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Adaptive Façade Strategies for Energy Efficiency: A Case Study Optimization in Cold and Semi-Arid Climates

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ABSTRACT

The increasing global energy consumption in the building sector highlights an urgent need for energy-efficient design solutions. This study investigates the optimization of residential building envelopes in Bojnord, Iran—a city with a cold and semi-arid climate (BSk), characterized by harsh winters and relatively warm summers. A simulation-based methodology was adopted using parametric modeling and building energy simulation tools to assess envelope performance. Five façade strategies were selected for evaluation based on their climatic relevance, geometric adaptability, and feasibility within common construction limitations: optimized Window-to-Wall Ratio (WWR), ventilated double-skin façades (DSF) with air insulation and shading, Voronoi-based shading systems, perforated panels, and variable-porosity façades inspired by traditional Iranian geometry. Adaptive versions of these strategies were also examined. Results indicate that optimizing the WWR to 20% significantly reduces energy consumption, while dynamic façade systems—particularly those with adjustable WWR—offer the highest energy savings, reducing total consumption by approximately 7.73% compared to the baseline model. Conversely, some fixed strategies such as static perforated façades led to increased energy use. The findings provide insights for architects and urban planners into the role of adaptive and climate-responsive envelope systems in achieving energy efficiency and thermal comfort in cold and semi-arid regions. Limitations related to material costs, control complexity, and long-term performance of dynamic systems are also discussed.

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1. Introduction

1.1. Global Energy Consumption and the Building Sector

The global energy crisis and climate change underscore the urgent need for sustainable and energy-efficient construction practices worldwide [1, 2]. The building sector contributes significantly to overall energy consumption and associated greenhouse gas emissions [3–5]. This contribution is on the rise due to population growth, urbanization, and increasing demand for thermal comfort [6, 7]. Within this context, the residential sector holds particular importance due to its widespread nature and direct impact on occupants' comfort and quality of life [8]. Therefore, improving the energy performance of residential buildings is not merely an environmental imperative but a crucial step towards enhancing societal well-being and productivity [9-11].

1.2. The Critical Role of Building Envelopes in Energy Performance

The building envelope serves as the primary interface between the controlled indoor environment and the uncontrolled outdoor conditions [12, 13]. This component plays a multifaceted role in mediating heat transfer [14], controlling daylight [15], and influencing indoor air quality [16]. The design and material properties of the building envelope directly determine a building's energy demand for heating, cooling, and artificial lighting [5, 17]. A significant portion of energy loss in buildings occurs due to improper design or poor performance of the external envelope [5, 18, 19]. Consequently, optimizing the building envelope is one of the most effective strategies for reducing energy consumption and enhancing building sustainability [20-22].

1.3. Climatic Challenges and Research Gap

Bojnord, the capital of North Khorasan Province, has been selected as the geographical focus of this study. The city experiences a cold and semi-arid climate (BSk) according to the Köppen climate classification, characterized by very cold winters and relatively warm summers [23]. The average annual number of frost days in Bojnord exceeds 100, indicating a prolonged heating season. Furthermore, the temperature range in this region is substantial; for instance, the difference between the average temperature in July and January at the Bojnord Synoptic Station is over 20°C [24]. These extreme temperature fluctuations pose significant challenges for maintaining thermal comfort and optimizing energy consumption in buildings.

Research indicates that buildings in these regions face unique challenges due to extreme temperature variations, necessitating tailored design strategies to optimize energy performance. For instance, according to Ghazwani *et al*. (2025), effective building envelope design can significantly reduce heating demands, which are particularly high in cold climates [25]. The integration of thermal mass [26, 27], insulation [28], and airtightness [29] has been identified as critical factors in minimizing heat loss and enhancing energy efficiency. However, while traditional insulation methods have been widely adopted, recent studies suggest that dynamic façade systems may offer superior performance by adapting to changing environmental conditions [30]. This shift towards dynamic solutions reflects a growing recognition of the need for innovative approaches to energy efficiency in cold climates.

Insulation and airtightness are fundamental strategies for improving energy efficiency in buildings, particularly in cold climates where heat retention is crucial [28, 29, 31]. The literature emphasizes that inadequate insulation can lead to significant energy losses, resulting in increased heating costs and reduced occupant comfort [32]. However, this paper proposes a rationale for de-emphasizing traditional insulation methods in favor of dynamic façade systems. By leveraging adaptive technologies, buildings can respond to real-time environmental conditions, potentially reducing reliance on static insulation while maintaining thermal comfort [32]. This approach aligns with recent findings that highlight the effectiveness of dynamic systems in optimizing energy performance without compromising occupant comfort [33-35].

