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Optimization of window solar gain for a building with less cooling load

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ABSTRACT

Considering solar gain through the window (SGW), this study investigated the effects of installing shading on cooling load. Approving energy analysis for the base building (without shading), the cooling, heating, and annual energy demand were calculated. The best window angle and the best shading projection were obtained using the genetic algorithm. For the yearly minimum energy demand scenario, it was found that the window should be placed in the south direction, accompanied by the shading project with a maximum length of 20 cm. The results of the genetic algorithm revealed that for windows at the angle of 75–90°, the positive shading effects on annual energy demand become maximum. In this case, the shading reduces the yearly energy consumption by 3.1 %. The optimization showed that the shades have the best results for reducing the cold load for windows that are located in the azimuth angle between 135 and 180 °.

1. Introduction

Buildings need energy to regulate the temperature, and the share of energy related to cooling and heating is high. To diminish the required energy, we can reinforce buildings thermal inertia by injecting phase change materials (PCMs) [1], insulation [2,3], adding PV [4,5], or other forms of renewable energies [6,7], installing PID controller for temperature regulation [7,8]. Different studies have been conducted on saving in building energy demand. Yari et al. [9] installed air-to-air heat recovery in an air handling unit and, examined its effect on the cooling load of the building subjected to a dry environment and compared it with the wet one. Based on the numerical results, cooling load reduction is not significant in a dry environment, but in a wet one, cooling load decreased from 37 to 27 kW, which means a reduction of 27 %.

Fagehi and Hadidi [10], for NEOM in Saudi Arabia, utilized different PCMs to make the building more efficient. They increased the base building thickness from 29 cm to 34 cm by installing a PCM layer with 5 cm thickness. The authors focused on heat exchange through the walls in different directions and found that for the east one, heat exchange can be dropped by 55.2 %, west one by 66.8 %, north one by 60.8 %, and finally, south one by 60.7 %. Therefore, in the west direction, PCM is more successful. If the roof heat transfer is examined, the heat exchange is lowered by 73.8 %. The PCM in the west and roof surfaces declined heat exchange by 3866 and 4000 kWh, respectively.

Renovation in buildings considering a Mediterranean climate was studied by Carpino et al. [11]. They found that after renovation,

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the building energy utilization can be dropped by 86 kWh/m2 annually.

Considering European Union climate conditions, as calculated by Tanasa et al. [12], PV cells are very cost-effective because the installation of PV cells decreases energy demand by 55 % and simultaneously increases the cost by only 3 %.

For Thailand's climate [13], several techniques were examined to decrease CO_2 emissions by considering CO_2 emissions of 186×10^6 kg. They estimated CO_2 emissions and concluded that by 2030, it would reach 403×10^6 kg by adopting the novel methodology. To prove the effectiveness of the proposed methods, they calculated CO_2 emissions without any modification and found that by 2030, it will reach 563×10^6 kg. Therefore, by adopting energy-efficient techniques, we have buildings with lower CO_2 emissions by at least 28.4 %.

Kalbasi and Hassani [14] proposed a novel method for evaluating the PCM influences in building thermal behavior. They assumed that there was no HVAC unit for temperature adjustment. In other words, the building temperature may rise or decrease freely depending on the ambient conditions. They defined a comfort temperature range of 20–27 $^\circ C$. They found that for conventional buildings without PCM, the indoor temperature (IDT) is more than 60 % of the year, and the temperature is either lower than 20 or higher than 27 $^\circ C$. However, due to installing of a PCM that is solid/liquid at 21/23 $^\circ C$, IDT for the building was changed within 21–27 $^\circ C$ for more than 50 % of the year.

Alghamdi et al. [15] propose a PID controller to reduce AHU energy utilization. To lessen the energy utilization, they defined five scenarios focusing on indoor temperature adjustment. Introducing the first scenario yields 177 Wh per square meter energy savings. This value for the second was 404 Wh, and for the third and fourth ones was 638 and 905 Wh. In the fifth scenario, not only the energy demand was lowered by 1277 Wh, but also the indoor temperature was kept at a predefined setpoint of 25 $^\circ C$. To intensify the energy demand reduction in AHU, they also added PCM to the building, and finally, they achieved a 20 % reduction.

In an arid climate, Hai et al. [16] supposed that there is ejector-based cooling for building cooling requirements to be met. The authors added three methods to make the building a zero-energy building. In the first one, they aimed to reduce the energy exchange of the building and made the building more efficient by introducing PCM. Because PCM had succeeded in reducing energy exchange by 16.3 % in several months. Since the ejector-based cooling required a hot source, they installed a solar system, including a solar collector, to raise the hot water's temperature. The solar system absorbs solar energy and consequently declines boiler power usage by 94.5 kWh annually. In the last method, they incorporated MWCNT nanoparticles into the solar system and observed that MWCNT boosts energy absorption inside the collector tubes. The second and third methods dropped energy demand in the boiler by 18.8 %.

Rawa et al. [17] obtained an exciting numerical result. They found that if PCM is added inside the roof, it raises the energy exchange, which is considered an undesirable result. But if the same material is added to the walls, it works well, especially in north and south directions. Whereas this result was valid at 1 cm thickness, they doubled thickness to 2 cm and found that heat exchange through walls also diminished in this case. They realized that increasing the thickness to 5 cm makes the performance of PCM in the ceiling significantly better than in the walls. At 5 cm thickness, PCM inside the roof could lower heat exchange by 33.8 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$ while for walls, under the best conditions, this value was up to 5 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$. If the thickness increases from 5 to 6 cm, the energy consumption increases for the whole building. This trend was true up to 10 cm. Therefore, the authors suggested a thickness of 5 cm.

In a numerical study, Alawadhi [18] focused on the effect of PCM installation on reducing radiation transmission through the window. He chose three different PCMs with melting temperatures of 27 $^\circ C$ (n-Octadecane), 37 $^\circ C$ (n-Eicosane), and 47 $^\circ C$ (P116) and injected a layer of 1–3 cm thickness into the window. According to the analysis, during the hours when PCM P116 (the best one) was installed in the window, the energy transfer from the window experienced a 23.29 % reduction.

The effect of shutter installation was experimentally investigated by Alawadhi [19]. The author investigated the shutter effect by measuring the heat gain on the inner surface of the window for one day, for four conditions. In the case that the shutter is completely closed, the heat gain through the window was 92.6 MJ per square meter (daily). If the shutter is opened (raised) by 10 cm, the heat gain rises by 22.1 %, and if the shutter is raised by another 20 cm, the heat gain is magnified by 73.4 %.

