



Article

Skin porosity geometry from the energy efficiency point of view; case study: an office building in Mashhad, Iran

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ABSTRACT

The construction sector accounts for a large portion of the world's energy consumption; in Iran, it's more than 40% of energy consumption. Office buildings have a relatively unfavorable energy consumption pattern due to impersonal ownership and lack of supervision and needs improvement. The aim of this research is to achieve the most optimal skin porosity geometry in terms of energy for a dynamic double-skin façade. Since this idea is intended to be used in Mashhad, which is one of the religious centers of Iran, so to create this feeling in users, the geometry used for its dynamic second skin porosity is inspired by Islamic patterns of tiles and decorations of the holy shrine of Imam Reza (AS). By analyzing the energy performance of 5 selected geometries with Ladybug and Honeybee plugins, the most optimal one will be determined. Daylight is one of the most influential parameters in the design of energy-efficient buildings. To make the most of this parameter, it is necessary to create facades with maximum transparency. But these facades face challenges such as overheating. Therefore, it's important to control the amount of daylight entering. In this research, an optimal geometry for a dynamic double skin façade porosity intended to be used for office buildings in Mashhad is presented, although the energy analysis results of all 5 geometries are very close to each other. This means that the porosity geometry does not have much effect on the optimization of energy consumption.

1. Introduction

The price of oil and fossil fuels is increasing, and this issue has turned the amount of energy consumption and its production method, into one of the main challenges in developing countries. In recent decades, the energy demand of our society, especially in the building sector, has been steadily increasing [1]. The energy consumption of buildings constitutes about 40% of the total energy consumption in developed and developing countries [2]. In the last decade, the proportion of energy consumption in Iran has been about five times its global consumption. The continuously increasing demand for energy-efficient buildings has drawn widespread attention to the role of various building elements [3]. Skin, as the main building element, plays a vital role in protecting internal environments and controlling interactions between internal and external spaces [4]. Building skins are usually considered to consist of penetrable and impenetrable surfaces [5]. Conventional facades can lead to poor natural ventilation, low levels of daylight, the absence

of thermal comfort, and an increased amount of energy consumption. These disadvantages are often aggravated in modern facades that have significant amounts of glass. As a result of high solar heat absorption or a significant amount of heat loss at night or in cold climates, wide glass facades lead to high energy consumption [4]. Solar heat absorption through glass leads to 50% of the building's cooling load and therefore has significant effects on thermal loads. Considering the fact that 22% of heat absorption and loss takes place through the building skin, the necessity of using passive technologies in building skins in order to reduce the energy consumption of the building becomes clear [5]. "Passive building" is a building in which the internal environment is controlled by the structure and architectural design of the building and its components instead of using mechanical cooling and heating systems. Among passive approaches, double skin facade (DSF) has recently become a popular technology. The desire to combine the transparent facade of modern buildings with energy efficiency has led to the use of

DSFs [6, 7]. The issue of natural lighting is effective in the self-efficiency of buildings; because lighting accounts for 15% of the energy consumption of buildings around the world [8, 9]. This issue requires more attention, especially in the case of office buildings; Because the energy consumption for the lighting of this sector alone includes between 20% and 40% of the total energy consumption [10]. In Iran, artificial lighting accounts for 25% of electricity consumption in office buildings. Studies and evaluations show that about 4800 million kWh of electrical energy (equivalent to 2.5% of the country's total energy consumption) is used to meet the needs of governmental offices. The amount of this consumption varies from 100 to 1000 kWh per person per square meter depending on the location of the office, its dimensions, and the number and type of equipment used in it [11]. Daylight is an important source of renewable energy that is simply available and unlikely to run out in the future [12]. Despite the fact that Iran possesses a lot of daylight during working hours (Mashhad has an average of 8 hours of sunshine per day), this level of electricity consumption remains relatively high. Along with the global awareness of the importance of more sustainable and efficient building performance, it is necessary to provide methods to minimize electricity consumption for lighting. An efficient method is to use natural daylight effectively in interior spaces [13]. The utilization of daylight plays a fundamental role in lighting the building, and its efficient use can reduce the overall energy consumption of the building. In addition, bringing daylight into the interior has a significant impact on the health and comfort of residents [14-16]. To provide light properly, three factors must always be considered: the quantity and quality of light and the way it is distributed. The light varies from moment to moment in terms of intensity and quality, and the desirable or tolerable degree of this change depends on the specific use of space [17].

In the past years, researchers have tried to reduce dependence on non-renewable energy sources by using natural daylight as the main source of energy for the building. Most of these studies have focused on the optimization of daylight inside buildings. However, in their methods, due to the limitations of their research methods, the highest possible efficiency was impossible. In certain approaches, although the daylight optimization strategies have achieved the best angle of the shading elements, the system cannot move in three dimensions; thus, the optimal and available amount of light during the day reduces [8]. In optimal designs, minimizing energy consumption is the main goal. Based on this issue, openings are considered for sunlight entrance into the space, and in this way, energy consumption is decreased by reducing electric lighting [18]. Various types of shading devices have been designed on the basis of the orientation, location, and glazing types of buildings to increase thermal and lighting performance [19]. Studies in recent years have shown a shift in approach from simple and static shader systems to complex ones [20]. In this research, an optimal geometry for the porosity of a dynamic double-skin facade that could optimize the amount of interior space illumination through daylight has been investigated.