Despite these climatic challenges, there is a notable scarcity of comprehensive, data-driven, and simulation-based studies specifically focusing on the optimization of residential building envelopes within this unique climatic context in Iran [36]. This research gap highlights the critical need for a detailed investigation into envelope design solutions to reduce energy consumption and enhance thermal comfort in Bojnord and similar regions. This study addresses this gap by providing a quantitative comparison of a wide range of both fixed and adaptive (smart) façade strategies, specifically tailored to Bojnord's cold and semi-arid climate, which represents a novel contribution to the field.

1.4. Research Objectives

The primary objective of this research is to systematically investigate and quantify the energy-saving potential of various building envelope optimization strategies for residential buildings in Bojnord, using advanced simulations. Sub-objectives include evaluating the comparative performance of fixed versus adaptive (smart) façade designs, proposing optimal materials suitable for high-performing strategies, and providing practical, evidence-based recommendations for architects and designers working in similar climatic zones.

2. Climatic Context of Bojnord

This section elaborates on the geographical and climatic characteristics of Bojnord, providing the necessary environmental basis for this study.

2.1. Geographical Location and Topography

Bojnord is situated in the northeast of Iran. It is located at 57° 20' longitude and 37° 28' latitude. Bojnord's elevation is 1070 meters above sea level, which influences its thermal characteristics. Topographically, it is nestled south of the Kopeh Dagh mountain range, east of the Aladagh mountain range, and north of the Alborz Mountain range [24].

2.2. Climatic Characteristics

Bojnord experiences cold winters and relatively warm summers, resulting in a wide range of temperature variations throughout the year. The average annual temperature in the city is 13.45°C. The difference in mean temperature between July (the warmest month) and January (the coldest month) can exceed 20 °C [23]. Bojnord city experiences an average of over 100 frost days annually, indicating a prolonged heating season. In terms of solar radiation, the sun's angle at local noon on July 1st (summer solstice) is 76 degrees, and on January 1st (winter solstice), it is 29 degrees [36]. These solar angles are crucial for passive solar design. Based on these characteristics, Bojnord falls under the cold and semi-arid climate (BSk) according to the Köppen climate classification, typically known for its cold winters and moderate summers [24].

Considering climatic parameters as dew point, dry temperature, and relative humidity are essential for creating a façade that is not only aesthetically pleasing but also functional, energy-efficient, and durable in the specific climate condition of Bojnord. The average dew point in Bojnord ranges from approximately -4.1°C in January to 11.0°C in July. This indicates that the air can hold varying amounts of moisture throughout the year, with higher dew points in the warmer months suggesting more humidity [37].

The mean daily temperatures vary significantly across the year, with average daily maximum temperatures ranging from about 0.9°C in January to 32.8°C in July. This range highlights the cold winters and hot summers typical of the region. The average relative humidity in Bojnord is generally high, ranging from about 72% in January to 42% in August. This suggests that the air is quite moist during the winter months, which can lead to condensation issues, while the summer months are drier [23]. More information about the climatic characteristics of Bojnord is presented in Fig. (**1**).

- The Bojnord region is also influenced by several local winds [37]:
- Gorgan Wind: Blows from the west in all seasons at a mild speed, bringing humidity and rainfall.
- Qibla Wind: Blows from the south during autumn and winter, causing dry air.
- Sortuk Wind: Comes from the north, mostly in summer and winter, making the air cold in winter and moderate in summer.