Table 1
A summary of energy-saving owing to modification in window.

Reference	Location	Energy-saving Technique	Findings
Zhang et al. [23]	Hong Kong	Installing new thermal insulation on the window	Up to 9.5 % reduction in cooling demand
Fleur et al. [24]	Sweden	Applying different techniques for building renovation under the lowest life cycle cost	Installing a modern window with a total U-value of 1.1 $\frac{W}{m^2.K}$ minimize life cycle cost
Ng et al. [25]	Singapore	Installing semi-transparent building-integrated photovoltaic (BIPV)	Although the installation of this model of cells reduces visible light transmittance by 10 %, leading to energy savings in the range of 16.7–41.3 %.
Ahmed et al. [26]	Egypt	Introducing a smart window including a PV cell to generate electricity and PCM to decrease the heat gain	Owing to PCM installation, heat gain declined by 73 %, and owing to installing PV, an electricity generation of 162 $\frac{W}{m^2}$ was obtained.
Datta [27]	Italy	Installing horizontal louvers	The optimum louver structure depends on the location. For Milan, owing to installing the optimum louvers structure, the heat gain in summer and winter was reduced by 70 % and 40 % respectively.
Nielsen et al. [28]	Cold north-European climate	Installing shading	The window in the south direction is the most suitable shade installation option. In this case, energy consumption reduced by 16 %.

Yang et al. [20], in an experimental study, investigated the effect of internal shading by changing the blade angle. They installed the blades at five angles ($0^\circ, 30^\circ, 45^\circ, 60^\circ$ *and* 90°) and then measured the amount of ventilation rate to regulate the temperature. They found that if the internal shade is not installed, the amount of ventilation is 1.76 kg/s, and if the blades are installed at an angle of 0°, $30^\circ, 45^\circ, 60^\circ$ *and* 90°, it reduces the ventilation rate by 25 %, 24.43 %, 23.86 %, 21 % and 3.97 %, respectively.

The roles of overhang installation on the window were numerically evaluated by Krarti [21]. The overhang installation angle and window-to-wall area ratio were considered input parameters, and energy consumption in the HVAC system as output variables. The author first considered the overhang angle constant and then changed the angle at different intervals and found that in Phoenix, AZ (33.4484°N, 112.0740°W), in the best case, the HVAC energy consumption declined by 45 %.

In a numerical experimental study that was associated to reduce solar heat gain reduction, the authors used the concept of a fluidic window [22]. By examining the internal temperature of the building that uses fluidic windows and comparing it with the building with normal windows, they found that in the first case, the temperature can be lowered by 10 $^\circ C$, reducing energy consumption significantly in the hot season.

In Table 1, a summary of energy-saving owing to modification in the window is reported.

The presence of windows helps to illuminate the building and at the same time, they are considered as a passage for fresh air supply. Especially in the summer, the sunlight passes through the windows and warms the interior. In this study, a horizontal shading installed above the window is used to reduce the heat gain through the windows. In addition, vertical windows (on the left and right sides) are added to reduce the solar heat gain through windows. The review of previous articles showed that there is no optimization on the length of the shade and its dependence on the direction of the window. In this study, three parameters are considered as inputs: the length of the horizontal shade as well as the vertical one, which is displayed with the projection, and the direction of the window, which is calculated as an angle from the north. The output variable is the reduction of energy consumption in the cooling sector, annual energy consumption, and heat gain from the window.

2. Problem

Consider a building where all the walls are insulated, and only energy exchange is done through the north wall where a window is installed over the wall (Fig. 1). Heat transfers to the building through the north wall along with the window and the sun's radiation

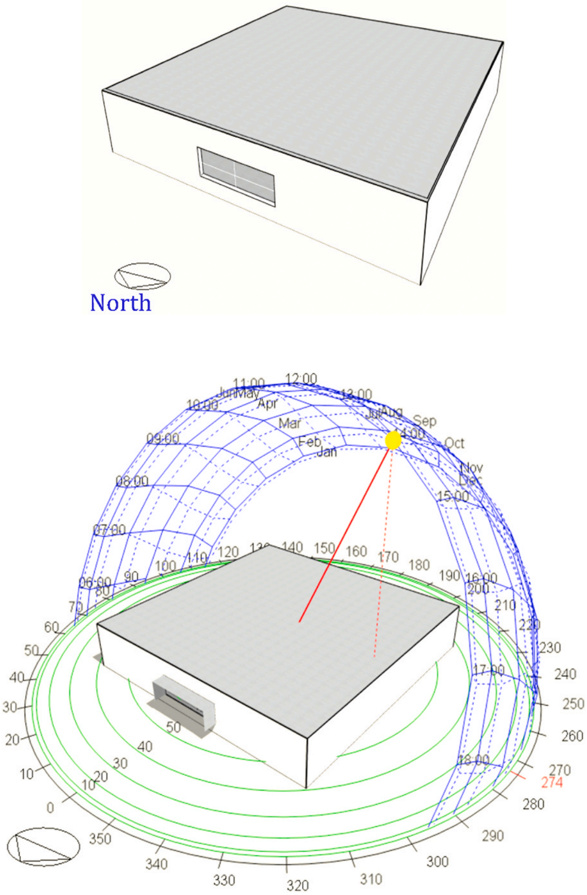

Fig. 1. Building without shading and building with horizontal/vertical shading.

passes through the window heat the building.

The main goal of this study is to investigate the effect of the presence of shading and its impact on three parameters cooling demand, total energy consumption and heat gain through the window. On the other hand, three variables affect the performance of the shading. The direction of the window, its length, and its angle relative to its mounting surface (horizontal or vertical) are shown in Fig. 2.

3. Weather conditions

Weather conditions have a significant effect on heat transfer through the walls. In this study, according to the time steps of 2 s, the temperature distribution inside the wall is determined. Then the heat transfer in the inner and outer walls is determined from Fourier's law.

Because the energy analysis is done annually in this study, the temperature distribution must be known at every moment. The temperature variations are demonstrated in Fig. 3 according to the geographical information.

The intensity of the sun's radiation changes with time, and therefore, the performance of the shading will also change with time. To determine the effect of the shading, the incoming radiation to the shade and the window should be determined first.

