Integrating Building Information Modeling Tool for Enhancing Energy and Daylight Performance in buildings' retrofit and Attaining Sustainability

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1 Introduction

Earthwide temperature increases and global environmental changes and challenges have been turning out to be prevalent issues, ranging from urban heat island effects (UHIEs) to climate change (CC) impacts [1, 2]. Such impacts and challenges attract global attention on the importance of enacting robust policies and planned actions for preserving the environment. In the European Union 27 member states, energy use and CO_2 emissions of buildings account for 40% and 36%, respectively [3]. About 35% of buildings in the EU are old (over 50 years), but nearly 75% of these buildings is energy inefficient [4]. In the MENA (Middle East and North Africa) region, buildings are responsible for more than 50 percent of the total energy use, yet are inefficient [5].

In Egypt, the building sector (residential, commercial, government, and public utilities) accounts for 67 percent of the 2016 total electrical energy [6]. Educational buildings (universities, research centers, and schools) worldwide are classified as the highest institutions in terms of energy use and greenhouse gas (GHG) emissions, yet the third of the total utilized areas [7]. Hence, sustainable transformation of university buildings is imperative for governments, policymakers, and owners/developers due to high-energy use intensity/m^2 according to the American National Energy Audit by CBECS (Commercial Buildings Energy Consumption Survey) [8].

There are real challenges that Egypt may face to meet future energy demands due to the rapid population increase [9], if no retrofitting measures are enacted and effectively implemented in the existing building stock. Due to global CC manifestation, buildings are increasingly in demand of energy use for cooling in summer months and heating in winter months, in response to the huge use of air-conditioning or heating. Such impacts increased the dependence on active solutions rather than on passive ones. However, in the context of low-energy cost, conventional concerns of effective envelope and green building materials were uprooted to a second level of significance and resulted in buildings that include leakages into windows and poor thermal insulations permitted the envelope to become viable to heat transmittance, thus high-energy use rates. Nevertheless, this is no longer the case since the Government of Egypt introduced new legislatives on the electrical energy tariff in 2014, 2016, 2018, and the last in June 2020, which led to lifting the energy subsidies and increased the electricity cost for all buildings' types [10–13].

Existing educational buildings form a large portion of the total building heritage that should be preserved and protected against deterioration worldwide [14]. For both occupants' well-being and performance enhancement, old buildings should never be neglected, but be retrofitted and renovated to increase their energy performance, comfort, and assets' value. The current building stock comprises mainly a high percentage of old buildings with high carbon footprints, and even the newly constructed buildings still have lofty carbon footprints. According to a study review conducted in 2016, the existing building stock forms 86% of the total buildings [15]. However, the negative effect of the building sector on the environment could be reduced by improving the efficiency of the current buildings rather than building new ones [16–18]. A fascinating case

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emerged to serve as an educational and moralistic approach; it aims at demonstrating the environmental supervision in schools to teach the children for the first time what it means to be in a world that holds stewardship for both the society and the environment [19].

The building stock constitutes a large share for old school construction, where more than 50% of these buildings are close to reaching the end of their life span, which gives priority to focus on sustainable retrofitting of the existing educational buildings' stock [20]. If schools are built according to sustainable principles and practices, a significant effect on energy and other resources' utilization would be better management and saved. Although the advantages of the sustainable design are highly noted in the recent 5 years and since the Paris Climate Agreement – 2015 [21], they are not considered primarily for the building sector. Nonetheless, the educational mission itself aims at cherishing the sustainability in design, construction, and how these principles and measures are executed.

A better environment for learning is available in sustainable schools [22]. The school designs are usually comprised of single corridor sided classrooms, where the opposing hallway combines expansive openings, which give adequate sunlight or a two-sided passageway that does not have adequate natural airflow, and these areas are being enhanced with electrical ventilation sources [23]. Regardless of the absence of ordinary air flow in the passages and hallways, usually the installation for mechanical ventilation within those spaces does not appear to be frequent, thus, thermal and visual conditions within the spaces are poorly provided [24].