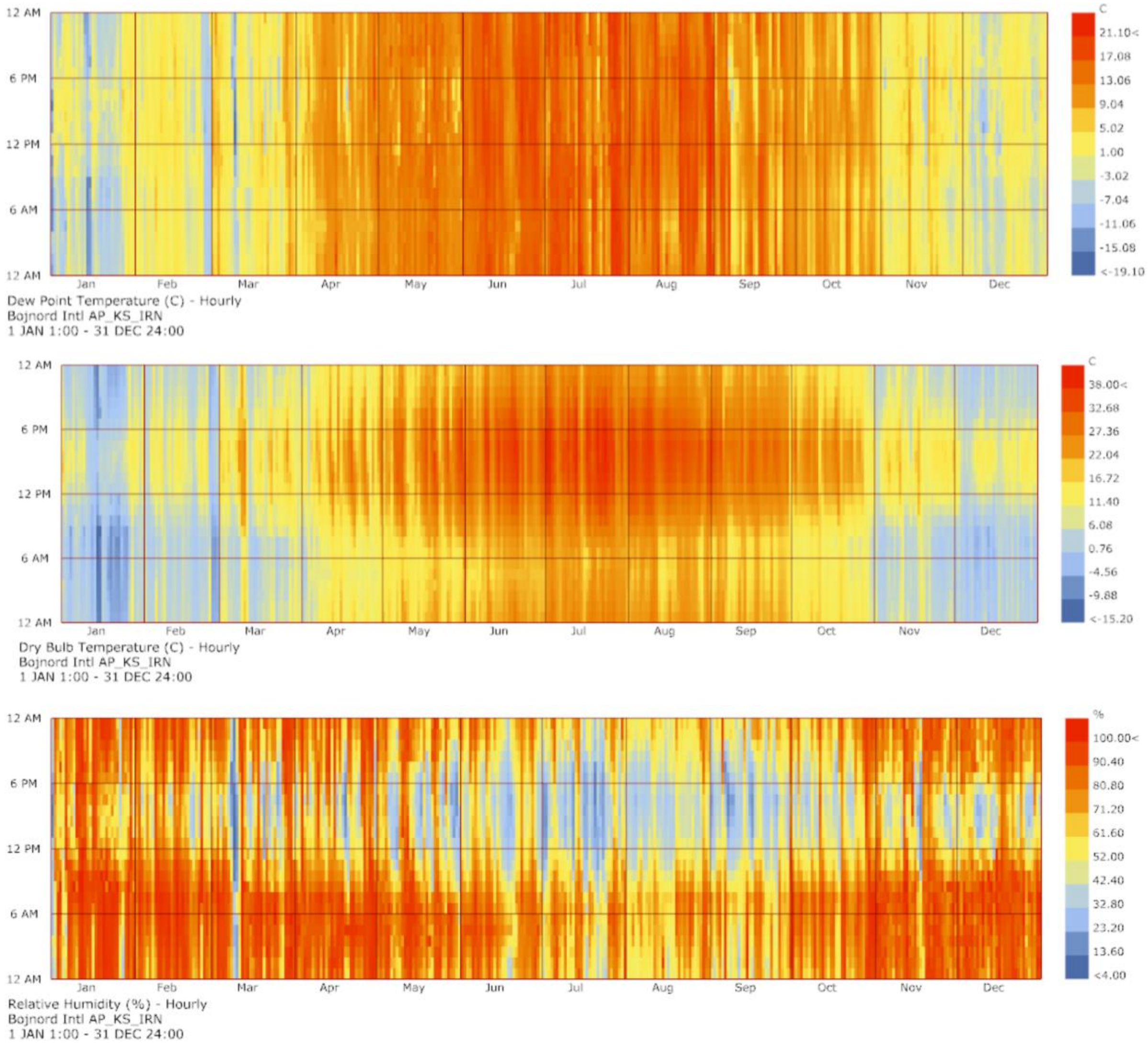


Figure 1: Dew point temperature, dry bulb temperature, and relative humidity in Bojnord.

- Aish Wind: Blows from the east and northeast during spring and summer.
- Dolan Wind: Blows from the west and northwest in all seasons and is beneficial for agriculture in the region [37]. For better understanding, the horizontal and vertical wind-rose diagram of Bojnord is presented in Fig. (**2**).

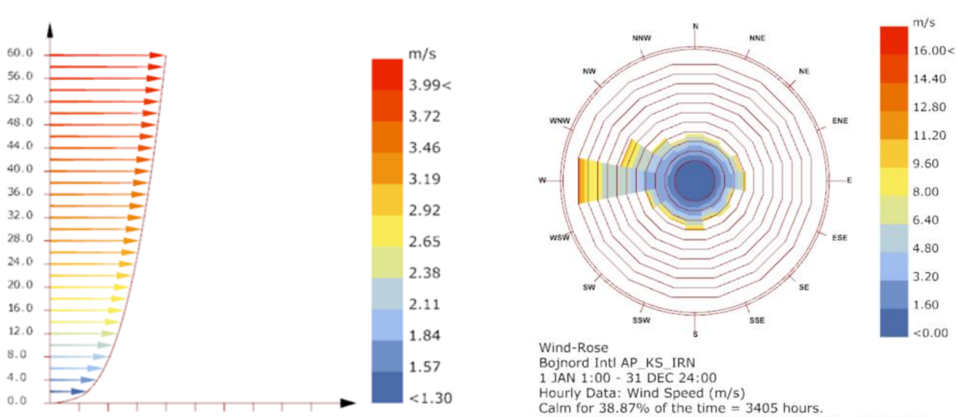


Figure 2: Wind Rose in the city of Bojnord.

2.3. Design Implications

A detailed analysis of Bojnord's climatic data reveals three significant implications for building envelope design:

2.3.1. Dominance of Heating Load and Its Design Directives

The climatic data indicate "cold winters" and "over 100 frost days annually" in Bojnord. These conditions imply a predominant need for heating throughout most of the year. Psychrometric chart analysis further identifies "passive solar heating" (with 15.2% effectiveness) and "internal heat gain" (with 25.6% effectiveness) as two effective strategies for achieving thermal comfort. Moreover, base model simulation results show that heating energy consumption (72.76 kWh/m^2) is approximately nine times higher than cooling energy consumption (8.44 kWh/m^2). This stark difference confirms that Bojnord's climate is primarily heating-dominated [36].