2. Methodology

In this project, with the aim of using daylight as much as possible, a wide glass facade is used in the sunlight-exposed face, and in order to control the amount of incoming daylight in different seasons, a dynamic second skin is applied on it. Since this idea is intended to be used in Mashhad, which is one of the religious centers of Iran, so to create this feeling in

users, the geometry used for its skin porosity is inspired by Islamic patterns of tiles and decorations of the holy shrine of Imam Reza (AS). By analyzing the energy performance of 5 selected geometries with Ladybug and Honeybee plugins in Rhino software, the most optimal one will be determined. These results show the energy consumption per kWh per year so that a better comparison of the results can be made. Between the two facade layers, there are foldable shader surfaces that open and close with the movement of skin and change the porosity percentage of skin in different seasons.

2.1 Skin primitive design idea

The primitive design idea consists of a dynamic skin with foldable shader surfaces placed in the space between the two facade layers, which open and close with the movement of skin and control the amount of daylight entering. The study of previous research in the field of double-skin facades shows that in order to have proper natural ventilation in the space between the two layers and also to prevent it from overheating, their distance should be 20 to 60 cm. Therefore, in this design, the movement of skin is considered in such a way that the distance between the two layers varies between 20 and 60 cm when opening and closing. Figure 1 illustrates the primitive design idea and its distance changes.

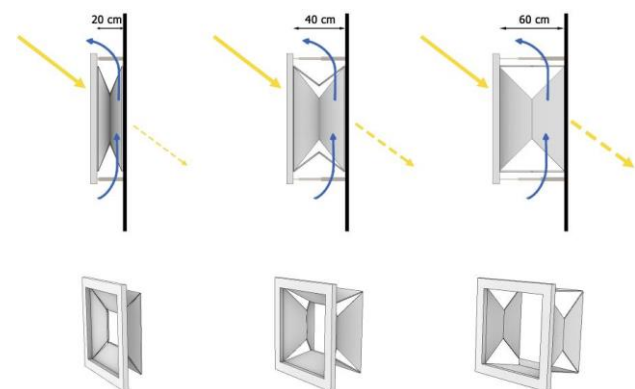


Figure 1. The primitive design idea

2.2 Skin porosity pattern

Considering the fact that this idea is intended to be used in the holy city of Mashhad, which is one of the religious centers of the country, so with the aim of creating this feeling in users, the second skin porosity geometry is inspired by Islamic patterns of tiles and decorations of the holy shrine of Imam Reza (AS), and then 5 geometries were selected and analyzed by the energy analysis software. Figures 2-6 illustrate the inspiration sources of those 5 geometries.

3. Case Studies

The main concern of this research is to provide a solution to reduce the level of fossil fuel consumption, to use sunlight as a renewable energy source as much as possible, and to use a passive method in the design of a dynamic skin in order to improve the building energy consumption. For this purpose, the background of the projects carried out in this field has been reviewed, and their goals and solutions have been analyzed in Table 1 (Appendix I). The study of case studies showed that a large part of efforts had been made in order to optimally control the entry of daylight, provide the comfort of the indoor environment and reduce the level of energy consumption. This approach provides the possibility of using the facade in two ways, completely transparent and

completely rigid, and besides creating a suitable view, it causes the potential to optimize energy consumption. In addition, the mobility of facade elements gives it dynamism and allows users to make changes based on their needs and, at the same time, create a different appearance in the facade.

3.1 First Geometry

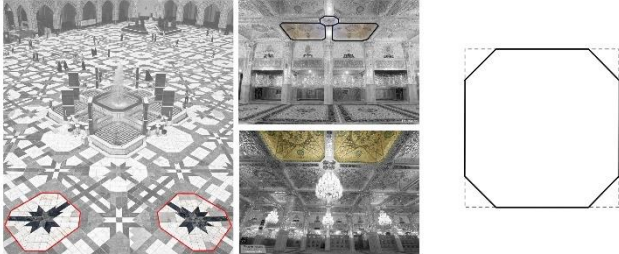


Figure 2. The first geometry, which is inspired by the courtyard and ceiling of the holy shrine of Imam Reza (AS)

3.2 Second Geometry

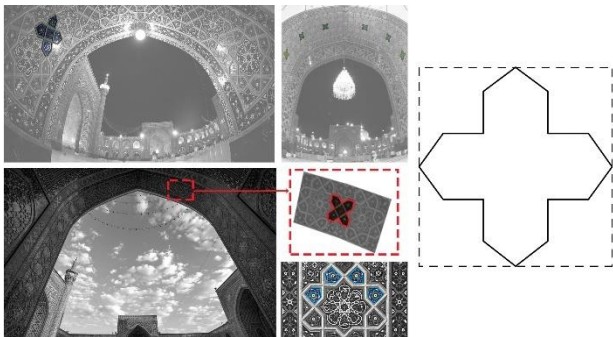


Figure 3. The second geometry, which is inspired by the porch of Goharshad mosque

