case	Description	Estimated Cost (€)	Energy Saving (%)	Cost /Saving
1	6mm clear glass, 13mm air gap, and 6mm clear internal glass	44975	3.80	11836
2	6mm blue-tinted glass, 13mm air gap, and 6mm clear internal glass	61680	8.90	6930
3	6mm clear glass, 13mm argon-filled void, and 6mm clear internal glass	77100	4.60	16761
4	6mm blue-tinted glass, 13mm argon-filled void, and 6mm clear internal glass	87380	9.00	9709
5	6mm clear glass, 13mm air gap, and 6mm clear internal glass with fixed internal louvers	93805	7.80	12026
6	6mm clear glass, 13mm air gap, and 6mm clear internal glass with internal louvers that activate when solar radiation exceeds 120 W/m^2	141350	6.60	21417
7	6mm clear glass, 13mm air gap, and 6mm clear internal glass with internal louvers that activate when solar radiation exceeds 400 W/m^2	165765	5.10	32503
8	6mm clear glass, 13mm air gap, and 6mm clear internal glass with internal louvers that activate when solar radiation exceeds 600 W/m^2	186325	4.30	43331
9	Installation of shading devices on the facade	86533	7.53	11492

In terms of energy savings, Case 4 (blue-tinted double glazing with argon filling) offers the highest reduction in energy consumption, with a savings rate of 9.00%, though it comes with a higher cost of €87,380. Case 2, which uses blue-tinted glass with an air gap, also performs well with 8.90% energy savings at a slightly lower cost of €61,680.

The cost-effectiveness of each intervention can be assessed by calculating the cost per 1% energy saving. Case 2, the installation of double glazing windows with 6mm blue-tinted glass, 13mm air gap and 6mm clear internal glass, emerges as the most cost-effective solution, with a cost of only €6,930 per 1% energy saving. This is the most economical option, making it an attractive choice for budget-conscious retrofitting. Case 4, using blue-tinted glass with an argon gap, provides a higher cost of €9,709 per 1% saving but achieves the maximum energy savings of 9.00%.

In contrast, Case 8 (internal louvres activated at 600 W/m^2) is the least cost-effective, with a cost of €43,331 per 1% energy saving. This high cost, coupled with relatively modest energy savings, suggests that the use of advanced louvre systems may not offer the best return on investment compared to simpler shading or glazing interventions.

These findings indicate that blue-tinted glass solutions offer the most cost-effective solution, while advanced louvre systems (Cases 6-8) involve higher costs for smaller energy savings. All cases may be combined with Case 9 to have additional energy saving as it includes a separate type of intervention. However, this option should be evaluated individually for each building. Same results may not be achieved for every building as it highly depends on the case at hand. Analyses show that for the case study building, 16.53% energy savings may be obtained for a cost of €10,521 per 1% of energy reduction by combining Case 4 and 9.

5. Discussion of Results

The analysis demonstrates that the installation of double-glazed units significantly improves the building’s insulation, leading to a noticeable reduction in energy consumption for heating and cooling. By reducing thermal transmission through windows, double-glazed systems, particularly those with argon-filled gaps, minimize heat loss in winter and heat gain in summer. This improvement not only enhances the building's energy performance but also contributes to better thermal comfort for occupants. Among the tested cases, blue-tinted double-glazed units with argon gaps (Case 4) proved to be the most efficient, achieving a 9.00% energy saving. However, even standard clear double-glazed units (Case 1) delivered improvements over the base case, offering 3.80% savings. Research by Nair et al. supports these findings, indicating that double-glazing can significantly enhance energy efficiency in heritage buildings without compromising their aesthetic value [15].

The implications of this intervention extend to the overall building performance, with a reduction in the load on HVAC systems, which could result in longer equipment lifetimes and lower operational costs. In heritage buildings like the Polytechnic University of Tirana, careful integration of double-glazing allows energy improvements without significantly altering the appearance or structure of the historic facade. This aligns with the work of Buda et al., who emphasize the importance of conservation-compatible retrofit solutions that respect the historical integrity of buildings while enhancing their energy performance [21].

Shading devices play a critical role in controlling solar heat gain, particularly in climates where solar radiation can lead to overheating. The internal louvres tested in this study were found to be effective in reducing cooling loads, especially in configurations where the louvres activated in response to higher solar radiation thresholds. Case 9, involving the installation of internal shading devices on the facade, provided a 7.53% reduction in energy consumption. It is one of the cost-effective interventions being close to low end of cost per energy saving values. This finding is consistent with research by Heidarzadeh, which highlights the effectiveness of shading devices in improving energy efficiency in office buildings [29].

Shading devices not only prevent excess heat gain but also contribute to visual comfort by reducing glare inside the building. Fixed internal louvres (Case 5) and automated louvres that responded to specific radiation levels (Cases 6-8) proved particularly useful for this purpose. However, in heritage buildings, the placement of external shading may clash with aesthetic and preservation standards, requiring internal or less visually intrusive solutions, as was applied in this case. This necessity is echoed in the work of Kim and Felkner, who argue for the importance of balancing energy efficiency measures with the preservation of historical aesthetics in adaptive reuse projects [30].