4. Energy analysis formulation

To examine the effects of the shading on the cooling/heating loads, the energy balance for the building should be done.

$$\frac{d\left(\rho c_p T_{indoor}\right)}{dt} = -\dot{Q}_{cooling} + \dot{Q}_{heating} + k_i \frac{dT_{wall,i}}{dx} + k_w \frac{dT_{window,i}}{dx} + SIE \tag{1}$$

where k_i is the thermal conductivity of the wall, k_w is the window thermal conductivity, SIE is the solar incoming energy. It is assumed that the infiltration/ventilation energy exchange is zero. Therefore, the heat transfer through the envelopes + window and solar heat gain are the main parameters. IThis study investigates the effect of sunshade installation on the heat gain caused by solar radiation Therefore, the amount of solar radiation must be known. The radiation on each plane depends on the amount of beam radiation (I_{beam}) and diffuse one ($I_{diffuse}$) which obtained as follows [29]:

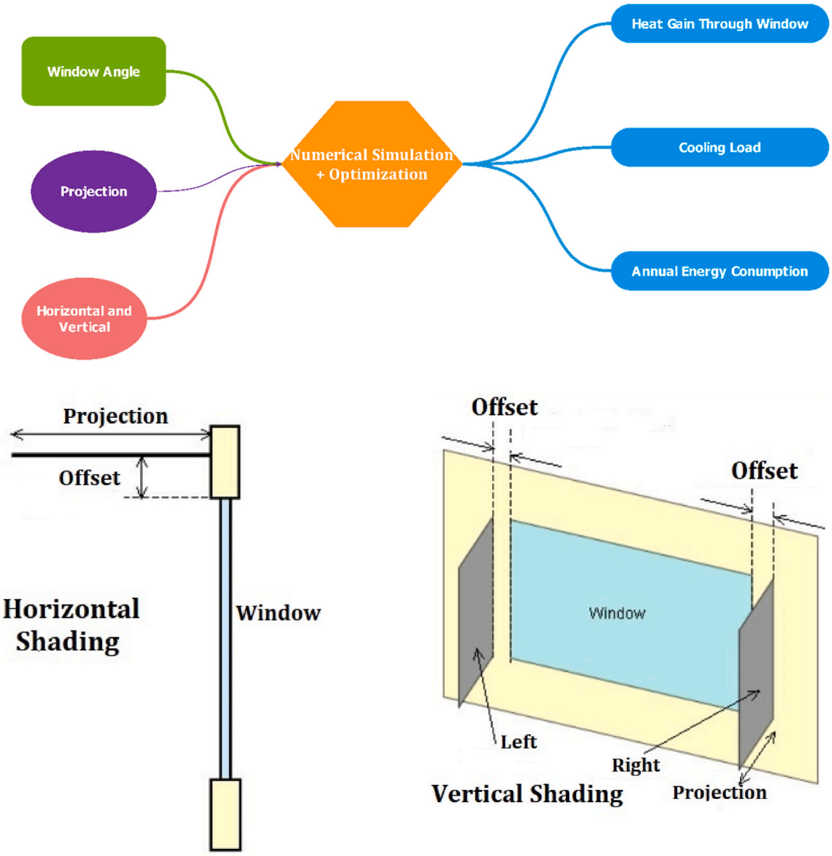

Fig. 2. The main parameters, vertical/horizontal shading and projection definition.

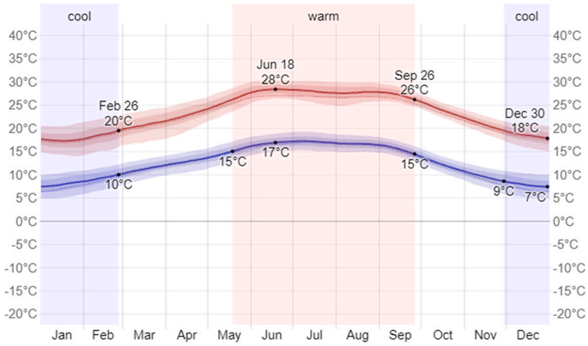

Fig. 3. Average Temperature (18.216 ° latitude, 42.505 ° longitude).

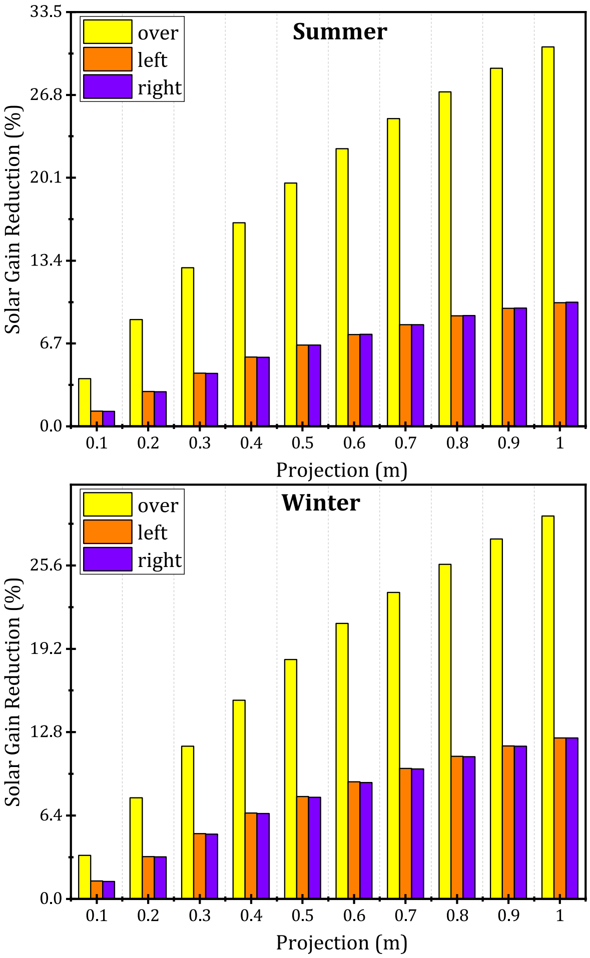

Fig. 4. Percent reduction in summer solar gain in three scenarios (Over, Left and Right).

$$I_{beam} = E \times \exp\left(-\tau_{beam} \times m^{b}\right) \tag{2}$$

$$I_{diffuse} = E \times \exp\left(-\tau_{diffuse} \times m^{d}\right) \tag{3}$$

where m is the air mass [29]:

$$m = \left(\sin\beta + 0.50572 \times (6.07995 + \beta)^{-1.6364}\right)^{-1} \tag{4}$$

where β is the solar attitude in degree. In Eqs. (2) and (3), the parameters of b and d are determined from the following equations [29]:

$$b = 1.454 - 0.406 \times \tau_{beam} - 0.268 \times \tau_{diffuse} + 0.021 \times \tau_{diffuse} \times \tau_{beam} \tag{5}$$

$$d = 0.507 + 0.205 \times \tau_{beam} - 0.08 \times \tau_{diffuse} - 0.19 \times \tau_{diffuse} \times \tau_{beam} \tag{6}$$

In Eqs. (5) and (6), the parameters of τ_{beam} and τ_{beam} are optical depth related to beam and diffuse components and can be determined from ASHRAE [29].

