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Mitigating Energy Consumption of Educational Buildings Using a Novel Simulation Method (Case Study: Faculty of Oil and Petrochemical Engineering, Razi University, Iran)

Soheil Fathi [a], Abbas Mahravan [b*]

[a] *Department of Architecture, Faculty of Architecture and Urbanism, Art University of Isfahan, Isfahan, Iran.*
[b] *Department of Architectural Engineering, Faculty of Engineering, Razi University, Kermanshah, Iran.*

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ABSTRACT

In many middle- and high-income countries, existing buildings will occupy the majority of building areas by 2050 and measures are needed to upgrade the mentioned buildings for a sustainable transition. This research proposes a method to mitigate the energy consumption of existing educational buildings using four energy efficiency measures (EEMs). The proposed method divides simulations into two main parts: simulations with and without using heating, ventilating, and air conditioning (HVAC) systems. Four passive EEMs are used, including window replacement, proposed shading devices, new insulations, and installing a new partition wall for the entrance part of the building. This research uses a simulation-based method to examine the effect of each EEM on the energy consumption of the building using DesignBuilder software. The steps of data collection and modeling in this research include collecting raw data related to the physical characteristics of the building experimentally and creating a basic model. Afterwards, simulation scenarios were defined based on the proposed method, and several simulations were carried out to examine the impact of each EEM on the energy performance of the building. Two environmental parameters of the simulation process, including indoor air temperature (IAT) and relative humidity (RH), were used. The measures reduced the heating and cooling demands in the building by 80.14 % and 15.70 %, respectively. Moreover, the results indicated that the total energy consumption of the building were reduced by 10.44 % after retrofitting measures.

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1. INTRODUCTION

Over the past decades, global energy demand has increased significantly and caused numerous problems, such as global warming escalation, air pollution, and other environmental disasters. Moreover, non-renewable energy sources are not permanent, and it is necessary to find ways to reduce the increasing global energy demand and greenhouse gases emisions (Abu-hamdeh et al., 2022; Alah Rezazadeh et al., 2014; Chien et al., 2021). Buildings consume nearly 40 % of the total energy consumption in Iran (Bagheri et al., 2013). Iran is a developing country whose energy demand will increase on average by 2.80 % annually (Moshiri et al., 2012). It is essential to reduce the energy consumption of buildings as much as possible to mitigate this annual growth. Accordingly, it is necessary to find various solutions to impede the growth of energy demand in developing countries like Iran. This research offers a new energy retrofitting method to reduce the energy consumption of educational buildings.

Energy retrofitting, defined as upgrading a building's components (Ahmed & Asif, 2020; Jafari & Valentin, 2017; Ahmed & Asif, 2021), can reduce the energy consumption of a building. It is able to positively affect the energy consumption of building stocks on an urban scale (Ascione et al., 2021; Dall'O' et al., 2012; Hirvonen et al., 2021; Magnani et al., 2020; Mata et al., 2018; Ozarisoy & Altan, 2021; Torabi Moghadam & Lombardi, 2019; Wang & Holmberg, 2015). Previous research works have offered various Energy Efficiency Measures (EEMs) on a building scale and indicated energy, cost, and carbon reduction of EEMs in their research works (Dabaieh & Elbably, 2015; Kadrić et al., 2022; Mejjaouli & Alzahrani, 2020; Rabani et al., 2020; Thomsen et al., 2016). Ahmed and Asif (Ahmed & Asif, 2020) investigated the techno-economic feasibility of retrofitting existing buildings in Saudi Arabia using two case studies (a villa and an apartment). They used eight various EEMs at three levels, including low-cost (minor retrofit), medium-cost (major retrofit), and high-cost measures (deep retrofit). Their research indicated that deep retrofit measures reduced the annual energy consumption in the villa and apartment buildings by 56.90 % and 58.50 %, respectively. Besides, the amount of CO_2 emission was reduced up to 56.90 % in the

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*Corresponding Author's Email: a.mahravan@razi.ac.ir (A. Mahravan)
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villa and 58.54 % in the apartment building. Moreover, they indicated that the deep retrofit measures would pay back the initial investment in 25.15 years for villa buildings and 24.60 years for the apartment building.

Furthermore, several previous studies have focused on the effect of EEMs on the energy consumption of various building types (Ascione et al., 2017; Huang et al., 2013; Piccardo et al., 2020; Urbikain, 2020; Zhou et al., 2016). Song, Ye, Li, Wang and Ma (Song et al., 2017) used various EEMs, including EEMs in exterior walls, infiltration rate, and shading coefficient in a 10-story office building. Results of this research demonstrated that EEMs could reduce the cooling demand of the building by 16.47 %. El-Darwish and Gomaa (El-Darwish & Gomaa, 2017) proposed a retrofit strategy to improve the energy performance of higher educational buildings in Egypt. This study used various EEMs including insulation and thermal bridge, airtightness and infiltration, window glazing, and solar shading. Moreover, they used a simulation-based method and indicated that these EEMs could reduce the energy consumption of a building by 33 %. Li, Zhang, Zhang, and Wu (Li et al., 2021) used a simulation-based approach to evaluate the effect of various EEMs on energy performance and environmental comfort level of occupants in a school building in China. They focused on external wall insulation, roof insulation, windows solar heat gain coefficient (SHGC), and window-to-wall ratio (WWR). As demonstrated by the research results, EEMs reduced energy consumption by 4 % and improved the environmental comfort level of occupants, too.

Previous research works have assessed the effect of various EEMs on the energy consumption of educational buildings in Iran. Tahsildoost and Zomorodian (Tahsildoost & Zomorodian, 2015) used an energy retrofit procedure to reduce the energy consumption of two schools in Iran. They employed various retrofitting techniques, including infiltration reduction, building envelope thermal improvement, building energy management system (BEMS), mechanical, electrical, and plumbing services (MEP) renovation/overhaul, and solar energy utilization. Their research indicated that the energy consumption was reduced up by 38.29 % and 29.87 % in old and new cases. Moreover, they compared the cost of energy retrofit actions and showed payback analysis for both cases in three categories (low, medium, and high-cost). Their results demonstrated that the low-cost measures had the longest down payback time (PBT) in the old school, while the medium-cost retrofit actions had the shortest PBT in the new school.

Zomorodian and Nasrollahi (Zomorodian & Nasrollahi, 2013) used various EEMs to improve the energy performance and thermal comfort in a typical school building in Iran. They used multiple EEMs, including orientation, WWR, space organization, sun shading, and building shape. Results of their research demonstrated that using the mentioned EEMs could reduce the energy consumption of the building by 31 % while maintaining the visual and thermal comfort levels of occupants. Pazouki, Rezaie and Bozorgi-Amiri (Pazouki et al., 2021) employed a multi-objective optimization method to evaluate the effect of various EEMs on the energy consumption of a university building in Iran. They applied multiple EEMs including retrofitting lighting systems, windows, roof insulation, wall insulation, and PV system. As indicated by the results, using the latter EEMs reduced the energy consumption of the building by 40 %.

Besides, the effect of user behavior and different behavioral patterns during the retrofit design procedures was assessed in previous research works (Gui et al., 2021; Lu et al., 2021). Jami, Forouzandeh, Zomorodian, Tahsildoost and Khoshbakht (Jami et al., 2021) utilized an integrated method (field measurements, questionnaire survey, and simulation) to assess the behavioral patterns of occupants during the retrofitting procedure of two dormitory buildings in Iran. Their research showed that energy conservation measures (ECM) could reduce buildings' energy consumption in energy spender, conventional, and austerity occupant energy behavior (OEB) models by about 32 %, 56 %, and 60 %, respectively.

Furthermore, previous research works illustrated the impact of EEMs on indoor environmental quality (IEQ) of various building types (Heidari et al., 2021; Liu et al., 2015; Maleki & Dehghan, 2021). Pungercar, Zhan, Xiao, Musso, Dinkel and Pflug (Pungercar et al., 2021) utilized various EEMs using prefabricated elements to improve the IEQ of a residential building in Germany. They replaced windows, installed insulation for exterior walls, installed covers for interior openings, and installed covers for ventilation units and exterior finishing. Their retrofitting plan reduced the heating demand of the building by 77 %, increased CO_2 concentration, reduced relative humidity (RH), and increased indoor air temperature (IAT). Alazazmeh and Asif (Alazazmeh & Asif, 2021) used ten different EEMs to improve the energy performance and IEQ in a commercial building. Their research indicated that application of various EEMs could decrease energy consumption by 39 %, improve IEQ, including thermal comfort, illumination, and noise control, and reduce air pollution.

Previous studies used various EEMs, including passive, active, and mixed measures (Amani & Reza Soroush, 2021; Dabaieh et al., 2016; Huang et al., 2020; Lolli et al., 2019; Qu et al., 2021; Sun et al., 2021; Wang et al., 2021; Yang et al., 2021). Serrano-Jiménez, Lizana, Molina-Huelva and Barrios-Padura (Serrano-Jiménez et al., 2019) introduced a new procedure for the decision-making process, which evaluated the profitability of various EEMs using parametric analysis. They employed four scenarios according to operating conditions and fixed parameters (Scenario 1), the highest energy consumption pattern (Scenario 2), the medium energy consumption pattern (Scenario 3), and the lowest energy consumption pattern (Scenario 4). Moreover, they used three groups of EEMs, including passive, active, and mixed measures. Their research showed that energy-saving potential ranged from 20 to 80 % using various measures. In addition, the results indicated that each EEM must be thoroughly analyzed so that each energy consumption pattern could reach high cost-effectiveness.