The economic analysis of the interventions highlights significant variations in the cost-effectiveness of different retrofitting measures. While double-glazing solutions offered substantial energy savings, their installation cost varied widely. The most cost-effective solution overall was the installation of double-glazing windows with 6mm blue-tinted glass, 13mm air gap and 6mm clear internal glass (Case 2), which achieved a 8.90% energy saving at a low cost of €6,930 per 1% energy saving. In contrast, more advanced louvre systems (Cases 6-8), while offering additional energy savings, came at a significantly higher cost. The louvres activated at 600 W/m^2 solar radiation (Case 8), for example, had the highest cost per unit energy saving, at €43,331 per 1% saving. This suggests that while advanced shading technologies can enhance energy performance, their financial viability may be questionable unless energy savings are maximized. Similarly, the use of tinted double-glazing with argon filling (Case 4) achieved the highest energy savings but with moderate cost-effectiveness.

Several challenges emerged during the retrofitting process, particularly concerning the building's status as a heritage structure. Retrofitting older, historically significant buildings requires careful balancing of energy efficiency improvements with the need to preserve architectural integrity. External shading devices, may not be preferable for buildings like the Polytechnic University of Tirana due to potential changes to the historic facade. As a result, internal solutions, such as internal louvres, were favored. This approach is supported by findings from Martínez-Molina et al., who emphasize the need for energy-efficient retrofitting measures that respect the historical value of buildings [31].

Another constraint involved the integration of double-glazing. Installing modern, high-performance windows in a heritage building requires customization to ensure that the new units fit within the existing frames without altering the building's historical appearance. Technical challenges also arose regarding the application of louvre systems, particularly in maintaining consistent operation of automated systems in response to fluctuating solar radiation levels. This complexity is echoed in the research of Bulut et al., which discusses the challenges of retrofitting secondary glazing in heritage contexts [32]

The findings from this case study provide valuable insights for the retrofitting of other heritage buildings. First, energy-efficient retrofitting measures, particularly the use of double-glazing and shading devices, can significantly reduce energy consumption without compromising the historical value of such structures. The most successful strategies in this study combined internal interventions, such as internal louvres, with high-performance glazing systems that can be integrated discreetly into heritage facades. This aligns with the recommendations of Usta and Zengin, who advocate for careful consideration of glazing types to optimize energy performance in heritage buildings [33].

Future retrofitting projects should aim to balance energy efficiency with historical preservation. This might involve using internal, automated shading devices or selecting glazing solutions that are tailored to the aesthetic and structural characteristics of the building. Cost-effectiveness should also be a key consideration, with particular attention paid to simple yet effective solutions like fixed shading devices or air-gapped glazing, which offer a high return on investment. The economic feasibility of such measures is supported by the work of Bahadır et al., who emphasize the importance of evaluating energy-cost efficient design alternatives [34].

Ultimately, these findings highlight that with the right combination of interventions, heritage buildings can achieve significant energy savings while maintaining their historical and architectural integrity, offering a model for future projects aiming to combine sustainability with cultural preservation. The integration of energy-efficient technologies in heritage contexts is not only feasible but essential for advancing sustainable practices in the built environment, as underscored by the comprehensive review conducted by Moghaddam [35].

6. Conclusion

This study examined the effects of two key retrofitting measures—replacing single-glazed windows with double-glazed units and installing shading devices—on the energy performance of the Polytechnic University of Tirana, a heritage building in nine different cases. Through energy simulations, the results showed that both interventions provided substantial energy savings and improved overall thermal comfort, without compromising the architectural integrity of the building if done with care.

The analysis revealed that double-glazed units, particularly those filled with argon and tinted glass, significantly reduced heating and cooling demands. Similarly, internal shading devices helped mitigate solar heat gain and maintained visual comfort, with some louvre systems performing better than others depending on their activation thresholds.

Main conclusions may be listed as:

- Double-glazed windows improved insulation, reducing both heating and cooling loads, with energy savings ranging from 3.80% to 9.00%, depending on the type of glazing used.
- Internal shading devices were effective in reducing solar heat gain, with fixed and automated louvres providing energy savings between 4.30% and 7.80%, depending on their activation threshold.
- The economic analysis highlighted that simpler interventions, such as standard double-glazed units and fixed shading devices, offered higher cost-effectiveness compared to more advanced automated louvre systems.
- Retrofitting heritage buildings require careful consideration of both energy-saving measures and the need to preserve architectural authenticity. Internal interventions, such as internal louvres, were especially effective in addressing this balance.

The findings of this study underscore the importance of double-glazing and shading devices in sustainable retrofitting projects for heritage buildings. These interventions not only significantly enhance the energy performance of such buildings but may also maintain their historical and architectural integrity. The results suggest that double-glazed windows and carefully integrated shading systems are critical components of any energy-saving strategy for older, historically significant structures.

For heritage buildings, the challenge often lies in finding solutions that both reduce energy consumption and respect conservation standards. This study demonstrates that with well-chosen retrofitting measures, it is possible to achieve substantial energy savings while preserving the building's historical value.

Future research may focus on combining these interventions with other sustainable retrofitting measures, such as improving insulation and integrating renewable energy systems. Additionally, exploring newer technologies for both glazing and shading devices could further enhance the energy performance of heritage buildings.

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