Solar gain over a tilted surface without any shading is:

$$\dot{Q} = \alpha\left(I_{beam} \times \cos\theta \times \frac{S_s}{S} + I_{diffuse} \times F_{ss} + I_g \times F_{sg}\right) \tag{7}$$

where α is the absorptance coefficient, I_g is the ground reflected solar intensity, F_{ss} the angle between the surface and sky, F_{sg} is the angle between the surface and the ground, S_s is the sunlit area and S is the surface area.

5. Results

In areas with hot weather, the sun's radiation usually shines on the walls with great intensity and therefore heats the space, although solar radiation is suitable in winter, and in summer, it increases the cold load of the building. This study discusses the effect of external shades to determine how much solar radiation can affect energy consumption.

5.1. Shading effects on solar gain

At first, the solar gain through the window (SGW) is investigated for the reference building (without external shadow). Then the external shading is added to the building under three scenarios. The percent reduction is calculated from the following equation:

$$\text{Percent Reduction (PR)} = \frac{\text{SGW}_{\text{ref}} - \text{SGW}_{\text{m}}}{\text{SGW}_{\text{ref}}} \times 100 \tag{8}$$

The percent reduction is shown in Fig. 4 for solar gain in summer/winter (May to end of Sep).

It can be seen that the value of SGW has a higher dependency on the conditions where the external horizontal shading is used, while for the case of left/right, the dependency is not significant. Both in winter and summer, the horizontal shade is the most effective. Vertical shades are more effective in winter than in summer. Moreover, shading installation is more beneficial in summer than in winter. This result is compatible with the result obtained by Datta [27].

5.2. Shading projection effects on cooling/heating demand

To check the effect of shade on energy consumption, annual energy analysis should be performed on the building. Energy analysis has been done for the following conditions (Table 2).

The temperature difference between indoor and outdoor spaces is the most important factor in the energy transfer between the building and the building. The air conditioning system must regulate the indoor temperature according to a schedule, within a predefined range. In Fig. 5, the temperature distribution for the indoor environment is shown.

As it is known, the cooling system stays on from May 1 to the end of September to regulate the temperature inside. During the rest of

Table 2
Conditions for evaluating cooling/heating demand.

Winter setpoint	20 $^\circ C$	Internal Heat gain	0 kWh
Winter setback	12 $^\circ C$	Occupancy	0.1 people/m^2
Summer setpoint	25 $^\circ C$	Setpoint schedule	8-18 referred to setpoint
Summer setback	28 $^\circ C$	Setback schedule	18-8 referred to setback
Wall/Roof U-Value	$1.657\,\frac{W}{m^2.K}$	Wall/Roof Thickness	21 cm
Window solar heat gain coefficient	0.691	Window U-Value	$1.96\,\frac{W}{m^2.K}$
Window solar transmission	0.624	Window light transmission	0.744
Internal/external convective heat transfer coefficient	$8.6\,\frac{W}{m^2.K}$ for indoor and $25\,\frac{W}{m^2.K}$ for the exterior	Internal/external Radiative heat transfer coefficient	$5.54\,\frac{W}{m^2.K}$ for indoor and $5.13\,\frac{W}{m^2.K}$ for the exterior

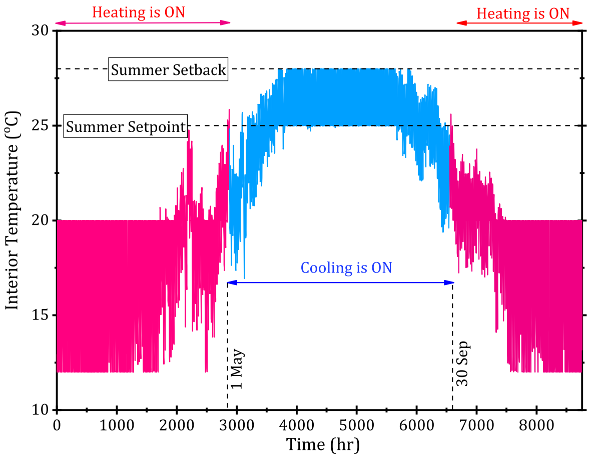

Fig. 5. Indoor temperature variations and dependency on cooling/heating schedule.