3.3 Third Geometry

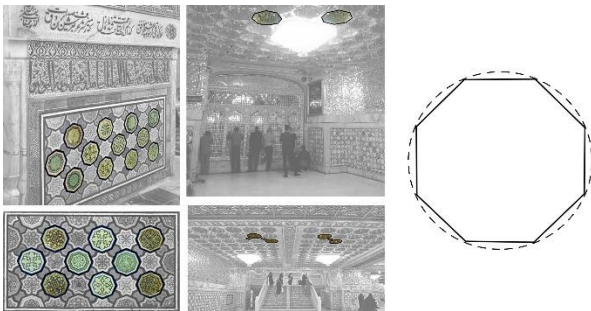


Figure 4. The third geometry, which is inspired by the ceiling and decorations of the holy shrine of Imam Reza (AS)

3.4 Forth Geometry

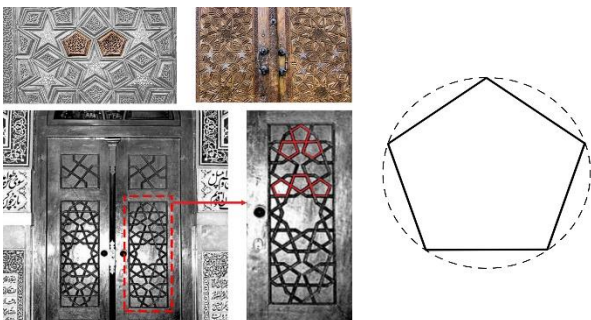


Figure 5. The fourth geometry, which is inspired by the door of Dar al-Siadeh porch (Goharshad courtyard)

3.5 Fifth Geometry

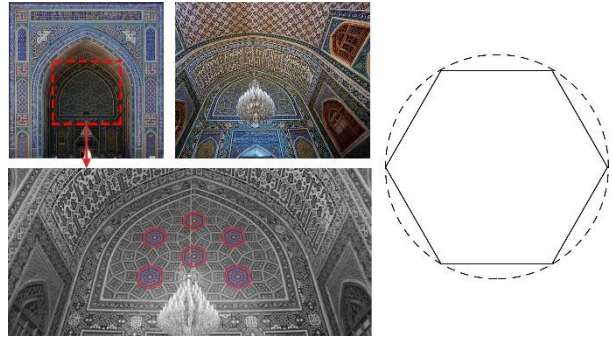


Figure 6. The fifth geometry, which is inspired by Dar al-Siadeh porch (Goharshad courtyard).

4. Results and discussion

By specifying the porosity geometries, a porous skin with these geometries is modeled with the same porosity percentage (50%), and each of them is analyzed by Ladybug and Honeybee plugins in terms of energy efficiency. Finally, the most optimal geometry will be determined. Figure 7 (Appendix I) illustrates the algorithm used for skin energy analysis with each geometry. The results support the related literature [21-40] strongly, which shows the validity and reliability of the research.

4.1 Energy Analysis of 5 Skin Porosity Geometries

4.1.1 Skin Energy Analysis with First Geometry (50% porosity)

Figure 8 illustrates the skin with the first geometry, and the graph of its energy loads in each section is shown in Figure 9. Figure 10 also shows the skin energy loads diagram individually with the first geometry. The result of energy loads for each month and the total energy loads of the first skin have been presented in Table 2.

4.1.2 Skin Energy Analysis with Second Geometry (50% porosity)

Figure 11 illustrates the skin with second geometry and the graph of its energy loads in each section is shown in Figure 12. Figure 13 also shows the skin energy loads diagram individually with the second geometry. The result of energy loads for each month and the total energy loads of the second skin have been presented in Table 3.

4.1.3 Skin Energy Analysis with Third Geometry (50% porosity)

Figure 14 illustrates the skin with the third geometry, and the graph of its energy loads in each section is shown in Figure 15. Figure 16 also shows the skin energy loads diagram individually with third geometry. The result of energy loads for each month and the total energy loads of the third skin have been presented in Table 4.

4.1.4 Skin Energy Analysis with Forth Geometry (50% porosity)

Figure 17 illustrates the skin with the fourth geometry, and the graph of its energy loads in each section is shown in Figure 18. Figure 19 also shows the skin energy loads diagram individually with the fourth geometry. The result of energy loads for each month and the total energy loads of the fourth skin have been presented in Table 5.