According to these previous research works, energy retrofitting has positive effects on the energy performance of educational buildings. Moreover, it is possible to reduce energy consumption and improve the IEQ of the mentioned buildings simultaneously. In addition, use of both active and passive EEMs contributes to upgrading the energy performance of the existing buildings. Table 1 shows EEMs, research methods, and simulation software used in previous studies.

These previous studies indicate that it is important to use passive EEMs to reduce the energy consumption of educational buildings. One of the main questions is: How is it possible to use computer simulations to select passive EEMs to optimize the energy consumption of educational buildings? Accordingly, this research attempts to improve the energy consumption of educational buildings using passive EEMs via computer simulations. This study introduces a new method, focusing on upgrading the energy performance of an existing faculty building on campus using a novel simulation process. Various research methods can be utilized based on the function of the proposed method via computer simulations. This simulation process can be used in future studies that use passive EEMs in educational buildings.

Table 1. Previous studies with various EEMs, research methods, and simulation software

Author	Climate region	EEM	Method	Simulation software
(Tahsildoost & Zomorodian, 2015)	Tehran	Thermal insulation	Simulation-based	DesignBuilder
		BEMS		
		Window replacement		
		External shading		
		MEP		
		PV panel		
(El-Darwish & Gomaa, 2017)	Tanta	Insulation	Simulation-based	DesignBuilder
		Infiltration		
		Window glazing		
		Shading		
(Pazouki et al., 2021)	Tehran	Lighting system	Simulation-based	DesignBuilder
		Windows		
		Roof insulation		
		Wall insulation		
		PV		
(Lu et al., 2021)	Singapore	Heating, ventilating, and air conditioning (HVAC)	Simulation-based	IES-EV
		Lighting system		
		Equipment		
		Wall insulation		
		Green roof		
		Occupant's behavior		
(Ascione et al., 2017)	Benevento	Special plasters	Simulation-based	DesignBuilder
		Innovative coatings		
		Thermal insulation		
		Thermal mass		
		New windows		
		Solar screen		
		HVAC		
		PV		
(Li et al., 2021)	Wuhan	External wall	Simulation-based	DesignBuilder
		Roof insulation		
		SHGC of windows		
		WWR		
(Zomorodian & Nasrollahi, 2013)	Shiraz	Orientation	Simulation-based	DesignBuilder
		WWR		
		Space organization		
		Shading		
		Building shape		

2. Methodology

This research investigates the effect of various passive EEMs on the energy consumption of an educational building in Iran. The main difference between this research and other similar research works is that this research introduces a new simulation method to select passive EEMs. The overall research process includes five main steps, shown in Figure 1.

2.1. Data collection

This research uses existing data on an educational building during the research process. This building is a large-scale building with a 5056 m^2 floor area and is located on the University Campus of Razi University, Iran (Figure 2). Figure 3, Figure 4, and Figure 5 show the architectural plans of the building, including the ground floor, first floor, and second-floor plans. This building is oriented at 10 degrees to the West and has a north-south slope. In the first part of this research, experimental data and physical characteristics of the building are collected. The experimental data are collected from various sources, including the number of people, working hours, domestic hot water (DHW), HVAC type, etc. Moreover, the physical characteristics data of the building are collected from the as-built maps and catalogs (windows, building materials, etc.).

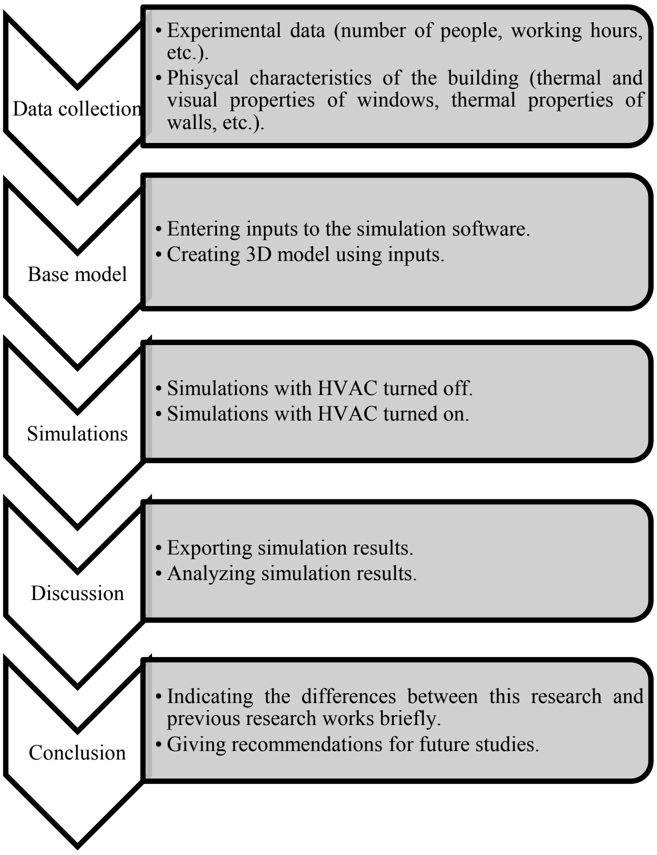

Figure 1. Overall research process

Figure 2. Faculty of oil and petrochemical building at Razi University: (a) Site plan view from Google Earth; (b) Perspective view of the building (from the southwest part of the site)

2.2. Base model

In the second step, inputs are added to the simulation software. Table 2 shows the added inputs in the simulation software. This research uses DesignBuilder as the simulation software. In addition, DesignBuilder uses the EnergyPlus simulation engine to run energy simulations. Besides, at the end of this step, a 3D model is created in the simulation software. Figure 6 represents a perspective view of the base model in the DesignBuilder software.

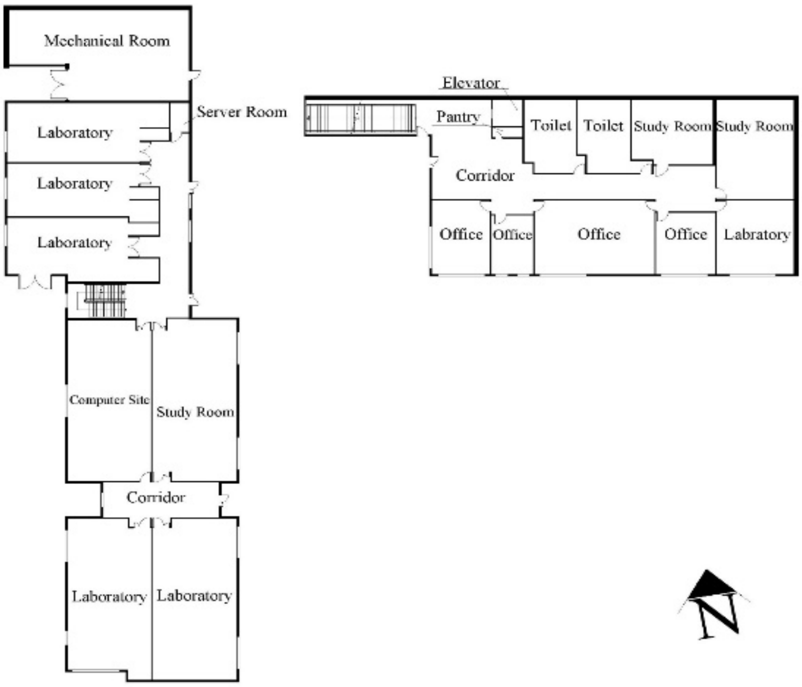

Figure 3. Ground floor plan of the building

Figure 4. First-floor plan of the building

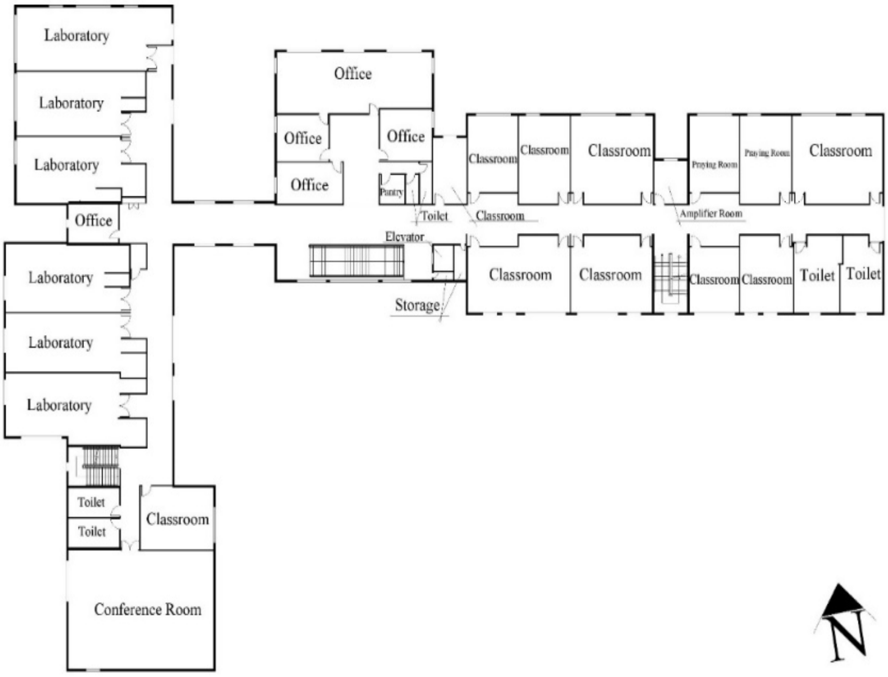

Figure 5. Second-floor plan of the building

Table 2. Inputs of the base model

No.	Design parameter	Value
1	Heating setpoint (°C)	25
2	Cooling setpoint (°C)	25
3	Natural ventilation set point (°C)(HVAC turned off)	21

4	Minimum fresh air (L/s per person)	7.50
		10 (laboratories)
		25 (Toilets, corridors)
5	Computers (W)	26332
6	Office equipment (monitor, printer, and projector) (W)	5844
7	Miscellaneous (W)	110700
8	Lighting (W)	39012
9	Glazing type	Double-glazed/3mm/10mm Air
10	T_{vis}	0.812
11	SHGC	0.763
12	U-value ($W/m^2.K$)	2.816
13	Above ground WWR (%)	15.57
14	HVAC type	VAV, Water-cooled Chiller (Airwasher)
15	Fuel	Electricity, Natural Gas
16	Maximum supply air temperature (°C)	66.50
17	Minimum supply air temperature (°C)	8.50

Figure 6. View of the base model of the building in the simulation software

2.3. Simulation

In this step, several simulations are performed to assess the effect of passive EEMs on the energy performance of the building. The main difference between this research and previous studies is that it uses a novel simulation method to evaluate the effect of passive EEMs on the energy performance of the building. The novelty of the simulation process is that it uses two different simulation types including simulations without using the HVAC systems and simulations using the HVAC systems. This research uses four EEMs: including window shading, insulation, replacing windows, and adding a partition to the entrance part of the building. This building has double-pane clear windows filled with air insulation. The existing type of window is replaced with a double-pane green window type. Besides, the glass thickness is changed from 3 mm to 4 mm. The insulation type is changed from air to argon gas.