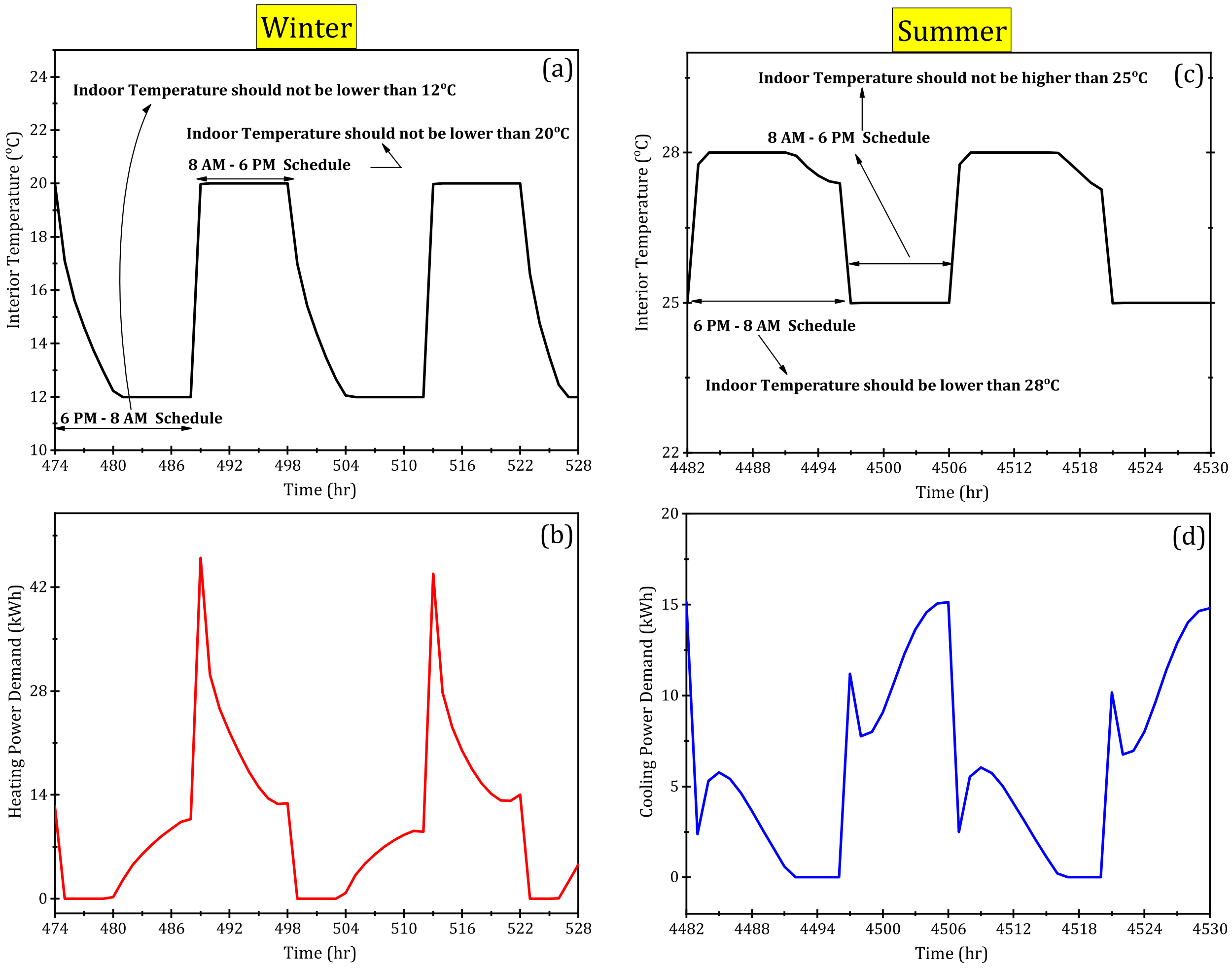

Fig. 6. Defining two schedules to adjust inside temperature.

the month, the heating system regulates the temperature. According to Table 2, the inside temperature changes in two schedules: between 8:00 a.m.-6:00 p.m., when the temperature inside is set at the setpoint, and between 6:00 p.m. - 8:00 a.m., when the temperature is set at the setback value. In Fig. 6, the temperature regulation schedule is demonstrated. The setpoint value in winter is 20

$^{\circ}C$, and the setback value is 12 $^{\circ}C$. This means the temperature should not drop below 20 $^{\circ}C$ between 8 Am and 6 p.m. Meanwhile, the temperature should not drop below 12 $^{\circ}C$ between 6 p.m. and 8 a.m. In summer, the concept of setpoint/setback is interpreted differently. Between 8 a.m. and 6 p.m., the indoor temperature should not exceed 25 $^{\circ}C$ (setpoint). IFrom6 PM to 8 a.m., the maximum room temperature will be 28 $^{\circ}C$ (setback).

In the summer, indoor heating causes the building's cooling system to consume more energy to maintain the temperature in the range of 25–28 $^{\circ}C$. But in winter, solar radiation causes the heating system to consume less energy to stabilize the temperature at the set point. Thus, external shading has a positive effect in the summer and a negative effect in the winter. The results of Fig. 4 indicate that the presence of a vertical shade (whether it is on the left or right side of the window) does not make much difference in shadow intensity on the window. Therefore, whether the vertical shade is on the right side or the left side, it seems that both vertical sshades have thesame effect on reducing energy consumption in summer and increasing energy consumption in winter (see Fig. 7). The energy analysis in the cooling section indicates that the energy consumption in this section reaches 10,014 $\frac{kWh}{year}$, while the annual energy consumption for winter reaches 26,017 kW h (see Fig. 7).

Energy consumption analysis in the cooling/heating sector shows that.

1 To intensify the cooling sector energy demand, adding a horizontal shade has a better effect than a vertical shade under the same length shade. In Fig. 4, it was observed that the intensity of radiation passing through the window when there is a horizontal shade is much lower than when the vertical shade is installed.

2 By increasing the length of the shade, the cooling load is reduced. In summer, at projection = 0.1 m, the cooling load reduces by 1.6 %, while at 5 cm and 10 cm, this value is 7.6 % and 11.7 %, respectively.

2 By increasing the length of the shade, the cooling load is reduced. In summer, at projection = 0.1 m, the cooling load reduces by 1.6 %, while at 5 cm, this value is 7.6 %. The reduction of energy consumption in the cooling sector by installing a vertical shade does not have a linear relationship with the length of the shade. If there was a linear relationship, it would be expected that when the shade length reaches 1 m, the energy consumption reduction would reach 16 % (10 × 1.6 %). The results show that in the length of the shade of 1 m, the reduction of energy consumption is 11.6 %.

3 Although the shade installation reduces energy consumption in summer, it raises energy consumption in winter, indicating that radiation significantly contributes to heating the building. Installing the shade reduces the energy input to the building, and therefore, the heating system of the building will consume more energy. In winter, due to the installation of the horizontal shading,

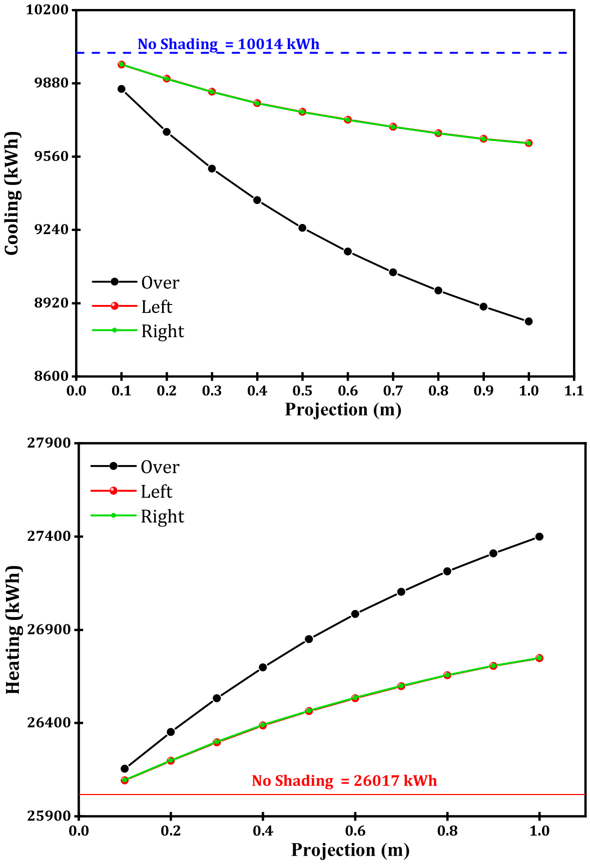

Fig. 7. Heating/Cooling dependency on the external shading.