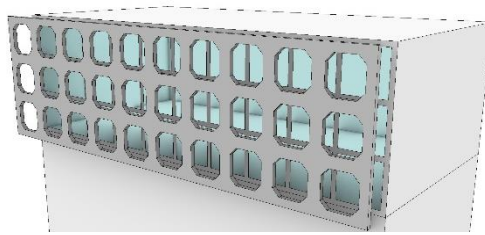


Figure 8. Skin with the first geometry

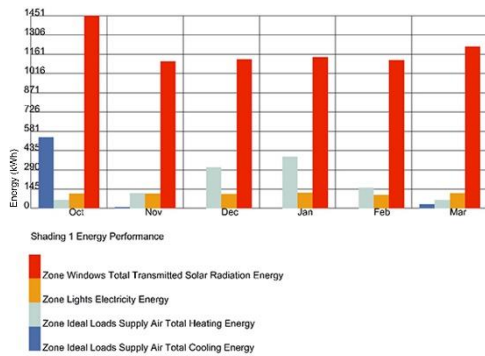


Figure 10. First skin energy analysis diagram

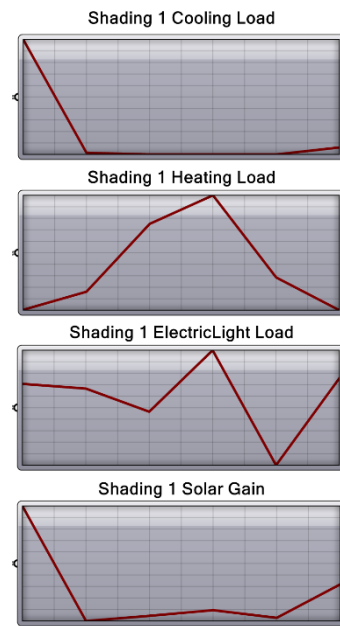


Figure 9. First skin energy loads graph

Table 2. Skin energy analysis results with the first geometry

	Cooling (kWh)	Heating (kWh)	Total Thermal Load (kWh)	Electric Light (kWh)	Total Energy Load (kWh)	Solar Gain (kWh)
October	417.375223	74.581807	491.95703	112.660928	604.617958	958.790672
November	6.790435	145.313598	152.104033	112.077593	264.181626	713.053085
December	0.278326	380.177939	380.456265	109.208945	489.66521	707.578703
January	0.433583	480.805871	481.239454	116.8296	598.069054	726.680824
February	0.402483	205.063776	205.466259	102.573579	308.039838	729.655292
March	27.325185	80.616207	107.941392	113.377617	221.319009	826.388818
	452.605235	1366.559198	1819.164433	666.728262	2485.892695	4662.147394

Table 3. Skin energy analysis results with the second geometry

	Cooling (kWh)	Heating (kWh)	Total Thermal Load (kWh)	Electric Light (kWh)	Total Energy Load (kWh)	Solar Gain (kWh)
October	414.901943	74.783893	489.685836	112.660928	602.346764	948.609272
November	6.783195	146.280437	153.063632	112.077593	265.141225	704.617394
December	0.276409	383.017287	383.293696	109.208945	492.502641	698.922888
January	0.430689	483.858704	484.289393	116.8296	601.118993	718.08324
February	0.397969	206.694061	207.09203	102.573579	309.665609	721.251032
March	27.270714	80.882152	108.152866	113.377617	221.530483	819.457508
	450.060918	1375.516535	1825.577453	666.728262	2492.305715	4610.941334