Table 3 shows the thermal and visual characteristics of the traditional window and other available types of windows. The data are collected from the window manufacturer's company catalog (www.kosarwin.ir). As shown in Table 3, the selected window type has an ideal U-value (2.594 ($W/m^2.K$)) and has the highest visual transmittance (Tvis) value (68 %). Therefore, it can provide an appropriate view to the outdoor environment better than other window types, and it can impede heat transfer as low as windows with blue, bronze, and grey colors. In addition, the color of the northern windows of the building will not change (double-pane, clear, 4mm, argon, 10 mm) since there is no direct solar radiation on these windows.

Table 3. Thermal and visual properties of different window types (Reference: www.kosarwin.ir)

Window type (panes, color, glass thickness, insulation type, and insulation thickness)	U-value ($W/m^2.K$)	SHGC	T_{vis}
Double-pane, clear, 3 mm, air, 10 mm	2.816	0.763	0.812
Double-pane, blue, 4 mm, argon, 10 mm	2.594	0.450	0.326
Double-pane, bronze, 4 mm, argon, 10 mm	2.594	0.584	0.471
Double-pane, green, 4 mm, argon, 10 mm	2.594	0.574	0.680
Double-pane, grey, 4 mm, argon, 10 mm	2.594	0.567	0.375
Double-pane, tinted, 4 mm, argon, 10 mm	2.600	0.516	0.395

The base model uses the physical characteristics data of the existing building for the initial simulation. The mentioned data indicate the existing layers of walls, floors, and roof of the building. Since the main objective of this research is to reduce the energy consumption of the building, it is necessary to reduce heat transfer as much as possible in this section. Table 4 shows the physical characteristics of the walls, floors, and roof of the building before and after the retrofitting process. As shown in the proposed scenarios, the interior walls and the ground floor remain unchanged, and the exterior walls, roof, and floors are upgraded. The prefabricated 3D panels are added to each exterior wall to stabilize IAT as much as possible. In addition, an expanded polystyrene (EPS) insulation layer is used in the outer part of the roof to avoid absorbing solar radiation as much as possible. Moreover, the EPS insulation layers are used on the internal floors to prevent heat transfer as much as possible.

Table 4. Physical characteristics of the building before and after the energy retrofitting process

Building component	**Layers**		**U-value (W/m^2.K)**	
	Before	**After**	**Before**	**After**
External wall	Brick (outermost) 30 mm, Mortar 30 mm, Brick 210 mm, Plaster (dense) 30 mm, Plaster (lightweight) 20 mm (innermost layer)	Brick (outermost) 30 mm, Mortar 30 mm, Brick 210 mm, Plaster (lightweight) 10 mm, EPS Expanded Polystyrene 50 mm, Plywood Coating 5 mm	1.251	0.556
Roof	Asphalt-reflective coating (outermost) 40 mm, Mortar 30 mm, Concrete (cells empty) 80 mm, Cast concrete 310 mm, Plaster (dense) 30 mm, Plaster (lightweight) 10 mm	Asphalt-reflective coating (outermost) 40 mm, Mortar 30 mm, EPS Expanded Polystyrene 100 mm, Mortar 30 mm, Concrete (cells empty) 100 mm, Cast concrete 310 mm, Plaster (dense) 30 mm, Plaster (lightweight) 10 mm	1.592	0.350
Internal floors	Plaster (lightweight) 10 mm, Plaster (dense) 30 mm, Cast concrete 310 mm, Concrete (cells empty) 50 mm, Mortar 50 mm, Ceramic 10 mm	Plaster (lightweight) 10 mm, Plaster (dense) 30 mm, Cast concrete 310 mm, Concrete (cells empty) 100 mm, Mortar 50 mm, EPS Expanded Polystyrene 100 mm, Mortar 30 mm, Ceramic 10 mm	1.377	0.335
Internal walls	Plaster (lightweight) 10 mm, Plaster (dense) 30 mm, Brick 210 mm, Plaster (dense) 30 mm, Plaster (lightweight) 10 mm	Not changed	1.444	1.444
Ground floor	Mortar (outermost) 10 mm, Marble stone 250 mm, Mortar 30 mm, Asphalt 30 mm, Mortar 150 mm, Concrete (cells empty) 100 mm, Mortar 150 mm, Ceramic 20 mm	Not changed	1.244	1.244

This research proposes an innovative method for using external window shadings. A fixed overhang is employed for the southern windows of the building (Figure 7). The fixed overhang is utilized in an innovative method in this building. The computer simulations are performed annually, and it is possible to export daily simulation results from the simulation software. Therefore, daily simulations are carried out in this research to find the maximum IAT on the building scale. The maximum IAT was 36.38 °C on August 2. Accordingly, the solar radiation angle can be identified on this day using the Grasshopper plugin, which gives the monthly, daily, and hourly solar radiation angles of the climate region (Kermanshah). Accordingly, the highest solar radiation angle is 72.22° at 12 PM. (on August 2). This research uses the mentioned angle to find the depth of the fixed overhangs. The depth of the fixed overhangs can be calculated using Eq. (1) and Eq. (2), where (b) is the angle between the solar radiation and the exterior part of the window, (a) is the solar radiation angle (altitude of the climate region), (h) is the height of the window, and (x) is the depth of the overhang.

$$\mathrm{b} = 90 - \mathrm{a} \tag{1}$$

$$\mathrm{x} = \tan \mathrm{b} \times \mathrm{h} \tag{2}$$

Figure 8 shows the innovative fixed louver system proposed for the eastern and western windows of the building. The mentioned louvers can impede overheating in the mornings and afternoons. Figure 9 shows pictures of the proposed louver system. The louvered canopy has already been used for the east-facing windows of the faculty of electrical and computer engineering at Razi University. This research uses a fixed louver system for the east and west-facing windows. The east-facing windows receive solar radiation in the beginning hours, and the west-facing windows receive solar radiation until the last hours of the day.

This research proposes a method to find the distance between the louver blades for the east-facing and the west-facing windows. The installed blades can reduce the direct solar absorption as much as possible. The solar radiation angle is 28.72° at 8:00 AM, and the solar radiation angle is 27.69° at 5:00 PM. Accordingly, the distance between the louver blades can be calculated using Eq. (3), where (b) is the solar radiation angle, (a) is the depth of the louver blades, and (h) is the distance between the louver blades.

$$\mathrm{h} = \tan \mathrm{b} \times \mathrm{a} \tag{3}$$

The entrance part of this building is located in the northern part of the building. This entrance is open in cold seasons, and cold air enters the building in winters. Accordingly, the entrance space is separated from other zones using an internal partition. Figure 10 shows the first-floor plan of the building with the proposed partition wall in the entrance part. The partition wall is made of the double-glazed glass and consists of an automatic door that prevents heat transfer between the inside and outside of the building.

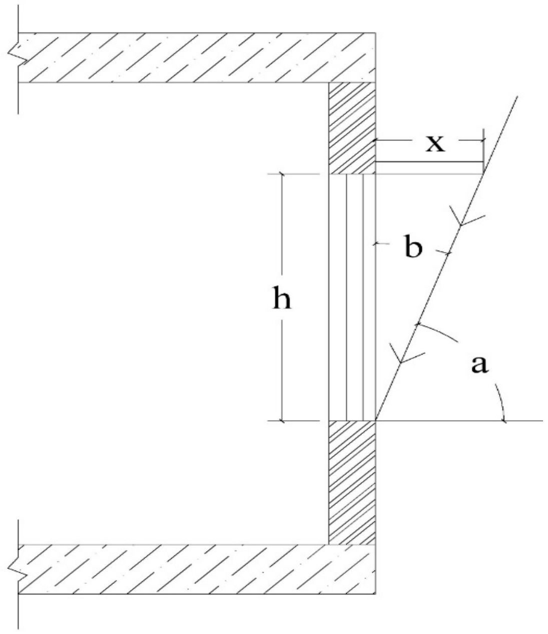

Figure 7. Section of a southern window with a fixed overhang

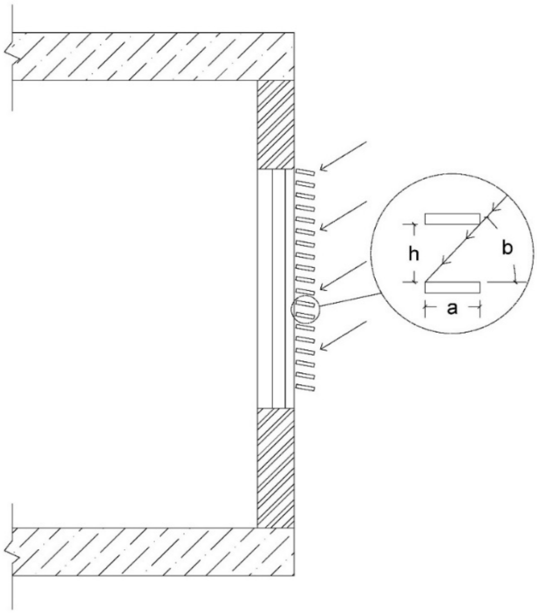

Figure 8. Section of east-facing and west-facing windows using the proposed fixed louver system