This dominance of heating load means that building envelope optimization strategies must primarily prioritize minimizing heat loss during the long winter period. While cooling in summer is also a concern, the most significant energy savings will be achieved through effective insulation and passive solar heat gain strategies. This situation necessitates a design approach that focuses on high thermal resistance for opaque elements and selective heat gain for transparent elements, rather than a balanced or predominantly cooling-focused approach.

2.3.2. Dual Role of Solar Radiation

Solar radiation angles vary significantly between summer and winter [38]. "Passive solar heating" is identified as a crucial strategy for thermal comfort [39, 40]. However, increasing the Window-to-Wall Ratio (WWR) to 80% leads to an increase in cooling load, indicating unwanted heat gain in summer. This situation highlights the need for precise solar radiation management. Solar radiation presents both a significant opportunity for passive heating in winter and a challenge for overheating in summer [41].

This phenomenon suggests that fixed shading solutions may be insufficient [42]. Instead, adaptive or dynamic shading systems that can allow beneficial low-angle winter sun to penetrate while blocking unwanted high-angle summer sun are essential [43, 44]. This duality reinforces the need for "smart building envelopes" or "climate-adaptive building shells" (CABS) that can dynamically respond to changing solar conditions throughout the year and even within a single day [45-47].

3.2.3. Wind as a Factor for Adaptive Ventilation and Protection

Bojnord experiences various local winds; some (like Gorgan wind) bring humidity and rainfall, others (like Qibla wind) cause dry air, while Sortuk wind affects temperature [37]. "Airflow" is explicitly identified as one of the four primary environmental drivers for Climate-Adaptive Building Shells (CABS) [48]. Additionally, Double Skin Façades (DSFs) are discussed as a means for natural ventilation [49]. Beyond solar control, the dynamic nature of local winds in Bojnord suggests that adaptive façade elements should also consider wind direction and speed. This could involve strategically opening and closing vents for natural ventilation during favorable conditions (e.g., mild summer breezes) and providing robust protection against cold and dry winter winds. This factor adds another layer of complexity and potential for optimization in smart façade design, extending beyond purely thermal considerations to include airflow management for comfort and energy efficiency.

3. Principles of Building Envelope Optimization

3.1. General Strategies for Reducing Energy Consumption Through the Envelope

3.1.1. WWR

Windows significantly impact a building's energy performance, affecting both natural lighting and thermal insulation. While increasing WWR can improve daylight, its thermal implications must be carefully considered [50, 51]. An excessively high WWR can lead to excessive light penetration, glare, fading of interior furnishings, significant heat loss in winter, and excessive heat gain in summer [44].

Research indicates that a WWR between 0.20 and 0.30 for the entire building is a suitable and logical ratio for balancing sufficient daylight provision and thermal performance . A WWR below 0.20 may not provide adequate daylight, while higher ratios can lead to substantial heat transfer. Reducing this ratio by up to 35% can have a dramatic impact on improving building energy efficiency [51]. As illustrated in Table **1**, the south façade should maximize WWR for winter solar gain, while the east and west façades require minimal WWR to control unwanted heat and glare [52].

Table 1: Optimal WWR strategies for different façade orientations in cold climates.

Façade Orientation	The Optimal Range of WWR
South	In climates with cold winters, it is best for the WWR to be maximized to receive the most daylight and passive solar heat gain from this façade during winter. Heat gain from the south façade is less than from the east and west façades during summer due to the sun's angle in this season.
North	It is recommended that the north façade's WWR be minimized as much as possible during winter. In climates with mild winters, this ratio can be maximized and close to 1.
East and West	Due to the sun's angle, it is advisable to keep the WWR as low as possible on east and west façades to prevent glare and unwanted heat gain. An appropriate value is between 0.1 and 0.2.

3.1.2. Thermal Performance of Windows

Improving the thermal performance of windows involves attention to six main criteria [53]:

- U-value: This coefficient determines the amount of heat passing through a building component like a window. The lower the U-value, the less heat transfer and the better the thermal performance. A poorly insulated and improperly installed window can have a U-value of 1.20, while a triple-glazed insulated window can have a U-value of 0.09. For many common double-glazed windows, this value is 0.35. If the building's walls are well-insulated and its WWR is low, a window with a U-value of 0.40 can be used [54].
- Solar Heat Gain Coefficient (SHGC): This coefficient specifies the reduction in solar heat gain. SHGC is rated between 0 and 1, indicating the amount of radiation transmitted into the interior. For example, a window with an SHGC of 0.35 transmits 35% of radiant heat into the space and reflects 65%. Correct SHGC selection is essential for optimizing window thermal performance, considering sufficient daylight provision, solar heat gain in winter, and minimizing heat gain in summer. For east, west, and north façade s, an SHGC of 0.30 is recommended, and for the south façade, an SHGC of 0.55 is considered [55].
- Low-emissivity Glass (Low-E Glass): The selection of this type of glass significantly impacts light entry and reduces solar heat gain by minimizing heat transfer through radiation [54].
- Visible Light Transmittance (VLT): VLT is a unit for measuring the amount of light entering a space, essentially indicating how transparent the glass is. This factor is valued between 0 and 1; a higher value means more light transmission. The optimal VLT is around 0.5, which maximizes daylight entry and reduces glare.
- Light to Solar Gain (LSG): This ratio (VLT/SHGC) compares the efficiency of light transmission with its heat gain. A higher value means the window has reduced solar heat gain while allowing more light into the building. The weakest state has a value less than 1, and the best state has a value greater than 1.55. For a high-energy-efficiency building, this coefficient should be 1.67 (0.50 VLT / 0.30 SHGC = 1.67) [55].