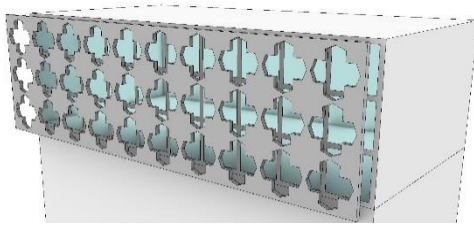


Figure 11. Skin with the second geometry

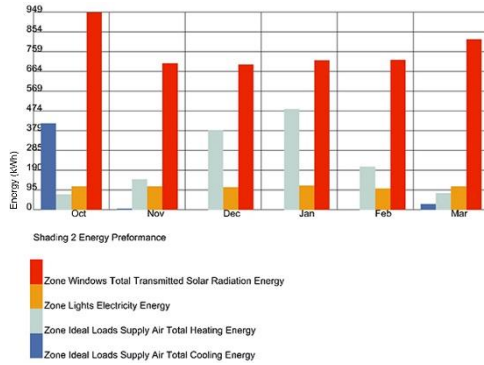


Figure 13. Second skin energy analysis diagram

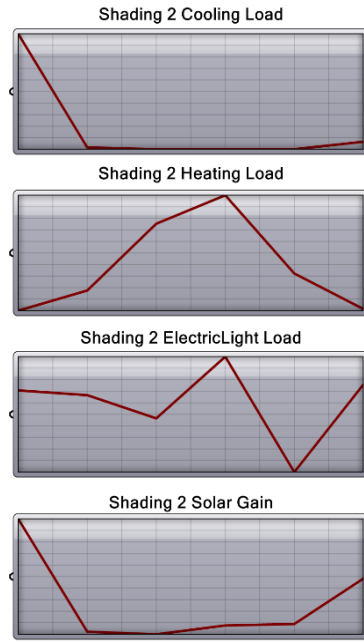


Figure 12. Second skin energy analysis graph

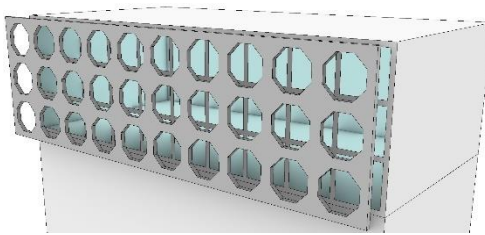


Figure 14. Skin with third geometry

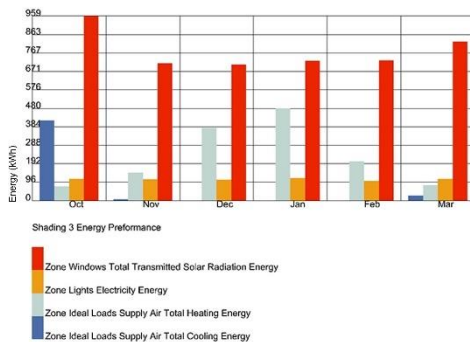


Figure 16. Third skin energy analysis diagram

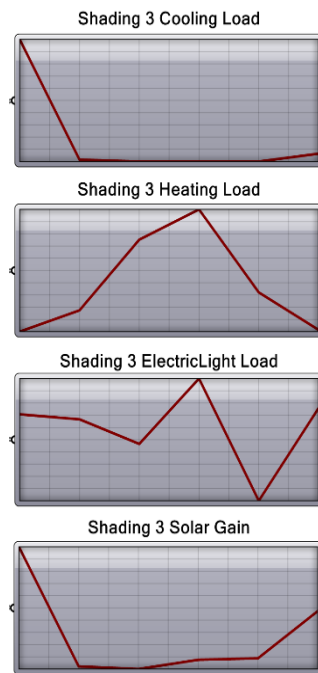


Figure 15. Third skin energy analysis graph

Table 4. Skin energy analysis results with the third geometry

	Cooling (kWh)	Heating (kWh)	Total Thermal Load (kWh)	Electric Light (kWh)	Total Energy Load (kWh)	Solar Gain (kWh)
October	417.452859	74.55712	492.009979	112.660928	604.670907	959.248034
November	6.801567	145.290961	152.092528	112.077593	264.170121	713.410499
December	0.28033	380.226824	380.507154	109.208945	489.716099	707.958743
January	0.435546	480.825401	481.260947	116.8296	598.090547	727.000047
February	0.403972	205.026208	205.43018	102.573579	308.003759	730.067929
March	27.351622	80.532076	107.883698	113.377617	221.261315	827.062075
	452.725896	1366.458589	1819.184486	666.728262	2485.912748	4664.747329

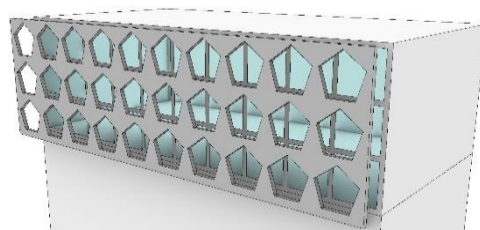


Figure 17. Skin with fourth geometry.

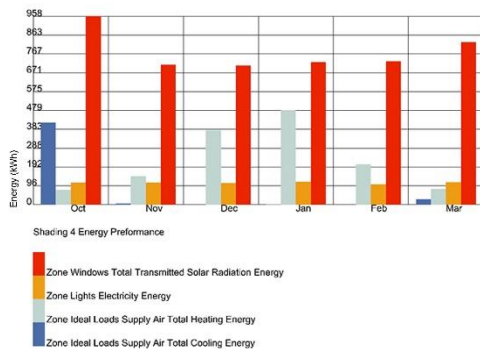


Figure 19. Forth skin energy analysis diagram.

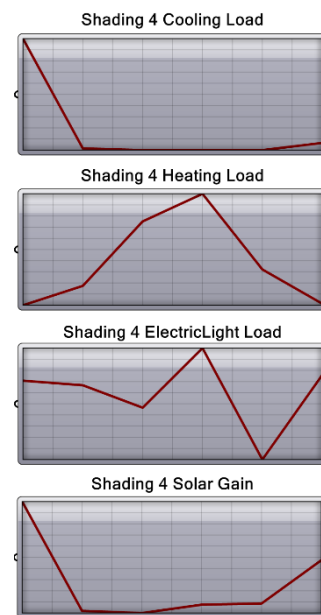


Figure 18. Forth skin energy analysis graph

Table 5. Skin energy analysis results with the fourth geometry

	Cooling (kWh)	Heating (kWh)	Total Thermal Load (kWh)	Electric Light (kWh)	Total Energy Load (kWh)	Solar Gain (kWh)
October	417.255597	74.576421	491.832018	112.660928	604.492946	958.478707
November	6.794514	145.430956	152.22547	112.077593	264.303063	712.314561
December	0.280046	380.441084	380.72113	109.208945	489.930075	707.380436
January	0.435974	481.137816	481.57379	116.8296	598.40339	726.285243
February	0.402483	205.278993	205.681476	102.573579	308.255055	728.974232
March	27.359219	80.567563	107.926782	113.377617	221.304399	826.468719
	452.527834	1367.432834	1819.960666	666.728262	2486.688928	4659.901898