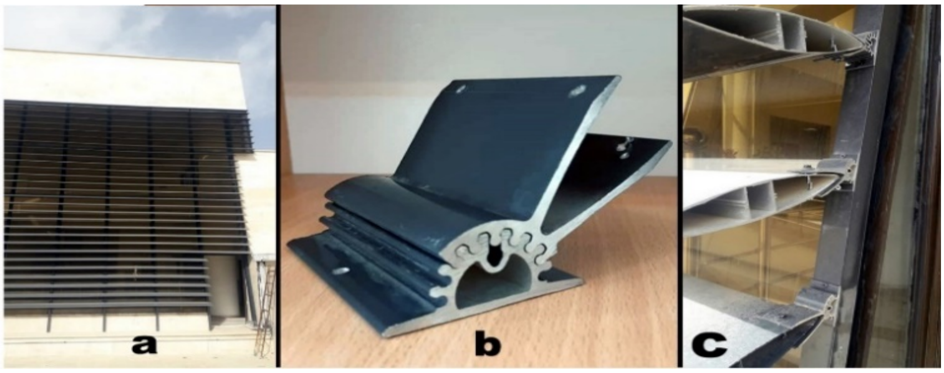

Figure 9. The proposed louver system: (a) front view; (b) the fixed support of the louver blades; (c) details of the connection between the fixed supports and louvers

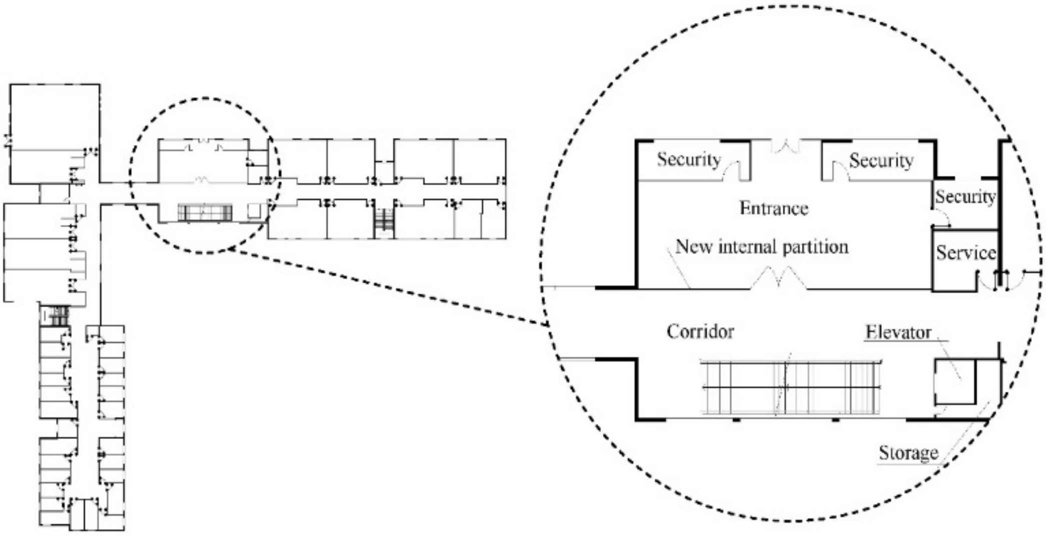

Figure 10. First-floor plan of the building and its entrance space

2.3.1. Simulations without using the HVAC systems

In the first part of the simulation process, several simulations assess the effect of EEMs on the energy consumption of the building. The simulations without using the HVAC systems indicate two environmental parameters, including IAT and RH of the building. These parameters are used to compare the comfort conditions of occupants in the building. In addition, the simulations are performed with natural ventilation in each zone. The setpoint for the natural ventilation is 21 °C and is added according to the comfort range of the site (Kermanshah).

2.3.2. Simulations using the HVAC systems

The second part of the simulation process includes several simulations using the HVAC systems in the building. These simulations compare new IAT and RH values with the previous ones. Moreover, the natural ventilation is turned off in these simulations since the windows are closed according to the behavioral patterns of the current occupants. Therefore, these simulations prove the energy-saving potential of each EEM and compare the IAT and RH values with previous values.

3. RESULTS AND DISCUSSION

Simulation results are divided into two main parts: the results without using the HVAC systems and the results using the HVAC systems. These simulations are performed with passive EEMs, including window replacement, shading devices, insulation, and addition of a new partition to the entrance part of the building. Accordingly, six different scenarios are defined for the simulation process (Table 5).

Table 5. Different scenarios used in the simulation process

Scenario	EEM(s)
1	-
2	Window replacement
3	Shading devices
4	Insulation
5	New partition for the entrance
6	Window replacement, Shading devices, Insulation, and New partition for the entrance

3.1. Simulations without using the HVAC systems

The first part of the simulation process consists of six separate simulations. These simulations without using the HVAC systems indicate IAT and RH values on a building scale. Accordingly, it is possible to identify the hottest and coldest days without using the HVAC systems. Therefore, daily simulations were performed to find the minimum and maximum IAT and RH values. The daily simulation results were added to an EXCEL file, and the IAT and RH values were identified in each scenario. According to these results, the hottest day is August 2 when the IAT of the building is 36.38 °C. Also, the coldest day is February 3 when the IAT is 12.17 °C. Accordingly, these passive EEMs were defined to reduce the heating and cooling demands of the building using these simulation results. For instance, the shading devices were designed according to the solar altitude on the hottest day (August 2).

3.2. Simulations using the HVAC systems

After performing the simulations without using the HVAC systems, various simulations using the HVAC systems were conducted that indicate the effect of each scenario on the energy performance of the building. These simulations showed the impact of each EEM on the heating and cooling demands of the building. Moreover, these simulations specify the IAT and RH values in different scenarios. Firstly, daily simulation results compare the minimum, maximum, and mean IAT and RH values.

Tables 6 and 7 show the minimum, maximum, and mean IAT and RH values in each scenario. As shown in Table 6, the mean monthly IAT values in Scenario 6 have changed considerably. In the cold season, from October to April, the IAT values increased. Moreover, the IAT values in the warm season, from May to September, increased slightly. The main reason is that these EEMs trap internal heat. Figure 11 shows the monthly IAT changes when the HVAC systems are turned off (simulations without using the HVAC systems). Since this building is in a heating dominant climate, these EEMs should increase the building IAT in the cold season. According to Figure 11, the minimum monthly IAT increased by 5.29 °C in December. Also, the maximum monthly IAT increased up to 3.11 °C in January. In addition, the average monthly IAT increased up to 3.87 °C in January. These results indicate that these passive EEMs could increase the IAT of the building remarkably. On the other hand, the maximum monthly IAT was reduced by 0.09 °C in July, which indicated the positive effect of using the EEMs in warm seasons.

Table 6. The minimum, maximum, and mean IAT values in each scenario

			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Scenario 1	HVAC Off	Mean IAT	15.39	15.96	18.31	22.71	26.83	31.92	34.84	34.79	31.13	24.87	20.11	16.02
	HVAC On		19.18	19.39	20.02	22.59	24.43	26.12	26.54	26.54	25.73	23.18	20.82	19.48
Scenario 2	HVAC Off		15.13	15.66	17.98	22.40	26.53	31.62	34.52	34.53	30.90	24.79	20.04	15.80
	HVAC On		19.10	19.28	19.86	22.37	24.25	26.03	26.49	26.48	25.63	22.97	20.63	19.09
Scenario 3	HVAC Off		15.05	15.51	17.74	22.06	26.08	31.18	34.04	34.05	30.50	24.54	19.98	15.75
	HVAC On		19.11	19.27	19.79	22.18	24.04	25.90	26.40	26.39	25.51	22.91	20.64	19.11
Scenario 4	HVAC Off		20.02	20.28	22.07	25.38	29.06	35.14	36.39	36.72	33.84	28.44	23.94	20.52
	HVAC On		21.25	21.52	22.37	24.14	25.07	26.03	26.27	26.33	25.88	24.57	23.17	21.46
Scenario 5	HVAC Off		15.38	15.95	18.30	22.70	26.83	31.92	34.87	34.79	31.14	24.87	20.10	16.01
	HVAC On		19.18	19.40	20.02	22.59	24.43	26.11	26.54	26.54	25.73	23.18	20.83	19.18
Scenario 6	HVAC Off		19.26	19.34	20.94	24.12	27.69	32.26	34.84	35.11	32.31	27.17	23.00	19.80
	HVAC On		20.83	21.00	21.63	23.45	24.55	25.65	25.99	26.01	25.51	24.12	22.69	21.07