3.1.3. Climate-Adaptive Building Shells (CABS)

Loonen *et al*. define CABS as an envelope with the ability to repeatedly and reversibly change certain functions, characteristics, or behaviors over time, in response to changing functional needs and surrounding conditions, to improve the overall building performance. CABS are considered a promising technology for achieving net-zero energy buildings with high levels of thermal and visual comfort. The goal of using this technology is to improve indoor environmental quality and reduce building energy consumption. In a 2013 study on CABS, four environmental factors were identified as primary drivers for building envelope changes: thermal, visual, airflow, and electricity [48, 56]. Understanding the interrelation of these environmental factors (Table **2**) is essential for developing effective adaptive building envelope strategies.

Table 2: Environmental factors influencing climate-adaptive envelopes.

Type of Environmental Factors	Description
Thermal	Adaptation changes the building's energy balance through conduction, convection, radiation, and thermal energy storage.
Visual	Adaptive behavior influences occupants' visual perception by changing the transparent surfaces of the building envelope.
Airflow	Airflow occurs across the façade boundary, and adaptive behavior is influenced by wind direction and speed.
Electricity	The integrated energy structure of the building occurs at the façade level, and electricity consumption is an important part of the adaptation mechanism (or: electricity consumption is an important component of the adaptive mechanism).

3.1.4. Double-Skin Façade (DSF)

The building envelope is the boundary between the controllable interior space and the uncontrollable exterior space, and it is precisely where a significant amount of energy loss occurs [21]. Therefore, by controlling the amount of energy loss and transmission through the external façade, building energy consumption can be significantly reduced. The use of double-skin façades is one solution that can make this possible. DSF has recently gained significant attention as a passive solution for cooling and heating the interior environment of buildings. This technology allows for the combination of modern glass façades with energy efficiency [56].

However, due to the complexity of thermal and airflow phenomena, as well as the adaptability of this solution to different climatic conditions, its implementation faces many challenges. In cold climates, DSFs are used differently. Shading devices are typically only used for certain hours of the day, and often, maximizing daylight is a primary concern in these climates for reducing energy consumption in the lighting sector [57]. Additionally, in summer, by opening the vents in the cavity between the two façade skins, the airflow created inside the cavity is used to reduce the cooling load inside the building. In winters, the air cavity acts as a thermal buffer, utilizing its insulating role to reduce the heating load inside the building [58].

3.2. Passive Climatic Design Strategies for Bojnord

A psychrometric chart analysis of Bojnord city was conducted to identify the most effective passive design strategies tailored to its climate (Fig. **3**).

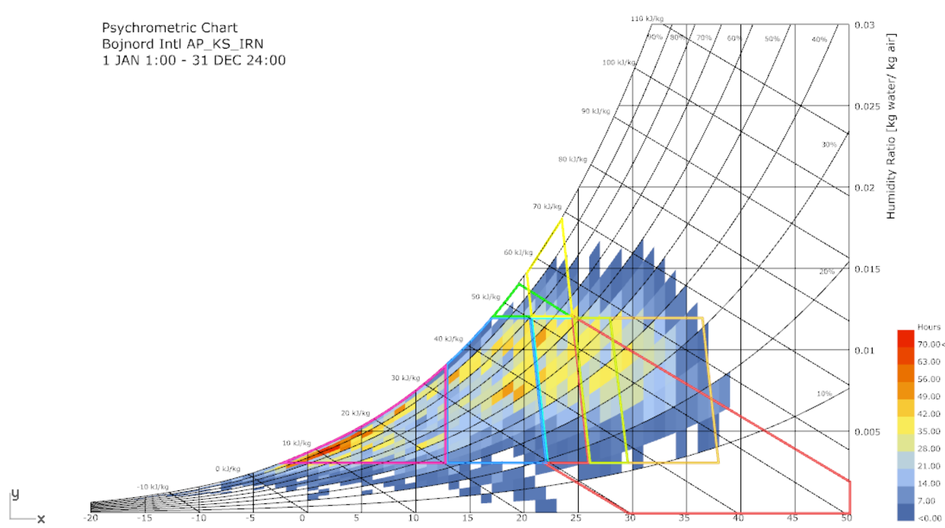


Figure 3: Psychometric chart of Bojnord (Ladybug's output).