4.1.5 Skin Energy Analysis with Fifth Geometry (50% porosity)

Figure 20 illustrates the skin with the fifth geometry, and the graph of its energy loads in each section is shown in Figure 21. Figure 22 also shows the skin energy loads diagram individually with the fifth geometry. The result of energy loads for each month and the total energy loads of the fifth skin have been presented in Table 6.

As seen in Figure 23, the energy analysis results of different geometries are very close to each other. It means that "the porosity geometry does not have much effect on energy consumption optimization". Therefore, all 5 geometries can be used for skin porosity. Nevertheless, the most optimal geometry (the third one), which has the less energy load and the most solar gain, has been specified. Figure 24 illustrates the final skin with optimal geometry.

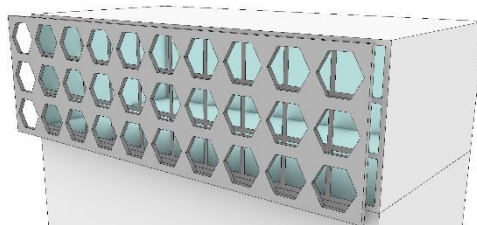


Figure 20. Skin with fifth geometry

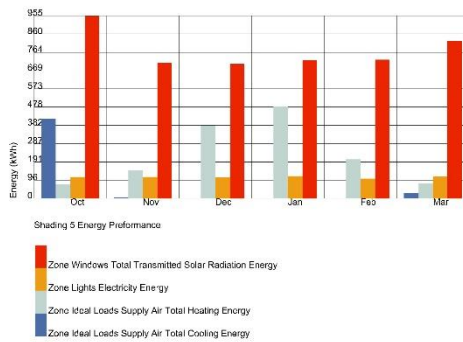


Figure 22. Fifth skin energy analysis diagram.

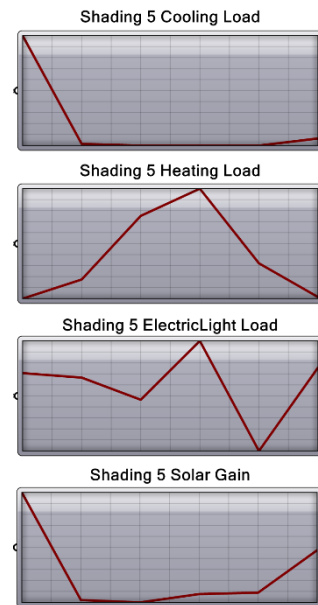


Figure 21. Fifth skin energy analysis graph.

Table 6. Skin energy analysis results with the fifth geometry

	Cooling (kWh)	Heating (kWh)	Total Thermal Load (kWh)	Electric Light (kWh)	Total Energy Load (kWh)	Solar Gain (kWh)
October	416.429234	74.674068	491.103302	112.660928	603.76423	955.439129
November	6.775631	145.699443	152.475074	112.077593	264.552667	709.683818
December	0.27952	381.214038	381.493558	109.208945	490.702503	704.223527
January	0.432493	481.947764	482.380257	116.8296	599.209857	723.330107
February	0.401914	205.627039	206.028953	102.573579	308.602532	726.589907
March	27.287363	80.759023	108.046386	113.377617	221.424003	823.658242
	451.606156	1369.921374	1821.52753	666.728262	2488.255792	4642.924731