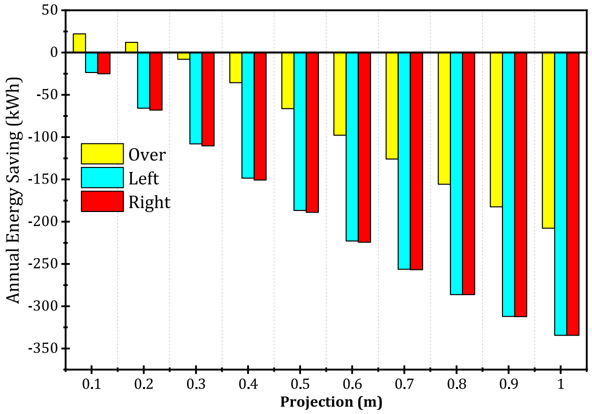

Fig. 8. Annual energy-saving for three shade types in different projections. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the heating load not only does not decrease but experiences an increase of 138 kWh (at a projection of 0.1 m), 832 kWh (at 0.5 m) and 1382 kWh (at 1 m).

The reduction of energy consumption in the cooling sector should be compared with the upsurge in energy consumption in the heating section to evaluate the final effect of the shade installation. Fig. 8 shows energy saving for all three shades in different thicknesses.

The most important points of Fig. 8 are.

1 If the shading is installed vertically (right or left), the energy used in the building will increase. Therefore, the vertical shade is not recommended.
2 If a horizontal shade is installed, the energy consumption in the cooling section will definitely decrease, but due to the increase in energy consumption in winter, its projection should be less than 0.2 m.
3 In the discussion of shading, it is better that the shading is collected in winter or made in such a way that there is no shading in winter.

5.3. *Effects of building rotation on external shading influences*

External shading reduces the amount of energy absorption in the space by reducing the amount of solar radiation. On the other hand, the amount of radiation on the window depends on its direction. In Table 3, the shading is added to the window in three scenarios for the four main directions. In the first scenario, the shade is horizontal, the length of which varies from 0.1 to 1 m. Vertical shading is added on the left and right sides in the second and third scenarios. It can be seen that the horizontal shade in all four directions has a much greater effect than the vertical shade. On the other hand, vertical shadings, whether they are in the left or right direction, do not differ much.

The results of Table 3 indicate that the south window has the greatest advantage for shade installation, which is completely consistent with the results obtained from Nielsen et al. [28].

Fig. 9 shows the amount of heat gained from the windows at different angles. It can be seen that the heat gain is the highest in the south direction and takes the lowest in the north direction. Even with the external shading, there is still the most heat gain from the window in the south direction.

In Fig. 10, solar gain reduction is reported. Even with the shading, there is still the most heat gain from the window in the south direction. However, the presence of shading has caused the heat gain to decrease by about 26 % for a length of 0.5 m and by about 43.1

Table 3
of reduction in SGW at main directions.

Projection (m)	North (%)			South (%)			East (%)			West (%)		
	Up	L	R	Up	L	R	Up	L	R	Up	L	R
0.1	2.7	0.5	0.5	4.6	0.5	0.5	3.1	0.4	0.2	3.1	0.2	0.4
0.2	6.4	1.2	1.2	10.7	1.2	1.1	7.6	1.1	0.5	7.5	0.5	1.1
0.3	9.8	1.8	1.8	16.3	1.8	1.7	11.9	1.7	0.8	11.8	0.8	1.7
0.4	13.0	2.4	2.4	21.4	2.3	2.3	16.1	2.2	1.1	15.8	1.1	2.2
0.5	16.0	2.9	2.9	26.0	2.8	2.7	19.9	2.7	1.3	19.6	1.3	2.7
0.6	18.6	3.4	3.4	30.1	3.3	3.2	23.4	3.1	1.6	23.1	1.6	3.1
0.7	20.8	3.8	3.8	33.8	3.7	3.6	26.5	3.5	1.8	26.2	1.8	3.6
0.8	23.0	4.2	4.2	37.2	4.1	3.9	29.4	3.9	2.0	29.1	2.0	3.9
0.9	24.9	4.6	4.6	40.2	4.4	4.3	32.1	4.2	2.2	31.8	2.2	4.3
1	26.7	4.9	4.9	43.1	4.7	4.6	34.6	4.5	2.4	34.2	2.4	4.6

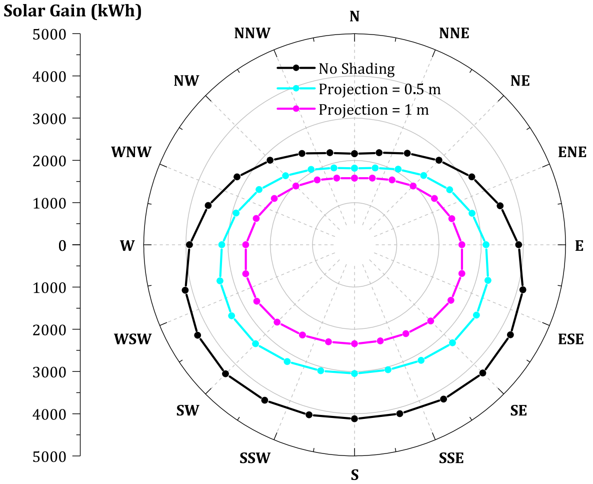

Fig. 9. Solar gain through each individual window at different directions (window area = 7.5 m^2).