The building efficiency and energy performance are highly affected by the building's cover-surface (envelope), since the energy consumed for cooling, and heating, or providing other electricity needs, is affected by the efficiency of the envelope system [25]. A building envelope compromises both opaque and translucent components, which the sun heat and light that impinges on these surfaces contribute to and affect the interior thermal conditions. The capacity of the envelope components to convey the thermal heat depends on the thermal properties of materials. According to Huang et al. (2014), mechanical systems are sometimes utilized to adapt the interior conditions to comfort levels [26].

Multiple studies explored the performance of the building envelope's different components for the sake of both the initial design decisions and the retrofitting options [27]. Fan and Xia investigated the components of the building envelope including walls, windows, and roofs for optimizing their energy performance with high economic value in a retrofitting approach [28]. They formulated a multi-objective optimization model to reach for optimum solutions.

Based on a study review conducted by Gan et al. on building performance optimization actions, it aimed at enhancing the building performance through their envelopes, HVAC systems, and other systems [29]. In this review, multiple performance assessment methods were used to realize that building thermal properties in addition to occupants' behavior are the most significant factors that account for high-energy consumption and carbon emissions through the building life cycle [29]. Also, Soler et al. studied the performance of the opaque components in the building envelope, and they assessed all the materials involved in the construction process. In this study, they optimized the integration of layers' properties that shaped the opaque components [30]. Using a mathematical procedure, it was possible to provide an efficient material integration scheme with low carbon emissions [30]. In addition, Sartori and Calmon explored the retrofit of two existing buildings in terms of building performance enhancement, analyzing their embodied, operational, and wasted energy values [31]. They simulated different retrofit scenarios that included different building envelope measures and concluded that insulating materials, such as mineral wool, sheep wall, and expanded polystyrene (EPS), are highlighted significantly to improve the external walls and pitched roofs' performance [31]. Also, EPS as a building thermal insulating material is assessed under variable conditions and is proven to be highly efficient [32].

Many studies emphasized the significance of the building envelope in improving the performance of the whole building. However, building façades particularly are the most influential factors in the performance of the building envelope in general and specifically, these façades are highly influencing on the thermal and visual performance of educational building spaces [33, 34]. In Egypt, educational buildings are highly significant, as they enclose young Egyptians for a long period of time. Students enrolled in precollege academic schools reach 17 million in Egypt within 40,000 schools (public and private) and incorporate 1.6 million employees [35]. The old educational structures in Egypt are conceived as heritage that can never be neglected or undeveloped.

Owners, developers, and government should pay more attention to the retrofitting of an existing school building through optimizing building energy consumption to reduce CO_2 emissions and buildings' footprint, yet preserving our heritage. It is significant to optimize the performance of old educational buildings in Egypt that are constructed and characterized with high-energy consumption and inefficient energy performance levels. One of the main parameters that influence buildings' energy consumption is the building envelope, mainly the façade. Inefficient façades are considered the main building elements contributing to high-energy consumption and utility costs, despite the direct effect on the occupants' discomfort. Thus, there is an urgent need to adopt an efficient retrofitting approach for existing buildings' façades to enhance the performance of these buildings and the educational experience, and above all to allow for sustainable usage of the total energy.

This research highlights the main energy consumption problem related to the building façade elements in old educational buildings in Egypt. The study presents an assessment of a case study in order to reduce the total energy consumption and improve the building performance level through analyzing two retrofit schemes emphasizing on the main façade of an educational building.

2 Objectives

The objective of this study aims at investigating how buildings' façade retrofit represents an energy-efficiency alternative for improving the energy performance of existing buildings. The study focuses on exploring and assessing buildings' envelopes and their energy efficiency through retrofitting schemes of existing educational buildings. In this research, an old public-school building is examined and analyzed for potential sustainable reuse and higher energy performance. Considering a typical educational building, it is possible to approach improvements for this type of building based on the Cairo climatic conditions. Part of this attempt is to explore the energy reductions due to several improvements in the façade system and conductive materials in order to identify the most efficient façades deduced from the retrofit process in the selected educational building.