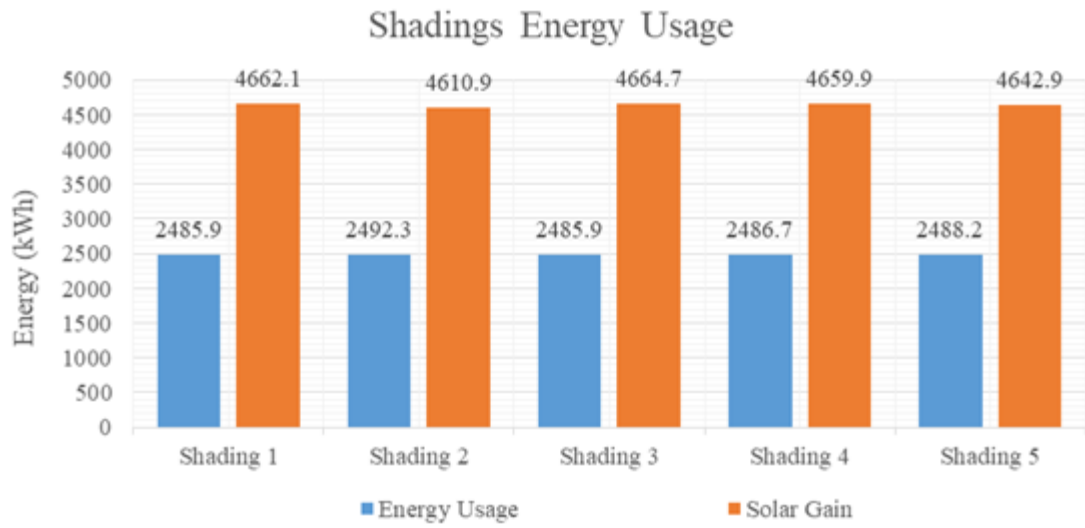


Figure 23. Skin energy analysis diagram with different geometries

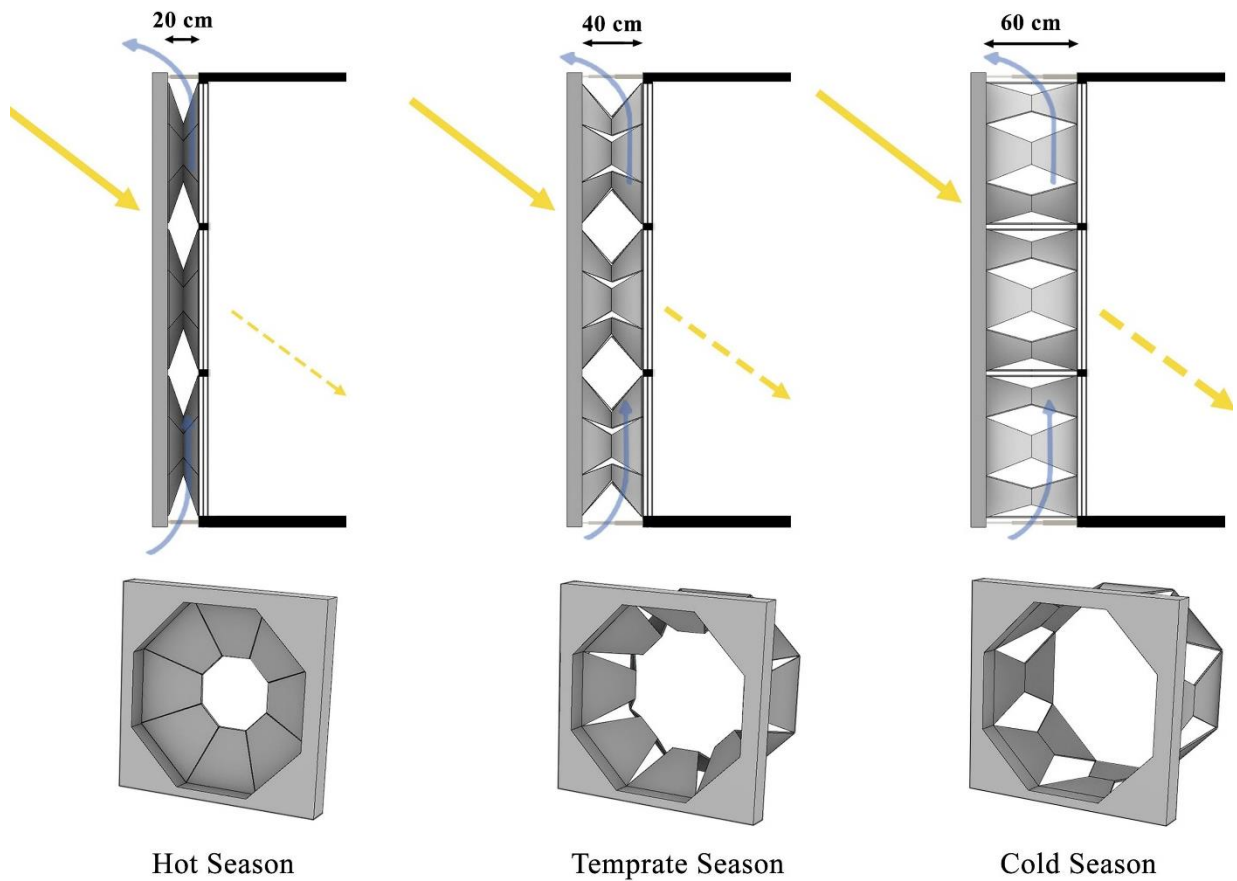


Figure 24. Final skin with optimal geometry

5. Conclusion

The increasing growing of population and urbanization around the world has turned the optimal use of energy resources and sustainable design into a global concern. In Iran, the construction sector accounts for 40% of this energy consumption. Meanwhile, office buildings have an unfavorable energy consumption pattern due to a lack of supervision and impersonal ownership and require special attention. In order to optimize the energy performance of buildings, there are many passive solutions, one of them being the use of renewable energy sources to meet energy needs. One of the most available sources of renewable energy, especially in Iran, is solar energy. The skin, as a boundary between the inside and outside of the building, is the component that has the most contact with the external environment and the sun; therefore, it can have a significant impact on the energy performance of the building. Today, various technologies are used to design skins, and one of the most effective methods is the use of double-skin facades and shading skins. Studies showed that in order to create optimal ventilation, the distance between two shells needs to be at least 20 and at most 60 cm. Basically, daylight is one of the most influential parameters in the design of energy-efficient buildings. To make the most of this parameter, it is necessary to create facades with maximum transparency. But these facades face challenges such as overheating in hot seasons. In order to solve this problem, it is necessary to control the amount of daylight entering in hot seasons. In this project, with the aim of using daylight as much as possible, a wide glass facade is used in the sunlight-exposed face, and in order to control the amount of incoming daylight in different seasons, a dynamic second skin is applied on it. Since this idea is intended to be used in Mashhad, which is one of the religious centers of Iran, so to create this feeling in users, the geometry used for its skin porosity is inspired by Islamic patterns of tiles