Table 7. The minimum, maximum, and mean RH values in each scenario

			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Scenario 1	HVAC Off	Mean RH	32.01	35.20	34.93	33.62	34.04	16.27	22.17	24.25	23.92	29.50	33.04	39.64
	HVAC On		25.47	29.08	32.28	34.03	36.90	19.22	28.50	29.88	28.59	31.59	32.50	32.99
Scenario 2	HVAC Off		32.71	36.03	35.77	34.32	34.67	16.88	22.82	24.94	24.53	30.17	33.69	40.40
	HVAC On		25.70	29.40	32.66	34.68	37.17	19.38	28.68	30.08	28.97	32.20	33.01	33.30
Scenario 3	HVAC Off		32.90	36.41	36.54	35.08	35.68	17.74	23.82	24.16	25.25	30.46	33.86	40.62
	HVAC On		25.59	29.37	32.83	35.27	37.85	19.57	28.83	30.32	29.19	32.23	32.91	33.18
Scenario 4	HVAC Off		28.51	30.75	31.64	32.70	34.75	20.15	27.11	28.47	26.34	27.75	31.18	34.21
	HVAC On		31.46	33.13	33.74	32.93	37.00	23.84	32.60	33.30	31.34	30.85	33.11	36.62
Scenario 5	HVAC Off		32.14	35.17	34.97	33.67	34.05	16.23	22.16	24.09	23.90	29.52	33.06	39.68
	HVAC On		25.45	29.08	32.22	33.99	36.61	19.18	28.53	29.92	28.62	31.61	32.51	32.98
Scenario 5	HVAC Off		30.69	33.41	34.45	35.42	37.95	23.62	31.01	32.26	29.44	29.96	33.18	36.14
	HVAC On		32.63	34.86	36.72	36.14	40.04	25.21	34.11	35.08	33.41	32.89	35.09	37.88

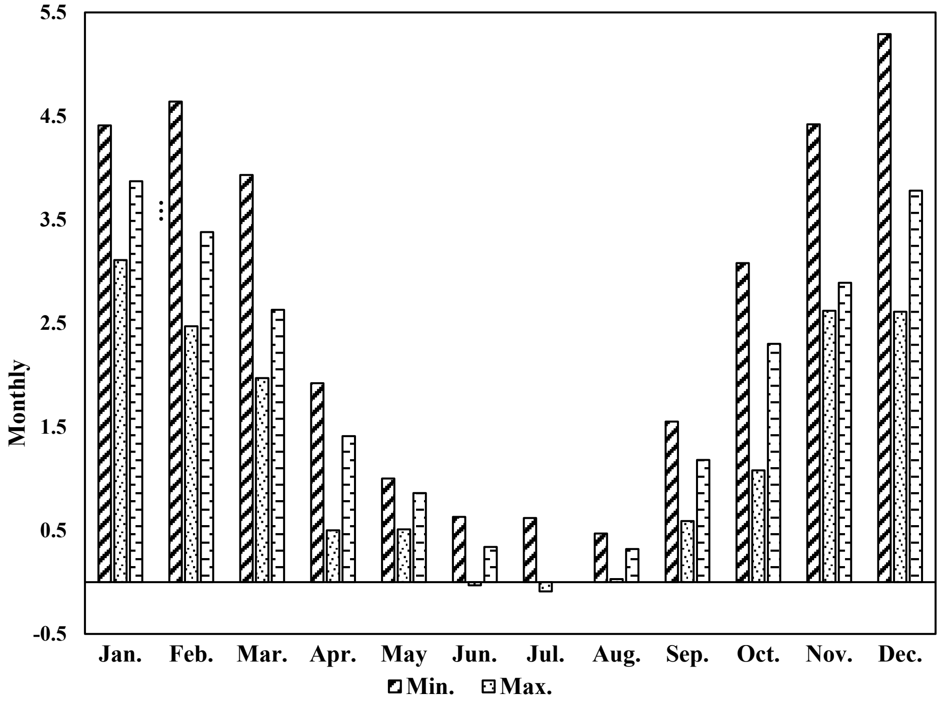

Figure 11. Monthly IAT changes of the building without using the HVAC systems

Figure 12 shows the monthly IAT changes for the building when the HVAC systems are turned on (simulations using the HVAC systems). According to Figure 12, the minimum monthly IAT increased by 5.12 °C in December. Also, the maximum monthly IAT increased up to 1.43 °C in December. Moreover, the average monthly IAT increased up to 1.89 °C in December. On the other hand, the maximum monthly IAT was reduced by about 2.17 °C in July, which indicated the positive effect of these EEMs in warm seasons. The mean monthly IAT was reduced considerably in warm seasons, from May to September, and increased remarkably in cold seasons.

Table 7 indicates the RH values before and after using the HVAC systems in the building. The mean monthly RH values increased considerably. In Scenario 6, the maximum mean RH value reached 53.22 % on November 15, which was in the acceptable thermal comfort range, according to the American Society of Heating, refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55-2010 metrics (ASHARE, 2013). Also, the average minimum monthly RH value was 25.21 % in June. Figure 13 shows the monthly RH changes for the building without using the HVAC systems. According to Figure 13, the minimum monthly RH value increased by 7.27 % in April. Also, the maximum monthly RH value increased 14.77 % in June, and the average monthly RH value increased 8.84 % in July. Furthermore, the maximum monthly RH value decreased by 6.38 % in December.

Figure 14 shows the monthly RH changes using the HVAC systems in the building. According to Figure 14, the minimum monthly RH value increased 10.27 % in June. Also, the maximum monthly RH value increased up to 6.84 % in February, and the average monthly RH value increased up to 7.16 % in January. Accordingly, the RH value for the building increased after the retrofitting process.