3 Methodology

The research method depends on analytical and measurable (applied) approaches. The analytical approach includes an assessment of the current building and its envelope as well as energy performance. The applied (simulation) of different façade retrofit schemes is performed in an existing educational building case study, located in Cairo, Egypt, as shown in Fig. 1. The analysis of the total building's energy performance, using the DOE-2.2 engine, is primarily applied to analyze the existing energy performance of the case study. A measurable procedure and defined set point for the building parameters are shown in Table 1, where the building baseline material properties are identified. Possible façade retrofit schemes are suggested for the transparent and opaque components of the main façade. They are evaluated for their operational energy consumption savings percentages (Fig. 1). The educational building refrains a typical single-sided corridor layout. Since the building main windows are oriented south-west as shown in the sun-path diagram of the building provided in Fig. 2, they are mostly subject to direct daylight. The energy consumed in the building is thus affected by the envelope thermal performance. In addition, the energy consumed depends on the occupancy level, and the behavior related to the school activities, schedules of classes, and operational habits. Understanding if the building has a seasonal operational schedule is crucial, and the level of occupancy of the different classes or floors throughout the building. The occupancy schedules' profile in the classrooms shows the percentage of occupancy in the classrooms during the day, where the peak hours are during the school day between 08:00 and 16:00 and only a drop in occupancy percentage during the break hours.

3.1 *Envelope Thermal Profile*

The core of this research is the building façades' performance. Hence, it is a fundamental part of this study to establish the relationship between the properties of the envelope and the building operational energy, which is partially wasted due to the building's current inefficient performance. The R-value refers to the capacity of the façade system to transfer thermal energy

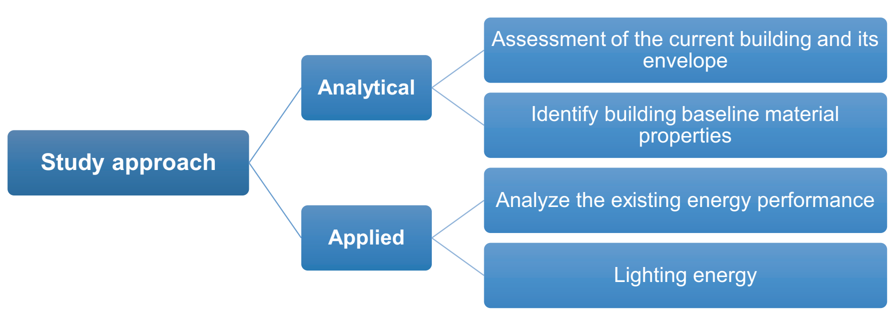
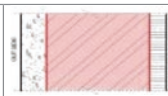
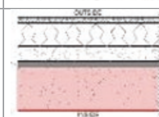


Fig. 1 Approaches conducted for the assessment of an educational building. (*Source: Authors*)

Table 1 The examined school building data

Building model dimensions		
Shape	Rectangular	
Volume	143 m^3	
Foot print	470 m^2	
External wall total area	758 m^2	
North east (NE) façade South west (SW) façade	390 m^2(434–18-30) 212 (434 m^2–222)	
NE and SW façade	156 (2 × 90 m^2–20-4)	
Windows total area	126 m^2 (W 1.2 m × H 1.6 m)	
Voids opening area	272	
Window wall ratio (WWR)	26%	
Building envelope specifications		
Exterior wall	120-mm thick wall with plaster, and paint Both sides with U-value 2.89 W/m^2 K	
Roof materials	Sloped concrete over reinforced concrete, and 50-mm thermal insulation, 20-mm water proofing, sand, and mortar Cement tiles with U-value 0.23 W/m^2K	
Glazing	Single glazing	Single glazing
Thermal properties		
Exterior walls	U-value	R-value
	2.89 W/m^2.K	0.34 m^2K/W
Roofing	0.23 W/m^2.K	4.35 m^2K/W
Glazing	5.44 W/m^2.K	0.18 m^2K/W
Glazing frame	2.88 W/m^2.K	0.34 m^2K/W
Glazing	Solar heat gain coefficient	0.42