and decorations of the holy shrine of Imam Reza (AS). By analyzing the energy performance of 5 selected geometries with Ladybug and Honeybee plugins in Rhino software, the most optimal one is determined; although the energy analysis results of all 5 geometries are very close to each other. This means that the porosity geometry does not have much effect on the optimization of energy consumption.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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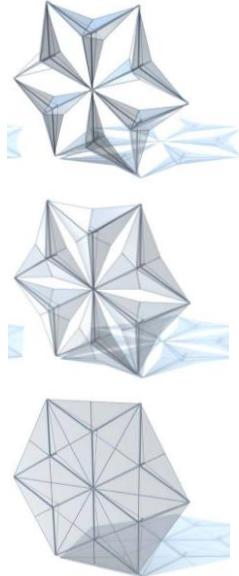
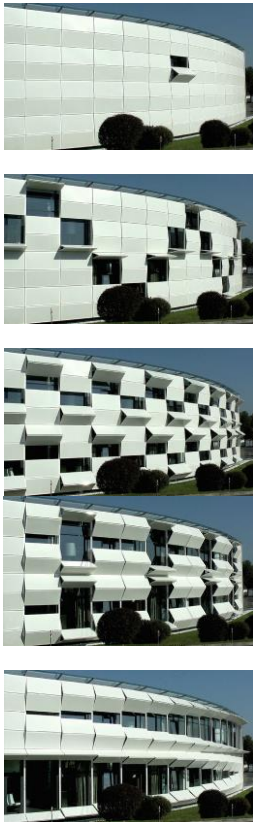
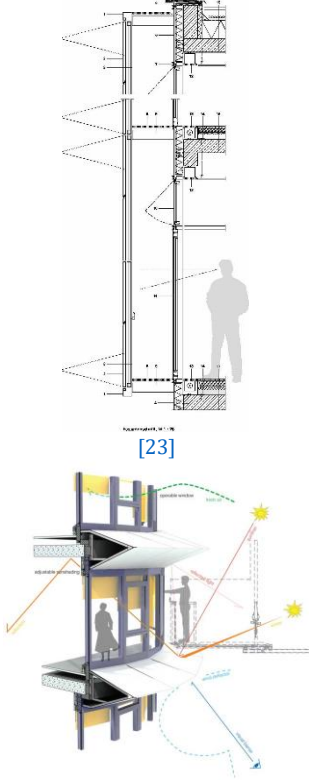
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Appendix I

Table 1. Examples of case studies carried out in this field and their goals and solutions

Case Study	Goal	Solution
<p>Al-Bahar Towers</p>  <p>[19]</p> <p>[20]</p>	<p>Compatibility with Abu Dhabi weather (intense sunshine, temperature above 100 degrees Fahrenheit with 0% chance of rain).</p> <p>A responsive facade to sunlight and changes in radiation angles during different days of the year.</p> <p>Reducing glare</p> <p>50% reduction in solar heat absorption.</p> <p>Reducing the building's need for energy for air conditioning.</p> <p>Light filtering</p> <p>Better view</p> <p>Less need for artificial light</p> <p>Facade transparency at night [20]</p>	<p>Mashrabiya shading system with actuated panels [20]</p> 
<p>Kiefer Technic Showroom</p>  <p>[20-22]</p>	<p>Changing based on outdoor environmental conditions</p> <p>Providing interior environment comfort</p> <p>Changing personal spaces to the taste of users</p> <p>Presenting different views throughout the day as a dynamic sculpture</p> <p>Ability to control by optimization programs [20]</p>	<p>A dynamic facade which adapts to changes of outdoor environment [20]</p>  <p>[23]</p> <p>[24]</p>
<p>SDU Campus Kolding</p>	<p>Responding to changes in daylight intensity</p> <p>Adaptation to specific weather conditions</p>	<p>Dynamic solar shading system [20]</p>

Case Study	Goal	Solution
 <p>[25]</p>	<p>Compatibility with user needs</p> <hr/> <p>Providing optimal daylight</p> <hr/> <p>Providing internal comfort conditions</p> <hr/> <p>Facade dynamism during the day [20]</p>	 <p>[25]</p>