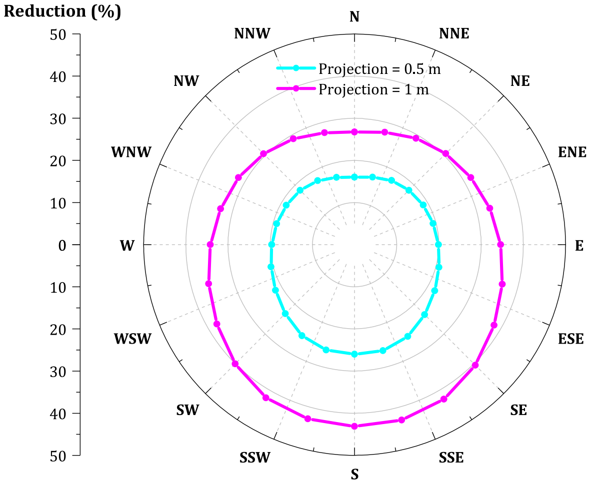

Fig. 10. Solar gain reduction in each individual window in different directions.

% for a length of 1 m. For the north direction, with the least shading effects, SGW has decreased by 16 % and 26.7 % for the lengths of 0.5 m and 1 m, respectively.

5.4. Using genetic algorithm to find minimum energy demand

Now, the effect of window installation location on energy consumption in the building is investigated. The problem analysis conditions are similar to Tables 2 and in addition, in this case, there is no occupancy heat gain. Out of the four walls of the building, only one wall contains a window, and the rest of the walls are insulated. Energy consumption, in this case, is only related to the transfer of solar energy through the glass as well as the sensible energy through the wall + window. For example, for a building with a window in the south wall and without shading, energy demand in heating/cooling is 2003 and 2428 kWh, and therefore the annual energy demand is 4431 kWh. These results are valid for the condition that the rest of the walls are insulated along with the roof and floor of the building. It is evident that at an angle of 180° (facing south), energy consumption almost reaches the lowest value. If the genetic algorithm is used to minimize the amount of energy consumption, the results show that at the angle of 180 and at the length of 0.1 and 0.2, the energy consumption reaches the lowest value (Table 4).

Table 4
The lowest energy demand using the Genetic algorithm.

Projection	Window Rotation (°)	Total Energy (kW)	Base Building (kW)	Percent of Reduction (%)
0.1	180	4411.7	4431	0.43
0.2	180	4422.5	4431	0.19

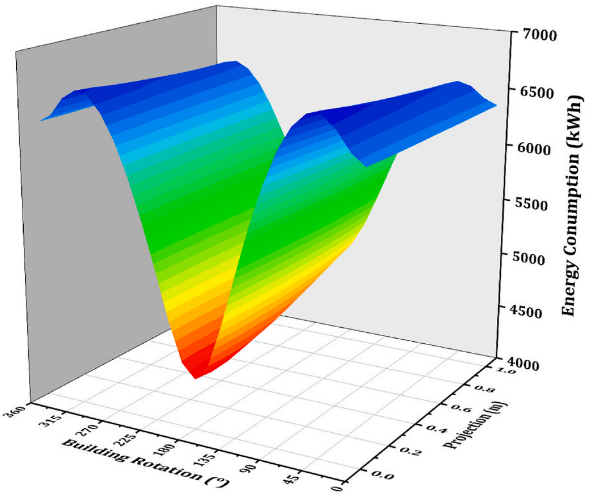

Fig. 11. Energy demand for building without shading (projection = 0) and building with shading.

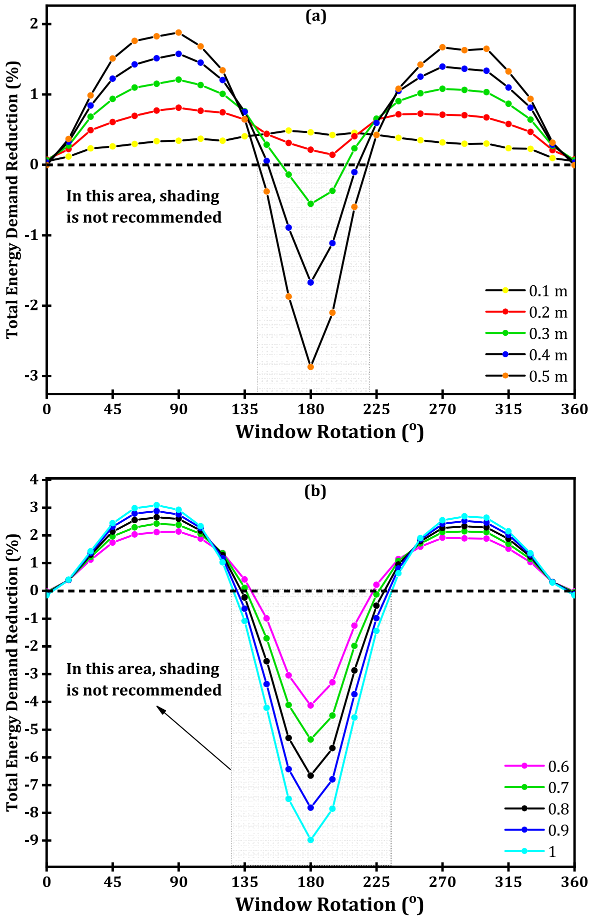

Fig. 12. Dependency of the percent reduction to window rotation at (a) projection within 0.1–0.5 m and (b) projection within 0.5–1 m.

Fig. 11 plots the changes in energy consumption compared to the base building. This figure shows in what conditions it is appropriate to add shading. According to the results obtained from the genetic algorithm, it has the maximum effect when the shade is installed on a window with an angle of about 75–90 ° compared to the zero angle (north). It should be noted that the angles of 90, 180 and 270° correspond to the east, south and west directions.

In Fig. 12, it can be seen that the shade's usefulness is highly dependent on the direction of the window. More details are provided in Fig. 12. The most important points of Fig. 12 are classified as follows.

1 If a shade with a length of 10 cm is added to the window (in any direction), it will reduce annual energy consumption. Also, this is true for 20 cm.
2 For a length of more than 20 cm, in some window orientations, the presence of shade increases energy consumption.
3 For a length of 30 cm, at angles of 165–195°, the canopy increases the energy consumption of the building. The angle of 180° means south direction.
4 For 40 cm–100 cm, between angles of 165–210°, the presence of shading upsurges energy consumption.

The maximum amount that the shade installation can affect the building's energy consumption is reported in Table 5.