Source: Authors

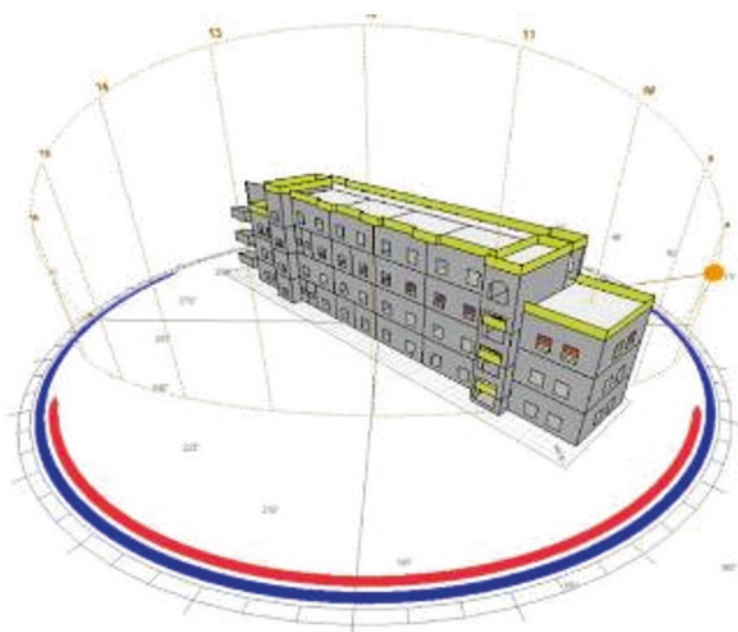


Fig. 2 Sun-path diagram for the base-case. (*Source: Authors*)

through façade components. After estimating the thermal resistance of the wall, the load through the façade is calculated. Also, both the summer and winter conditions are analyzed, despite cooling being the predominant load in the building. Two calculations have been carried out: (a) instantaneous heat transfer (for peak high and low temperatures) and (b) cumulative heat transfer.

In order to pursue such an assessment, the energy simulation programs employed in simulating the current energy consumption before and after the retrofit of the building façades are Ecotect and Insight 360 [36–38]. In addition, the monthly energy consumption for the different combinations of opaque and translucent parts of the façade is analyzed in two retrofit scenarios.

4 Retrofit Schemes

Based on the typology developed, two different schemes were chosen and simulated for comparison against the baseline case of the building. Energy reductions could be visualized from these different schemes identified in Fig. 3 and Table 2.

4.1 The Simulation

In the applied assessment and simulation, the outer wall composition and insulation for the single-/double-skin façade typologies are set by using five types of wall systems as the following (1A-5A); while the translucent component of the façade is simulated using four types of glazing retrofit schemes as the following (1B-4B). These settings are as follows:

- 1A- Standard Egyptian wall 120-mm thickness with U-value 2.89 W/m^2.K;
- 2A- Standard Egyptian wall 250-mm thickness with U-value 2.31 W/m^2.K;

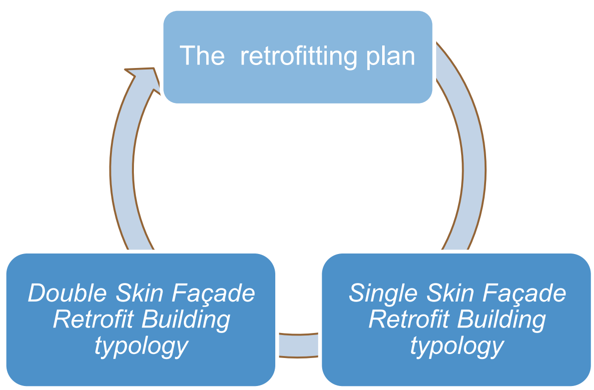


Fig. 3 The retrofitting plan of the case study. (*Source: Authors*)