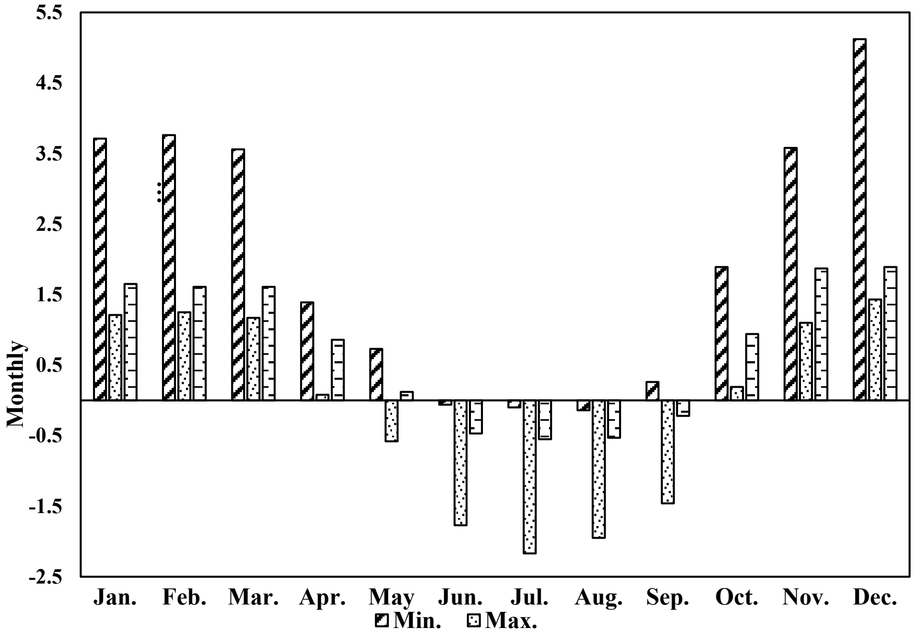

Figure 12. Monthly IAT changes for the building using the HVAC systems

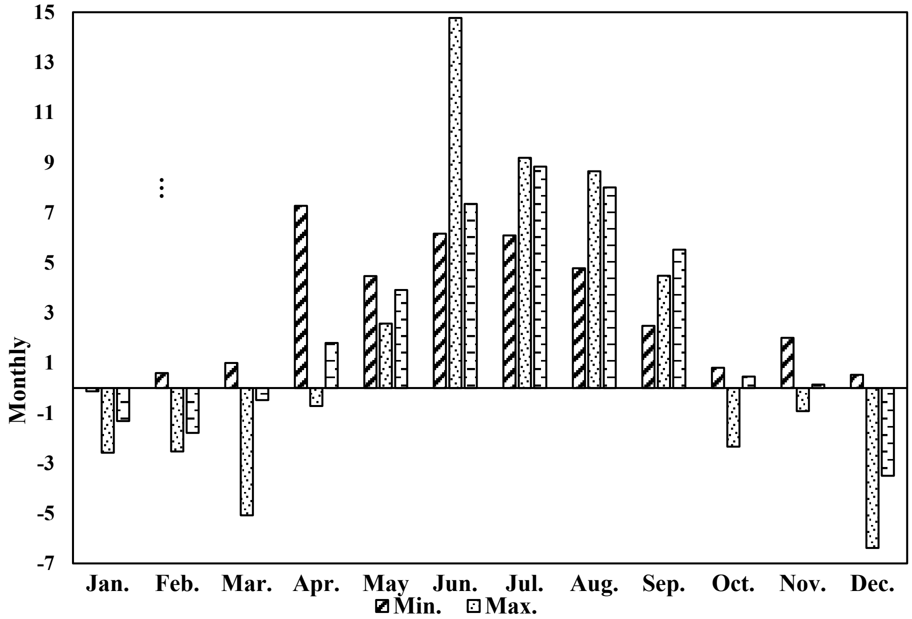

Figure 13. Monthly RH changes without using the HVAC systems

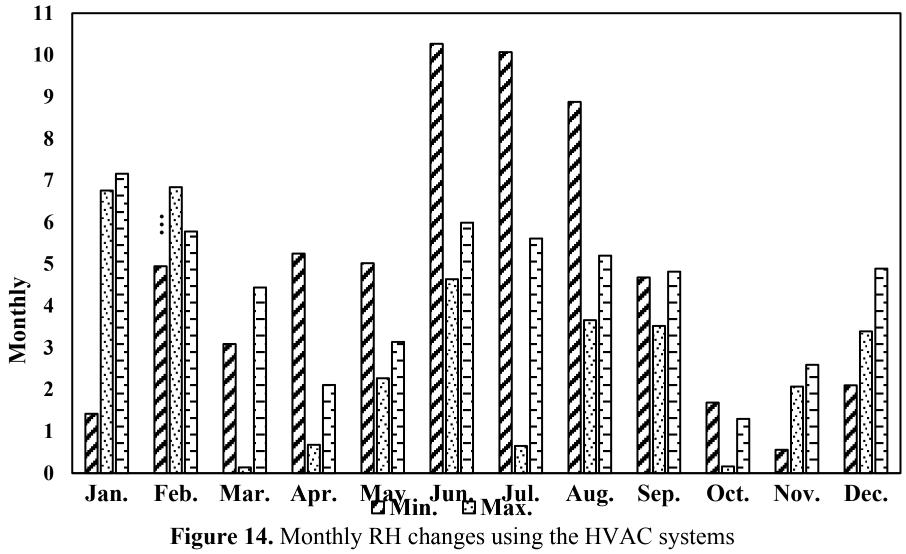

Figure 14. Monthly RH changes using the HVAC systems

Figure 15 indicates the monthly IAT of the building when the HVAC systems are turned off during the simulation process. Figure 15 represents the monthly IAT values before and after the retrofitting process. According to Figure 15, the monthly IAT of the building increased considerably in the cold seasons, and it is within the comfort range in the cold seasons. This comfort range is defined according to ASHRAE Standard 55-2010 metrics (ASHARE, 2013). The results show that the EEMs can affect the heating demand of the building positively. Furthermore, Figure 16 shows the monthly IAT of the building using the HVAC systems. According to Figure 16, the IAT increases in cold seasons, which confirms the simulation results of the previous section without using the HVAC systems.

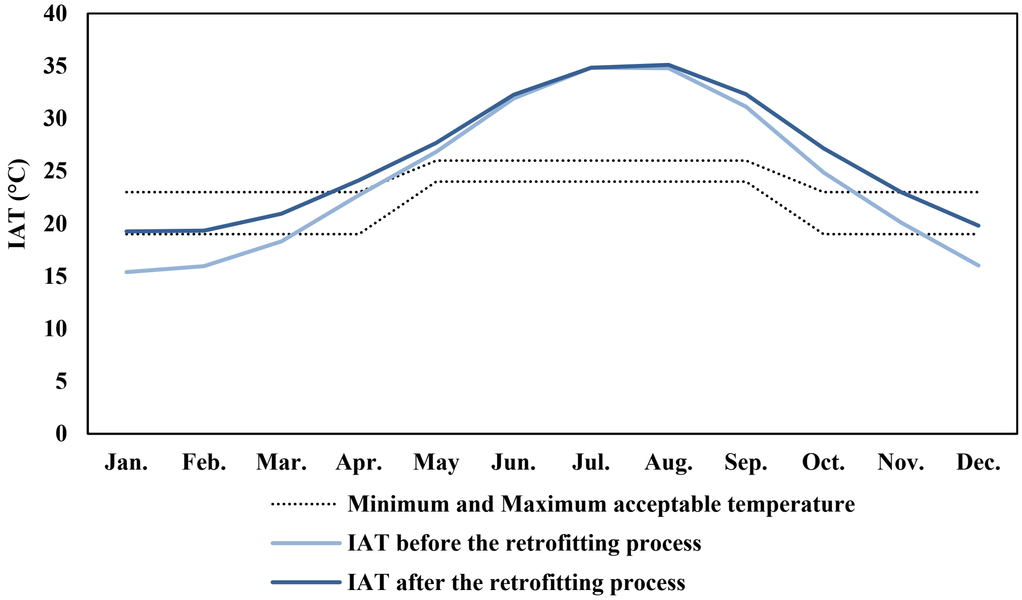

Figure 15. The monthly IAT of the building without using the HVAC systems before and after the retrofitting process

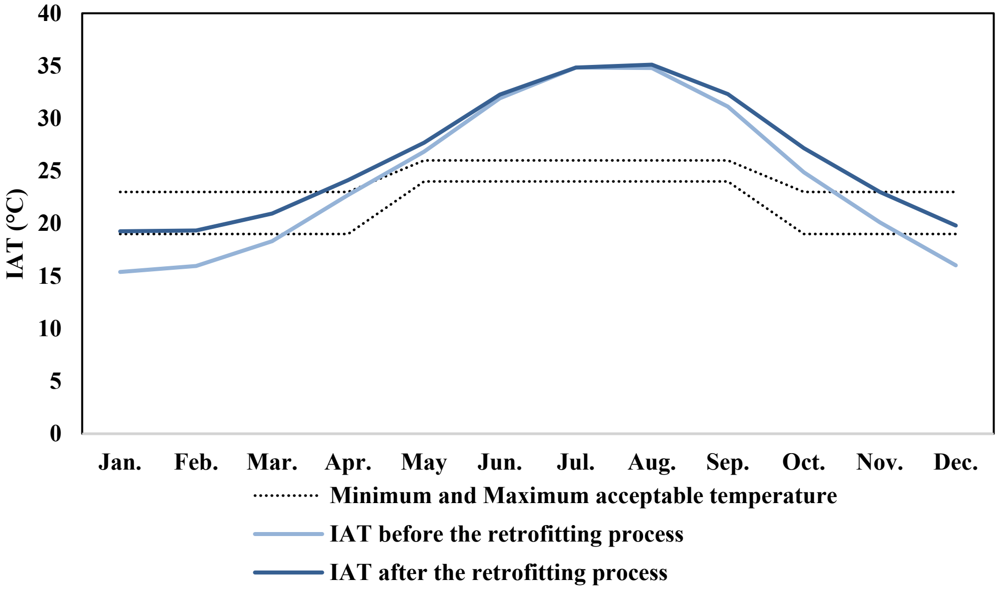

Figure 16. The monthly IAT of the building using the HVAC systems before and after the retrofitting process

Since the primary purpose of this research is to demonstrate the positive effects of passive EEMs on the energy consumption of educational buildings, this section introduces the energy-saving potential of the EEMs. This section uses simulation data of the building using the HVAC systems since the simulations without using the HVAC systems cannot show the heating and cooling demand of the building. Figure 17 shows the mentioned heating and cooling demand in each scenario. In Scenario 2, the new window type increased the heating demand by 6.51 %, while the cooling demand was reduced up to 3.42 %. In Scenario 3, the heating demand increased by 8.79 %, and the cooling demand was reduced by 7.73 % using the new shading devices.

The proposed insulations reduced the heating and cooling demand of the building by 84.52 % and 4.56 %, respectively. The main reason for this considerable reduction is that the infiltration rate of the building changed from 1 to 0.50 (ac/h) after using the new insulations. The new partition in the entrance part of the building did not affect the overall energy performance of the building, but it could increase the IAT values on a building scale. The last scenario indicates the effect of all EEMs on the energy performance of the building. These EEMs reduced the heating demand up to 80.14 % and reduced the cooling-demand up to 15.70 %.

Figure 18 shows the energy consumption of the building in each scenario. The Energy Use Intensity (EUI) of the building was 394.30 (kWh/m^2. year) before the retrofitting process. After replacing the existing windows with the proposed new windows, the building energy consumption decreased by 0.15 %. The proposed shading devices mitigated the energy consumption of the building by 0.88 %. The most effective EEM was using the new insulations, which reduced the energy consumption by 8.46 %. Also, the new partition had no considerable effect on the energy consumption of the building. The latest scenario indicated a 10.44 % reduction in energy consumption of the building. According to the simulation results of the mentioned scenario, each EEM had a positive effect during the retrofitting process of the building.

3.3. Validation

This research uses a simulation-based method during the research process. It is necessary to compare simulation results with experimental data, including electricity and natural gas bills. This research compares the simulation results with the monthly electricity bill of the building. Figure 19 shows the difference between the simulation results and the electricity bill of the building. The minimum difference between the simulation results and the monthly electricity bill of the building was 1.60 %. Moreover, the maximum difference between the simulation results and the monthly electricity bill of the building was 4.98 %.