The results of this analysis indicate the efficiency percentage of each strategy for achieving thermal comfort in residential buildings:

- Comfort conditions: Approximately 10.2% of the year is within comfort conditions, requiring no active intervention.
- Evaporative cooling: This strategy shows an efficiency of 10.1%.
- Thermal Mass: The use of thermal mass in building materials is effective for 7.6% of the time.
- Natural ventilation: Natural ventilation, often facilitated by occupants using fans, contributes 6.8% to comfort.
- Internal heat gain: This strategy accounts for a significant 25.6% of the effectiveness. This refers to heat generated within the building from occupants, lighting, and equipment. While primarily a consideration for building layout, it indirectly impacts envelope design by contributing to the overall thermal balance.
- Passive solar heating: This strategy is identified as a highly effective solution, contributing 15.2% to comfort conditions (Table **3**).

Based on psychrometric analysis, passive solar heating is highlighted as the "most crucial strategy" for building envelope design in Bojnord to enhance thermal comfort and reduce energy consumption. This is due to its direct interaction with the building envelope and its significant contribution to overcoming the predominant heating load in this climate.

Table 3: Design strategies (Ladybug's output).

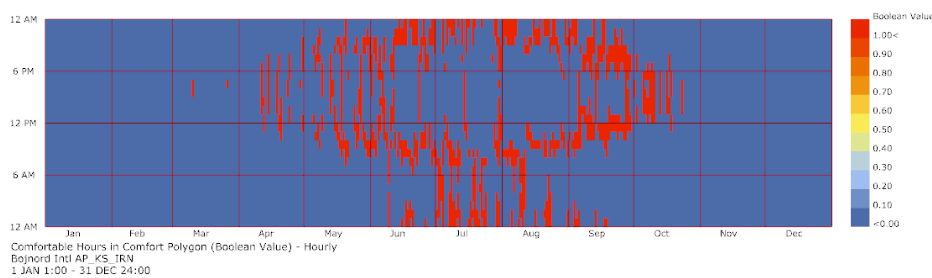
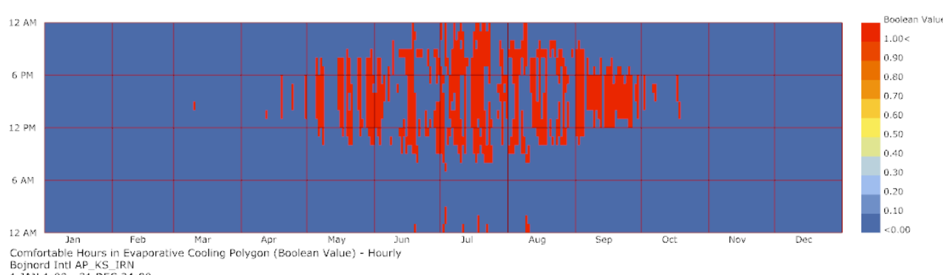
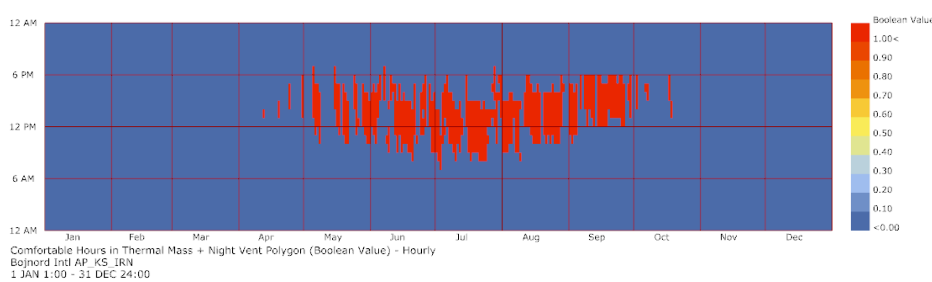
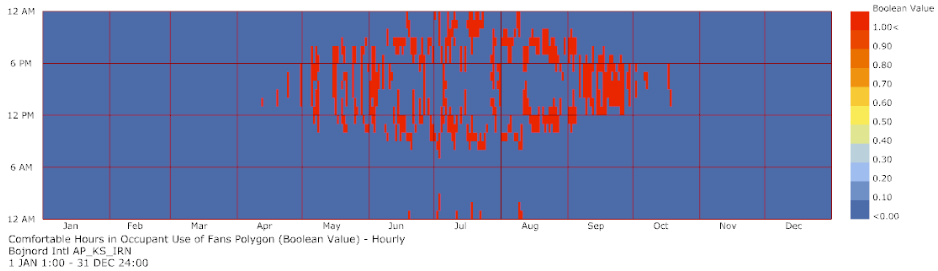
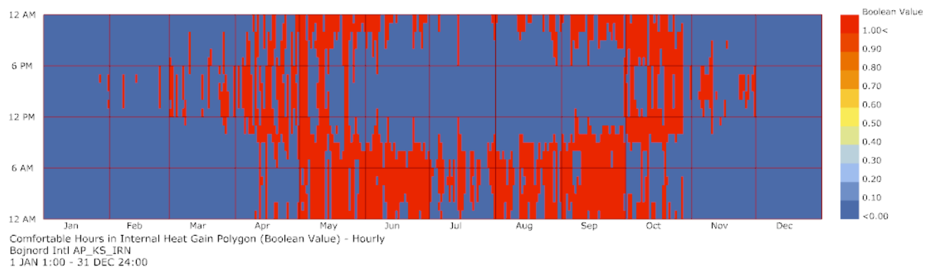
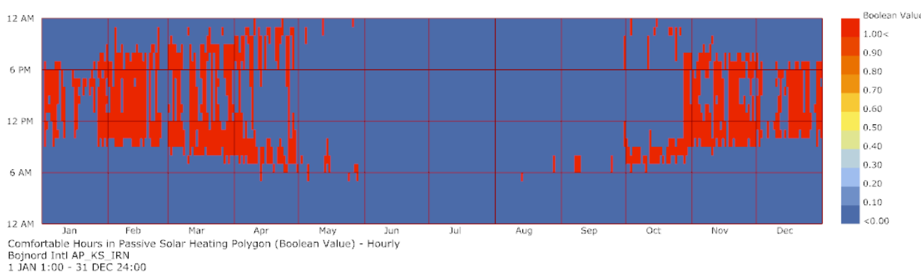
Type of Strategy	Efficiency Percentage	Chart
Occupants' comfort	10.2	
Evaporative cooling	10.1	
Thermal mass	7.6	