Table 2 Simulated retrofit schemes

South-west façade		WWR	Description	Façades' interventions
Single skin/ regular window		26%	The original façade is maintained, but some components or all of them are upgraded or replaced	Window replacement Different walls' compositions Shadings added
Double skin/ fully glazed		90%	An additional glazed skin is added to the original façade, allowed to receive ventilation. Both the original façade and the additional skin are modified.	Glazing systems Different walls' compositions Shadings added Full-height double skin with catwalk

Source: Authors

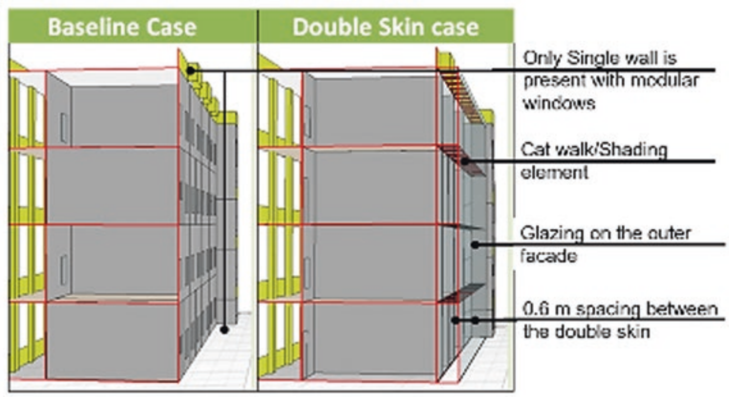


Fig. 4 Single- and double-skin approaches for the examined educational building. (Source: Developed by authors)

- 3A- ASHRAE 90.1-2013 American standard with U-value 0.86 W/m^2.K [38];
- 4A- Autoclaved aerated concrete (ACC) with U-value 0.44 W/m^2.K; and
- 5A- Exterior insulation finishing system (EIFS) with U-value 0.34 W/m^2.K.

– Scenario 1 B- Single glazing with U-value 5.44 W/m^{2}K
– Scenario 2 B- ASHRAE 90.1-2013 glazing 2.71 W/m^{2}K
– Scenario 3 B- Double glazing with air gap 1.5 W/m^{2}K
– Scenario 4 B- Double glazing with argon filled 1.1 W/m^{2}K

In all the above, 1B, 2B, 3B, and 4B, these are considered with the main properties for this glazing type, which are defined through the simulated model which shows that the SHGC is 0.81, VT is 0.639, and glazing thickness is 6 mm with total thickness 24 mm (Fig. 4).

5 Results and Discussions

The monthly energy consumption rates for the different combinations of opaque and translucent parts of the analyzed façades in the two retrofitting schemes are shown in Fig. 5. The total monthly cooling/heating loads are compared with the different wall compositions for the single-skin façade typology in kWh and are illustrated in Fig. 5a, and for the double-skin façade typology in kWh they are presented in Fig. 5c. The EIFS applied on the façade shows the most energy saving results of the different walls applied scenarios. The total heating/cooling loads for the single-skin/regular windows façade building and double-skin façade building are 134,941 kWh and 84,312 kWh, respectively. Figure 5b and d illustrate the energy performance of different glazing systems applied for the building façade in kWh. The double glazing with argon-filled system applied on the single-skin façade shows the most energy saving results of the different systems applied. The total annual energy consumption (heating/cooling loads) for the building was found for single-skin and the double-skin façade typology to be 12,742 kWh and 14,502 kWh, respectively. However, the energy consumption of all systems shows their maximum values during the summer months (June, July, and August) to encounter for the electricity used by cooling loads in these hot months as shown in Fig. 5.