Except for the length of 10 cm, for the rest of the cases, the presence of shade on the windows facing east (or almost facing east) has the most significant effect. By increasing the length of the shade, the maximum impact of the shade increases.

5.5. *Finding the best window rotation, taking into account the cooling load*

Supplying the cold load is very critical for regions with hot climates. The sun's radiation is high in these areas, so much energy is directed inside through the walls and windows. In Fig. 13, the amount of cold load is drawn for a place where only one wall faces outside, and the rest of the walls are insulated. For example, in the case when the window is on the south wall, and a shade of 0.5 m is installed on it, the cooling load is equal to 1660 kWh. This value is equal to 2003 kWh for the case where there is no shader. Therefore, the cooling load is less when there is shading. As shown in Fig. 13, if the windows face north, there is the least cold load (with and without shading).

Fig. 14 plots the amount of reduction in cold load for the window at different angles and various projections.

According to the results presented in Fig. 14, the cold load is reduced in each shade length in the range of 0.1–1 m. The positive effect of the shade is a function of the window angle. For the shading at the length of 0.1 m, the most significant impact is seen at 180° (south window) so that the cooling load reduces by 4.12 %. The maximum effect for shading at the length of 0.2 m is on the south window, and its value equals 8.6 %. Shadings with a length of 0.3–0.6 m require the window at an angle of 165° to have the maximum reduction in cooling load. In this region, the cooling load declines by 12.2%–17.7 %. The authors, in a numerical study [30], by dynamically adjusting the shades, succeeded in reducing the monthly energy consumption by 18 %. However, the energy needed to adjust the shade was not mentioned.

Windows that are installed at an angle of 150°, if a shade with a length of 0.6–0.9 m is installed, the most significant reduction in cold load compared to the window without shading is experienced. Finally, for a window that is located in the southwest direction, if a shade is installed with a length of 1 m, the effect of the presence of the shade reaches the maximum value, and in this case, the cold load is reduced by 25.6 %

6. Conclusions

In this study, the effect of the presence of external shading on the amount of solar gain through the window (SGW) was investigated. Then, the effect of window angle and shade projection on cooling/heating loads was discussed by solving the energy equation. Numerical methods solved the energy equation, and to bold the shading effects, all the building's envelopes (walls/roof and ground) except for one wall containing the window were assumed to be adiabatic. Therefore, in the energy equation, only sensible heat transfer from the wall + window alongside the solar gain through the window had an effect. The shading was placed in three positions; in the first one, it was installed horizontally above the window, and in the second and third cases, it was placed vertically on the left and right sides. The results showed that horizontal shadings have a more significant effect than vertical ones in all cases.

- According to the geographical location, it was found that the SGH parameter has the maximum value for the south window and the minimum value for the north window. Shading has a more significant effect on the south window than the north one. If an external shading with a projection of 0.5 m and 1 m is installed on the south window, SGH is reduced by 26 and 43.1 %, respectively. For the north window, these values were 16 and 26.7 %.

Table 5
Max percent of reduction and its angle.

Length (m)	The maximum percent of the reduction	Window angle
0.1	0.48	165
0.2	0.81	90
0.3	1.21	90
0.4	1.57	90
0.5	1.88	90
0.6	2.14	90
0.7	2.42	75
0.8	2.65	75
0.9	2.87	75
1.0	3.08	75

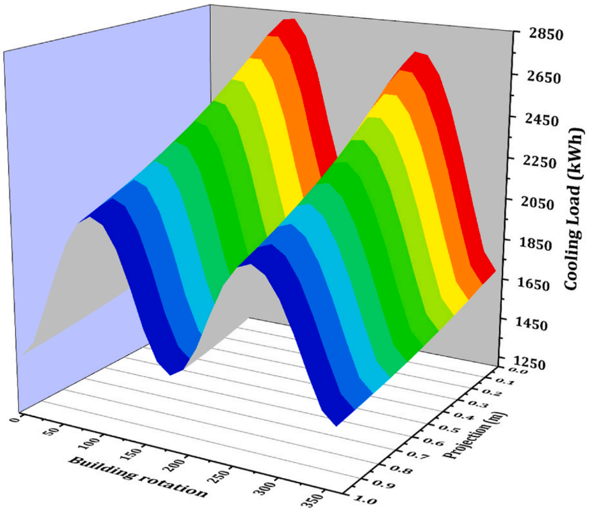

Fig. 13. Cooling load at various rotation/projection.

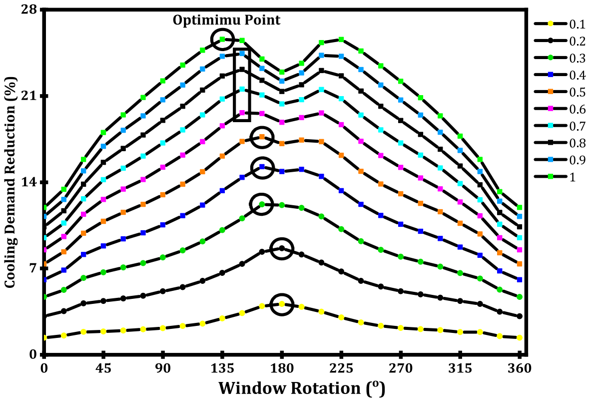

Fig. 14. Cooling load dependency to the window rotation.

- Energy consumption in the heating and cooling sector was investigated according to the set points of 10 and 20 for the windows in different directions, along with shades of different lengths. By defining the parameter of annual energy consumption as an output variable, the genetic algorithm was used to minimize it, and it was found that if the window is located in the south direction and the length of the shade is 10 cm, the energy consumption for the building reaches the lowest value.
- By defining the percentage of annual load reduction due to the installation of shade, the genetic algorithm was used to maximize it, and it was determined that the windows should be placed at angles of 70–90 and a shadow of 1 m should be installed for them.
- At a fixed shade length, the angle of the window was changed to determine in which direction the shade effect is maximized at each shade length. Considering the annual energy consumption, it was determined that for a height of 0.1 m, the window should be placed at an angle of 165°, for a length of 0.2–0.6 m, at an angle of 90° (east window) and for lengths of 0.7–1 m, the angle of the window should be 75° to see the maximum effect of installing the window.

CRediT authorship contribution statement

Jawed Mustafa: Data curation, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Saeed Alqaed:** Methodology, Writing – review & editing. **Mohsen Sharifpur:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Josua Meyer:** Investigation, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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