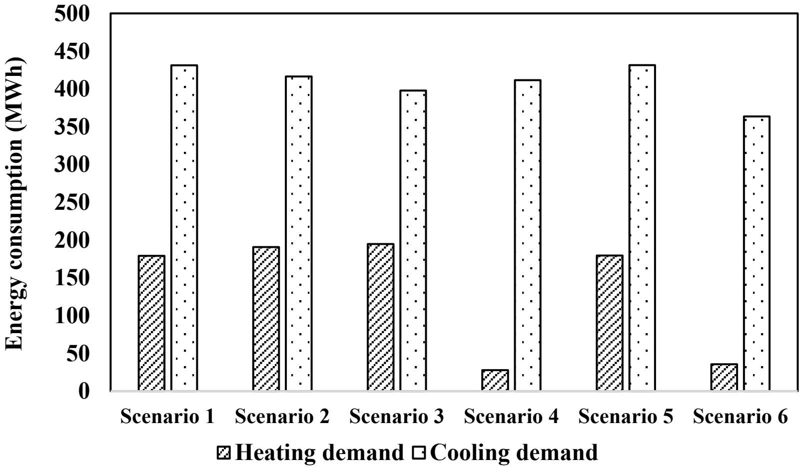

Figure 17. The heating and cooling demand of the building in each scenario

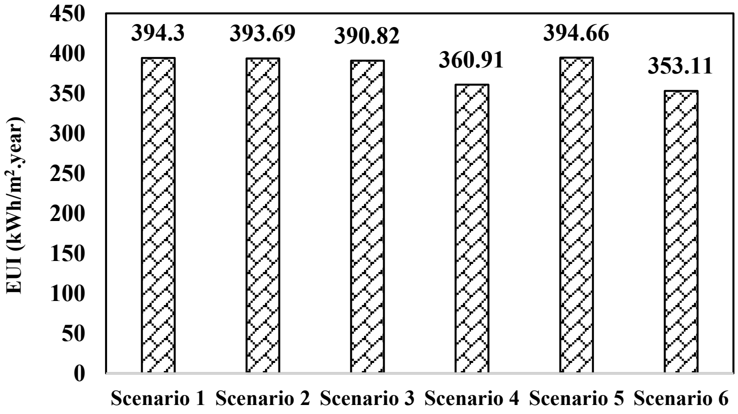

Figure 18. Energy consumption of the building in each scenario

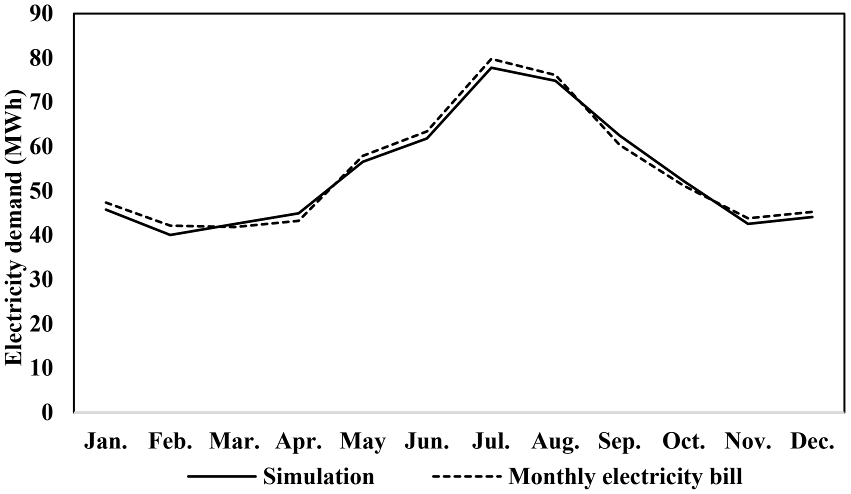

Figure 19. A comparison between the simulation results and the monthly electricity bill of the building

4. CONCLUSIONS

This research investigated the effect of various passive EEMs on the energy performance of an existing educational building. A new simulation method was introduced that divided the simulations into two main parts. This new method consisted of simulations without using the HVAC systems and simulations using the HVAC systems. Simulations without using the HVAC systems gave an overview of the current IAT and RH values for the building. This initial step was taken to offer some passive EEMs to enhance the IAT of the studied building, located in a heating-dominated region. Since the main focus of this research was to reduce the energy consumption of the building, the positive effects of these EEMs on the cooling demand of the building were identified, too.

This research used a simulation-based method to examine the effect of each EEM and the total effect of using the integrated retrofitting EEMs on the building energy efficiency. The data collection and modeling in this research include collecting raw data related to the physical characteristics of the building experimentally and creating a basic model in DesignBuilder software by entering the mentioned data and the official climate information. The next step included examining the impacts of the proposed EEMs on the energy consumption of the building by performing several simulations using the proposed simulation method. The latest stage of the research included comparing the energy performance of the building in each scenario by analyzing the simulation results. The results confirmed that the use of the proposed integrated retrofitting EEMs could contribute to mitigating the heating and cooling energy demands of the building. The results showed that the building heating demand was reduced up to 80.14 %, like the results of the previous research obtained in (Pungercar et al., 2021). In addition, using the EEMs reduced 15.70 % of the building cooling demand, which is in line with the results of the previous research in (Song et al., 2017). The final simulation illustrated that using the EEMs reduced 10.44 % of the total energy demand of the building.

However, combining the proposed passive EEMs with other passive and active retrofitting measures such as using the building integrated photovoltaic system, phase change materials, solar chimney, and prefabricated hybrid passive cooling and heating systems still needs further research. This study focused on the importance of simulations without using the HVAC systems in the case study building. Then, these simulation results were compared with normal simulations using the HAVC systems in the building. Therefore, this research did not find optimal solutions for this case study building. Future studies can focus on finding optimal solutions for educational buildings and other building types using the method used in this research.

5. ACKNOWLEDGEMENT

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NOMENCLATURE

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BEMS	Building Energy Management System
CHP	Combined Heat and Power System
DHW	Domestic Hot Water
ECM	Energy Conservation Measures
EEM	Energy Efficiency Measure
EPS	Expanded Polystyrene
EUI	Energy Use Intensity (kWh/m^2.year)
HVAC	Heating, Ventilating, and Air Conditioning
IAT	Indoor Air Temperature (°C)
IEQ	Indoor Environmental Quality
MEP	Mechanical, Electrical, and Pumping Services
OEB	Occupant Energy Behavior
PBT	Payback Time
PV	Photovoltaic
RH	Relative Humidity (%)
SHGC	Solar Heat Gain Coefficient
Tvis	Visual Transmittance
VAV	Various Air Volume
WWR	Window to Wall Ratio (%)

REFERENCES

1. Abu-Hamdeh, N.H., Khoshaim, A., Alzahrani, M.A., & Hatamleh, R.I. (2022). Study of the flat plate solar collector's efficiency for sustainable and renewable energy management in a building by a phase change material: Containing paraffin-wax/graphene and paraffin-wax/graphene oxide carbon-based fluids. *Journal of Building Engineering*, *57*, 104804. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104804
2. Ahmed, W., & Asif, M. (2020). BIM-based techno-economic assessment of energy retrofitting residential buildings in hot humid climate. *Energy and Buildings*, *227*, 110406. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110406
3. Ahmed, W., & Asif, M. (2021). A critical review of energy retrofitting trends in residential buildings with particular focus on the GCC countries. *Renewable and Sustainable Energy Reviews*, *144*, 111000. https://doi.org/https://doi.org/10.1016/j.rser.2021.111000
4. Alah Rezazadeh, S., Mirzaie, I., Pourmahmoud, N., & Ahmadi, N. (2014). Three dimensional computational fluid dynamics analysis of a proton exchange membrane fuel cell. *Journal of Renewable Energy and Environment (JREE)*, *1*(1), 30-42. https://doi.org/10.30501/jree.2014.70054
5. Alazazmeh, A., & Asif, M. (2021). Commercial building retrofitting: Assessment of improvements in energy performance and indoor air quality. *Case Studies in Thermal Engineering*, *26*, 100946. https://doi.org/https://doi.org/10.1016/j.csite.2021.100946
6. Amani, N., & Reza Soroush, A.A. (2021). Energy consumption management of commercial buildings by optimizing the angle of solar panels. *Journal of Renewable Energy and Environment (JREE)*, *8*(3), 1-7. https://doi.org/10.30501/jree.2020.241836.1134
7. Ascione, F., Bianco, N., De Masi, R.F., Mauro, G.M., & Vanoli, G.P. (2017). Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance. *Energy and Buildings*, *144*, 303-319. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.03.056
8. Ascione, F., Bianco, N., Mauro, G.M., & Napolitano, D.F. (2021). Knowledge and energy retrofitting of neighborhoods and districts. A comprehensive approach coupling geographical information systems, building simulations and optimization engines. *Energy Conversion and Management*, *230*, 113786. https://doi.org/https://doi.org/10.1016/j.enconman.2020.113786
9. ASHARE. (2013). ASHRAE Standard 55-2010: Thermal environmental conditions for human occupancy. *American Society of Heating, Refrigeration and Air Conditioning Engineers, ASHRAE Sta.* https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy
10. Bagheri, F., Mokarizadeh, V., & Jabbar, M. (2013). Developing energy performance label for office buildings in Iran. *Energy and Buildings*, *61*, 116-124. https://doi.org/https://doi.org/10.1016/j.enbuild.2013.02.022
11. Chien, F., Ajaz, T., Andlib, Z., Chau, K.Y., Ahmad, P., & Sharif, A. (2021). The role of technology innovation, renewable energy and globalization in reducing environmental degradation in Pakistan: A step towards sustainable environment. *Renewable Energy*, *177*, 308-317. https://doi.org/https://doi.org/10.1016/j.renene.2021.05.101
12. Dabaieh, M., & Elbaly, A. (2015). Ventilated trombe wall as a passive solar heating and cooling retrofitting approach; A low-tech design for

off-grid settlements in semi-arid climates. *Solar Energy*, *122*, 820-833. https://doi.org/https://doi.org/10.1016/j.solener.2015.10.005