The energy saving is compared with the different wall compositions for both scenarios – the single-skin façade and the double-skin façade. Table 3 presents the energy saving of such comparative analysis. Using different wall compositions within each of the skin typologies allows different energy saving percentages. Considering the 120-mm wall as the baseline model wall composition; with comparison to the other wall compositions of the EIFS gives the highest energy saving percentage in both typologies. But when compared with the regular window and the double-skin typologies, the first typology results show higher energy saving percentages, higher than 42% of the total energy saving (Table 3). This very high percentage is related to the higher opaque content in the simulated regular window typology. It is clear that in the single-skin/regular windows, the façade typology that incorporates wooden windows with 26% WWR, as shown in the baseline case, reveals better thermal performance over the applied double-skin/fully glazed for this building. This is due to the fact that the direction of the south-west orientation of the façade of the simulated building shows lower performance with the increased glazing area represented in the double skin, especially with the absence of any additional shading device. Nevertheless, different glazing types are compared for their total energy savings within the simulated single-skin building and double-skin building scenarios.

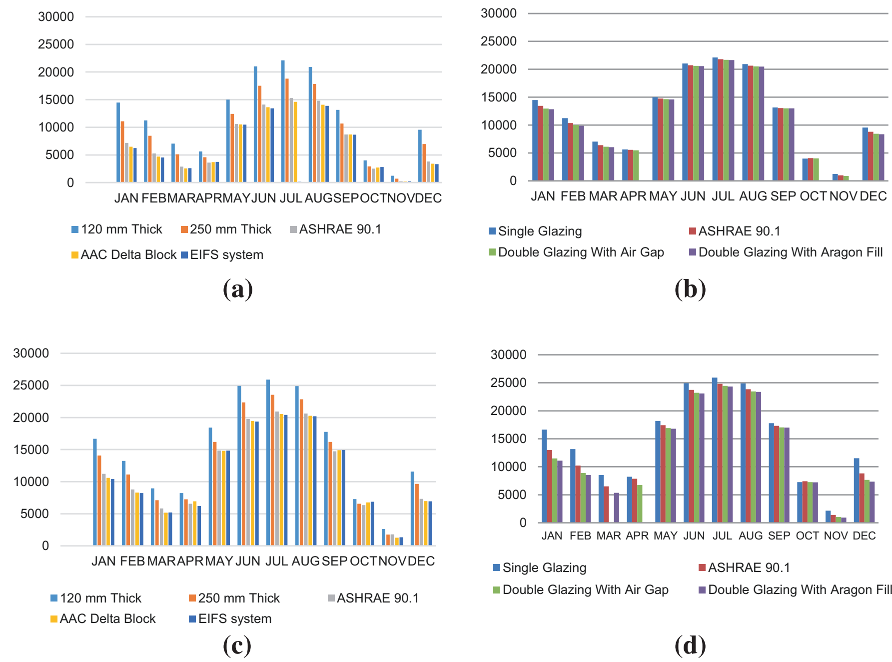


Fig. 5 Monthly energy consumption for the different retrofit façade retrofit schemes. (**a**) Opaque in a regular window façade. (**b**) Translucent in a regular window façade. (**c**) Opaque in double-skin façade. (**d**) Translucent in double-skin façade

Table 3 Energy saving percentage for the wall compositions applied within the façade typologies

Energy saving %	120 mm thick baseline	250 mm thick	ASHRAE 90.1 American standard	AAC delta block	EIFS
Single-skin façade	%0	19.46%	38.80%	41.33%	42.03%
Double-skin façade	%0	%12.11	%23.00	%24.66	25.23%

Table 4 Energy saving percentage for the glazing types applied within the façade typologies

Energy saving %	Single glazing baseline	ASHRAE 90.1 American standard	Double glazing with air gap	Double glazing with argon fill
Single-skin façade	0%	%3.3	%4.87	12.40%
Double-skin façade	0%	9.43%	17.35%	19.08%

The simulation readings for the building's operational energy consumption are compared with the base-case values and percentages as listed in Tables 3 and 4. Considering the single glazing as the baseline model glazing property; with comparison to the other glazing models of both retrofit typologies, the double glazing with argon fill gives the highest energy saving percentage in both typologies, as shown in Table 4.