Table 3: contd….

Natural ventilation	6.8	
Internal heat gain	25.6	
Passive solar heating	15.2	

3.3. Design Implications

The analysis of building envelope optimization principles reveals three further significant implications for design in Bojnord:

3.3.1. Interdependence of WWR and Glazing Properties

The general recommendation for optimal WWR is between 0.20 and 0.30, and subsequent simulation results for Bojnord indicate that a 20% WWR is the most efficient option for fixed façades. However, the performance of any WWR is fundamentally modulated by the thermal properties of the glazing itself (U-value, SHGC, VLT, LSG). For instance, a high WWR with advanced, low-emissivity (Low-E) and spectrally selective glazing might outperform a low WWR with standard, inefficient windows. This situation suggests that WWR should not be considered in isolation.

A holistic design approach is essential, where the optimal WWR is determined in conjunction with high-performance glazing specifications tailored to the specific climate. For Bojnord, this means selecting windows that balance maximizing beneficial winter solar heat gain (potentially higher SHGC for south-facing windows) with minimizing unwanted summer heat gain (lower SHGC for east/west/north-facing windows), while always prioritizing low U-values to combat heat loss in cold winters.

3.3.2. Climate-Adaptive Building Shells (CABS)

Bojnord's climate is characterized by significant seasonal and diurnal temperature fluctuations, varying solar angles, and diverse wind patterns. Static building envelopes are inherently challenged in optimally adapting to such dynamic conditions. The definition of CABS explicitly refers to their ability to "change... in response to changing needs and conditions", and subsequent simulation results for "smart façades" demonstrate superior performance compared to fixed options [45, 48, 59]. This indicates that while conventional, fixed envelopes offer improvements, they are likely to fall short of achieving true optimal performance year-round in Bojnord. CABS, with their inherent adaptability across thermal, visual, airflow, and even electrical domains, offer a more sophisticated and ultimately more effective paradigm for maximizing energy efficiency and occupant comfort in climates with significant seasonal variations. This analysis provides a strong theoretical foundation and justification for the detailed investigation of adaptive façade solutions.

3.3.3. Passive Solar Heating

The psychrometric chart analysis unequivocally identifies "passive solar heating" (with 15.2% effectiveness) as the "most crucial strategy" for building envelope design in Bojnord. This finding is particularly significant when compared to other passive strategies like evaporative cooling or natural ventilation, which show lower effectiveness percentages. This implication dictates a fundamental shift in the design philosophy for buildings in Bojnord and similar climates. Rather than merely insulating, architectural design should actively prioritize maximizing beneficial solar heat gain during the cold winter months. This means strategically orienting the building, optimizing the size and properties of south-facing glazing (e.g., higher SHGC for winter gain), and integrating effective thermal mass elements into the building structure to store and slowly release this solar heat. This emphasis should guide the early conceptual stages of architectural design to ensure solar energy is harnessed as a primary heating source.