13. Dabaieh, M., Makhlouf, N.N., & Hosny, O.M. (2016). Roof top PV retrofitting: A rehabilitation assessment towards nearly zero energy buildings in remote off-grid vernacular settlements in Egypt. *Solar Energy*, *123*, 160-173. https://doi.org/https://doi.org/10.1016/j.solener.2015.11.005
14. Dall'O', G., Galante, A., & Pasetti, G. (2012). A methodology for evaluating the potential energy savings of retrofitting residential building stocks. *Sustainable Cities and Society*, *4*, 12-21. https://doi.org/https://doi.org/10.1016/j.scs.2012.01.004
15. El-Darwish, I., & Gomaa, M. (2017). Retrofitting strategy for building envelopes to achieve energy efficiency. *Alexandria Engineering Journal*, *56*(4), 579-589. https://doi.org/https://doi.org/10.1016/j.aej.2017.05.011
16. Gui, X., Gou, Z., & Lu, Y. (2021). Reducing university energy use beyond energy retrofitting: The academic calendar impacts. *Energy and Buildings*, *231*, 110647. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110647
17. Heidari, A., Taghipour, M., & Yarmahmoodi, Z. (2021). The effect of fixed external shading devices on daylighting and thermal comfort in residential building. *Journal of Daylighting*, *8*(2). https://doi.org/10.15627/JD.2021.15
18. Hirvonen, J., Heljo, J., Jokisalo, J., Kurvinen, A., Saari, A., Niemelä, T., Sankelo, P., & Kosonen, R. (2021). Emissions and power demand in optimal energy retrofit scenarios of the Finnish building stock by 2050. *Sustainable Cities and Society*, *70*, 102896. https://doi.org/https://doi.org/10.1016/j.scs.2021.102896
19. Huang, H., Binti Wan Mohd Nazi, W.I., Yu, Y., & Wang, Y. (2020). Energy performance of a high-rise residential building retrofitted to passive building standard – A case study. *Applied Thermal Engineering*, *181*, 115902. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2020.115902
20. Huang, Y., Niu, J., & Chung, T. (2013). Study on performance of energy-efficient retrofitting measures on commercial building external walls in cooling-dominant cities. *Applied Energy*, *103*, 97-108. https://doi.org/https://doi.org/10.1016/j.apenergy.2012.09.003
21. Jafari, A., & Valentin, V. (2017). An optimization framework for building energy retrofits decision-making. *Building and Environment*, *115*, 118-129. https://doi.org/https://doi.org/10.1016/j.buildenv.2017.01.020
22. Jami, S., Forouzandeh, N., Zomorodian, Z.S., Tahsildoost, M., & Khoshbakht, M. (2021). The effect of occupant behaviors on energy retrofit: A case study of student dormitories in Tehran. *Journal of Cleaner Production*, *278*, 123556. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.123556
23. Kadrić, D., Aganovic, A., Martinović, S., Delalić, N., & Delalić-Gurda, B. (2022). Cost-related analysis of implementing energy-efficient retrofit measures in the residential building sector of a middle-income country – A case study of Bosnia and Herzegovina. *Energy and Buildings*, *257*, 111765. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.111765
24. Li, Q., Zhang, L., Zhang, L., & Wu, X. (2021). Optimizing energy efficiency and thermal comfort in building green retrofit. *Energy*, *237*, 121509. https://doi.org/https://doi.org/10.1016/j.energy.2021.121509
25. Liu, L., Rohdin, P., & Moshfegh, B. (2015). Evaluating indoor environment of a retrofitted multi-family building with improved energy performance in Sweden. *Energy and Buildings*, *102*, 32-44. https://doi.org/https://doi.org/10.1016/j.enbuild.2015.05.021
26. Lolli, N., Nocente, A., Brozovsky, J., Woods, R., & Grynning, S. (2019). Automatic vs manual control strategy for window blinds and ceiling lights: consequences to perceived visual and thermal discomfort. *Journal of Daylighting*, *6*, 112-123. https://doi.org/10.15627/jd.2019.11
27. Lu, Y., Li, P., Lee, Y.P., & Song, X. (2021). An integrated decision-making framework for existing building retrofits based on energy simulation and cost-benefit analysis. *Journal of Building Engineering*, *43*, 103200. https://doi.org/https://doi.org/10.1016/j.jobe.2021.103200
28. Magnani, N., Carrosio, G., & Osti, G. (2020). Energy retrofitting of urban buildings: A socio-spatial analysis of three mid-sized Italian cities. *Energy Policy*, *139*, 111341. https://doi.org/https://doi.org/10.1016/j.enpol.2020.111341
29. Maleki, A., & Dehghan, N. (2021). Optimum characteristics of windows in an office building in Isfahan for save energy and preserve visual comfort. *Journal of Daylighting*, *8*(2). https://doi.org/10.15627/JD.2021.18
30. Mata, É., Kalagasidis, A.S., & Johnsson, F. (2018). Contributions of building retrofitting in five member states to EU targets for energy savings. *Renewable and Sustainable Energy Reviews*, *93*, 759-774. https://doi.org/https://doi.org/10.1016/j.rser.2018.05.014
31. Mejjaouli, S., & Alzahrani, M. (2020). Decision-making model for optimum energy retrofitting strategies in residential buildings. *Sustainable Production and Consumption*, *24*, 211-218. https://doi.org/https://doi.org/10.1016/j.spc.2020.07.008
32. Moshiri, S., Atabi, F., Panjehshahi, M.H., & Lechtenböehmer, S. (2012). Long run energy demand in Iran: A scenario analysis. *International Journal of Energy Sector Management*, *6*(1), 120-144. https://doi.org/10.1108/17506221211216571
33. Ozarisoy, B., & Altan, H. (2021). A novel methodological framework for the optimisation of post-war social housing developments in the South-Eastern Mediterranean climate: Policy design and life-cycle cost impact analysis of retrofitting strategies. *Solar Energy*, *225*, 517-560. https://doi.org/https://doi.org/10.1016/j.solener.2021.07.008
34. Pazouki, M., Rezaie, K., & Bozorgi-Amiri, A. (2021). A fuzzy robust multi-objective optimization model for building energy retrofit considering utility function: A university building case study. *Energy and Buildings*, *241*, 110933. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.110933
35. Piccardo, C., Dodoo, A., Gustavsson, L., & Tettey, U. (2020). Retrofitting with different building materials: Life-cycle primary energy implications. *Energy*, *192*, 116648. https://doi.org/https://doi.org/10.1016/j.energy.2019.116648
36. Pungercar, V., Zhan, Q., Xiao, Y., Musso, F., Dinkel, A., & Pflug, T. (2021). A new retrofitting strategy for the improvement of indoor environment quality and energy efficiency in residential buildings in temperate climate using prefabricated elements. *Energy and Buildings*, *241*, 110951. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.110951
37. Qu, K., Chen, X., Wang, Y., Calautit, J., Riffat, S., & Cui, X. (2021). Comprehensive energy, economic and thermal comfort assessments for the passive energy retrofit of historical buildings - A case study of a late nineteenth-century Victorian house renovation in the UK. *Energy*, *220*, 119646. https://doi.org/https://doi.org/10.1016/j.energy.2020.119646
38. Rabani, M., Bayera Madessa, H., Mohseni, O., & Nord, N. (2020). Minimizing delivered energy and life cycle cost using graphical script: An office building retrofitting case. *Applied Energy*, *268*, 114929. https://doi.org/https://doi.org/10.1016/j.apenergy.2020.114929
39. Serrano-Jiménez, A., Lizana, J., Molina-Huelva, M., & Barrios-Padura, Á. (2019). Decision-support method for profitable residential energy retrofitting based on energy-related occupant behaviour. *Journal of Cleaner Production*, *222*, 622-632. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.089
40. Song, X., Ye, C., Li, H., Wang, X., & Ma, W. (2017). Field study on energy economic assessment of office buildings envelope retrofitting in southern China. *Sustainable Cities and Society*, *28*, 154-161. https://doi.org/https://doi.org/10.1016/j.scs.2016.08.029
41. Sun, H., Heng, C.K., Reindl, T., & Lau, S.S.Y. (2021). Visual impact assessment of coloured building-integrated photovoltaics on retrofitted building facades using saliency mapping. *Solar Energy*, *228*, 643-658. https://doi.org/https://doi.org/10.1016/j.solener.2021.09.087
42. Tahsildoost, M., & Zomorodian, Z.S. (2015). Energy retrofit techniques: An experimental study of two typical school buildings in Tehran. *Energy and Buildings*, *104*, 65-72. https://doi.org/https://doi.org/10.1016/j.enbuild.2015.06.079
43. Thomsen, K.E., Rose, J., Mørck, O., Jensen, S.Ø., Østergaard, I., Knudsen, H.N., & Bergsøe, N.C. (2016). Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. *Energy and Buildings*, *123*, 8-16. https://doi.org/https://doi.org/10.1016/j.enbuild.2016.04.049
44. Torabi Moghadam, S., & Lombardi, P. (2019). An interactive multi-criteria spatial decision support system for energy retrofitting of building stocks using CommuntiyVIZ to support urban energy planning. *Building and Environment*, *163*, 106233. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106233
45. Urbikain, M.K. (2020). Energy efficient solutions for retrofitting a residential multi-storey building with vacuum insulation panels and low-E windows in two European climates. *Journal of Cleaner Production*,

269, 121459. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.121459

46. Wang, Q., & Holmberg, S. (2015). A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings. *Sustainable Cities and Society*, *14*, 254-266. https://doi.org/https://doi.org/10.1016/j.scs.2014.10.002
47. Wang, Z., Liu, X., Deng, G., Shen, H., & Xu, Z. (2021). A framework for retrofitting existing houses to nearly zero energy buildings: Development and a real-life case study. *Energy and Buildings*, *252*, 111438. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.111438
48. Yang, S., Cho, H.M., Yun, B.Y., Hong, T., & Kim, S. (2021). Energy usage and cost analysis of passive thermal retrofits for low-rise residential buildings in Seoul. *Renewable and Sustainable Energy Reviews*, *151*, 111617. https://doi.org/https://doi.org/10.1016/j.rser.2021.111617
49. Zhou, Z., Zhang, S., Wang, C., Zuo, J., He, Q., & Rameezdeen, R. (2016). Achieving energy efficient buildings via retrofitting of existing buildings: A case study. *Journal of Cleaner Production*, *112*, 3605-3615. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.09.046
50. Zomorodian, M., & Nasrollahi, F. (2013). Architectural design optimization of school buildings for reduction of energy demand in hot and dry climates of Iran. *International Journal of Architectural Engineering & Urban Planning*, *23*, 41-50. http://ijaup.iust.ac.ir/article-1-152-en.html