However, in comparison between the single-skin and the double-skin typologies, the double-skin shows higher energy saving percentages concluding better skin efficiency. Though, it is concluded that using the double-skin façade with more efficient glazing systems that allow more light transmission due to the higher window-to-wall ratio results in higher levels of natural lighting as provided in Fig. 7, and higher energy savings in kW/h as shown in Fig. 6. Such modification resulted in lowering electricity bills' costs.

When applying the single glazing system without any upgrade in the façade's glazing, but altering the exterior wall system with different wall compositions, higher efficiency for the single-skin/regular window façade typology of design is provided. Only with higher glazing standards, the double-skin façade results in a more efficient retrofit scheme. An efficient retrofit scheme is the one that considers all the comfort-related variable conditions, that is, suitable interior temperature range, higher natural lighting levels lying within the comfort range for reading (300–400) Lux, good view to the outside, and more environmental indoor air quality.

Comparing the operational energy loads and the total saving percentages for the optimum selection of façade materials (opaque and translucent) within both the double-skin façade and single-skin façade shows that a maximum of 72% energy

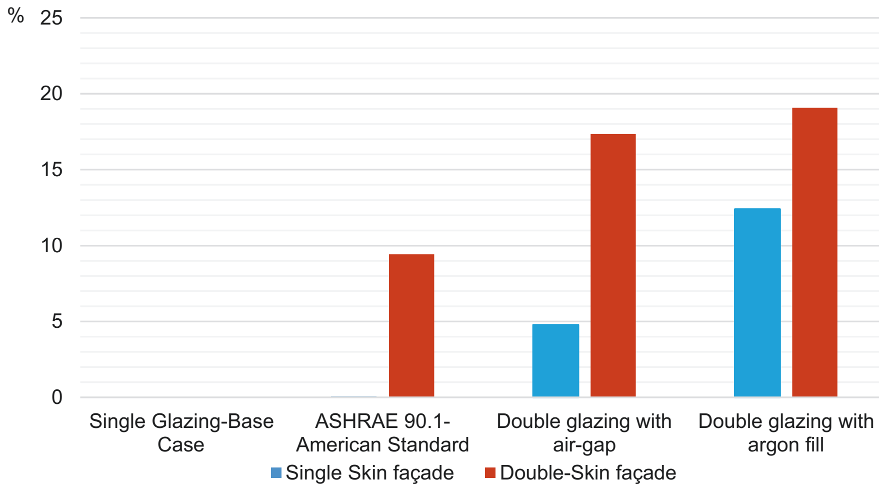


Fig. 6 Comparing the energy saving percentage for the different glazing systems

Table 5 Energy load reduction and saving percentage for optimum façade design systems

Energy savings	Baseline single skin	Baseline double skin	Optimum material selection (single skin)	Optimum material selection (double skin)
Total loads (kW/h/m^2)	74	92	21	58
Energy saving %	0%	0%	72%	37%

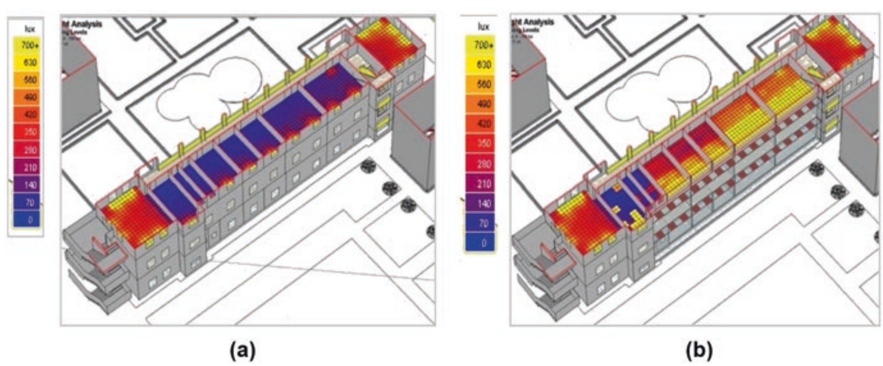


Fig. 7 Daylight distribution for the upper floor of the retrofitted school building – 21 March. (**a**) Single-skin (wall/window) façade. (b) Double-skin full glazing façade

saving could be the outcome of a regular window/single-skin façade retrofit (Table 5), which proposes the most efficient combination of the external façade wall composition and glazing type in a simulated building optimum façade retrofit, to be able to compare their total energy consumption profiles and their related energy saving percentages which highlighted the capability of the regular window façade in retaining higher thermal performance levels. In contrast, Fig. 7 presents the positive effect of the double-skin façade in enhancing interior daylight conditions. Finally, a comparative evaluation approach is provided in Table 6, combining the simulation results of the two building typologies for the façades. The comparison provides optimum estimated energy savings based on the studied criteria.

Table 6 Proposed checklist for achieving low-energy performance in educational buildings

Performance criteria	After retrofitting	
	Single-skin façade	Double-skin façade
Retrofitting the opaque system only		
Opaque system	EIFS	EIFS
Opaque U-value	0.58	0.58
Energy consumption (kW/h/m^2)	43	68.8
Energy reduction	42%	25%
Retrofitting the translucent system only		
Translucent system	Double-glazing (argon filled)	Double-glazing (argon filled)
Translucent U-value	1.85	1.85
Energy consumption (kW/h/m^2)	65	74
	12.4%	19%
Combined retrofit of optimum opaque and translucent façade systems		
Energy consumption (kW/h/m^2)	**31**	52.4
Air shaft	None	500 mm shaft
Air flow	Normal	**Stack-cooling effect**
Illuminance %	26%	**66%**
Costs	**Moderate** **Lower construction and maintenance costs**	**High**

6 Conclusions

This study is a compilation of building retrofits with special emphasis on the façade system. In this regard, the current concern of global warming and the essential role of buildings urge the need for more environmental studies. Currently, the tangible benefits of retrofitting the façade in existing buildings are not broadly studied. Therefore, the focus is to comprehend the building retrofit as an energy-efficient tool for decreasing the operational energy consumption in buildings, and one particular building example gives an idea of the possible savings in similar hot-climatic conditions.

The building total energy consumption is 145,459 kWh and the total energy consumption per square meter 74 kWh/m^2. The simulated energy consumption does not take into consideration the air gaps or the thermal bridges or some other heat leakages through the façade systems. The surveyed energy use intensities in the existing school buildings range from 25 to 50 kWh/m^2. Therefore, it was found that the building is relatively inefficient in the overall energy consumption, when compared to buildings of the same vintage.

The façade modifications that include exterior wall replacements and insulation upgrade affect the building's total energy consumption by maximum 42% in a single-skin building typology and 25% in a double-skin typology. Also, the high-efficiency glazed system within building façades could reduce the energy consumption by 12.4% and 19% in a single-skin building and double-skin building typologies, respectively. Illumination levels are highly enhanced with a proper design for the façade openings. However, the thermal analysis results are not highly accurate for rigorous quantitative analysis of a detailed building assessment and are accounted for further calibration values using building energy meters.

All the previously indicated percentages of reduction are expressed as a function of the total heating/cooling-related energy consumption in the building, which is considered two-thirds of the total energy, and the other one-third energy consumption is not affected by the façade retrofit, but, affected by the internal loads, which are mainly not affected by the façade alteration. However, if all other loads are encountered for in the analysis, then the total savings compute 28.9% of that universe. It also seems a challenging task to achieve the remaining energy reduction toward net zero energy (NZE) in this particular existing building.

Further exploration should consider other retrofit aspects such as lighting and mechanical retrofit. This study should contribute to the emerging literature on retrofitting investments by proposing a guideline approach to façade retrofits and implementing an integrated analytic framework to examine different façade retrofit typologies and reach an effective building performance-related decision. This participates in creating retrofit decision framework to integrate the façade performance dimension and support decision-making.

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