4. Case Study and Simulation Methodology

4.1. Description of the Case Study Building Model

For this study, a 5-story residential building was considered as a representative model of typical urban housing in the city of Bojnord, northeastern Iran (Fig. **4**). The building includes a parking space and a commercial unit on the ground floor. This selection reflects common typologies in the region and aligns with previous studies on adaptive façade systems in similar climatic conditions (e.g., Mashhad), thereby providing continuity and a comparative foundation.

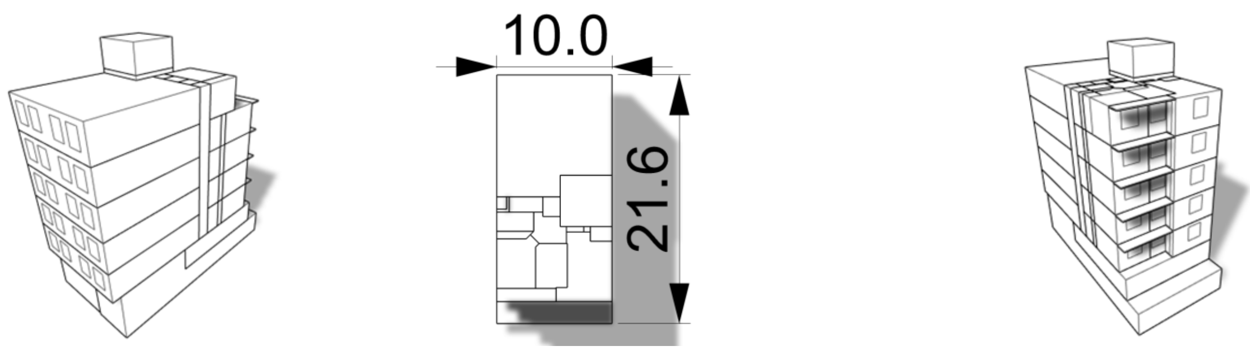


Figure 4: Architectural plan and schematic views of the selected building.

The main façade is oriented toward the south, which allows optimal solar access for heating-dominated climates. The HVAC system was considered to be a Packaged Terminal Air Conditioner (PTC). The visual programming environment Grasshopper within Rhino 3D, along with Honeybee and Ladybug plugins, was employed for parametric modeling and energy simulation. These tools enable integration of real-time climatic data and detailed control over envelope variables, including solar gain parameters.

While advanced holistic energy modeling tools such as EnergyPlus exist, the selection of Ladybug/Honeybee (version 0.0.64) was based on their compatibility with parametric design workflows, geometric flexibility, and their ability to directly link to solar radiation, daylighting, and envelope response strategies in early design phases. All simulation steps, including material assignment and boundary conditions, were structured in Grasshopper, as shown in Fig. (**5**). Although distinct simulation modules were used, consistency in boundary conditions, location data, and HVAC system ensured coherence and comparability across cases.

Envelope parameters were kept consistent across all case studies to isolate the influence of façade geometry and opening percentage. For instance, wall construction included layers of brick, air gap, Heblex, and gypsum-soil composites, as detailed in Table **4**. While insulation levels were not altered between scenarios, their thermal properties (U-values, thermal mass) are defined and constant, forming a stable basis for comparative analysis. The decision to hold these constants is justified by our focus on the kinetic geometry and opening behavior of adaptive façades, based on results of prior studies which showed that solar-responsive openings had the highest energy impact in heating-dominated climates like Mashhad and Bojnord.

Table 4: Software and simulation parameters [60].

Properties	Layer 1	Layer 2	Layer 3	Layer 4
External wall material	Brick (10 cm thickness, thermal conductivity (k)=1, density (ρ)=1700, heat capacity (Cp)=840)	Air (thermal conductivity (k)=0.3, density (ρ)=36, heat capacity (Cp)=984)	Heblex (30 cm thickness, thermal conductivity (k)=0.1, density (ρ)=500, heat capacity (Cp)=1500)	Gypsum and soil (2.5 cm thickness, thermal conductivity (k)=0.4, density (ρ)=900, heat capacity (Cp)=1100)
Interval wall material	Gypsum and soil (2.5 cm thickness, thermal conductivity (k)=0.4, density (ρ)=900, heat capacity (Cp)=1100)	Heblex (10 cm thickness, thermal conductivity (k)=0.4, density (ρ)=500, heat capacity (Cp)=984)	Gypsum and soil (2.5 cm thickness, thermal conductivity (k)=0.4, density (ρ)=900, heat capacity (Cp)=1100)	-
Window				
U-value		SHGC (Solar Heat Gain Coefficient)	VT (Visible Light Transmittance)	
2.15		0.41	0.46	
Base Model Energy Consumption				
Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	Total annual energy consumption (kWh/m²)	
8.44		72.76	81.2	

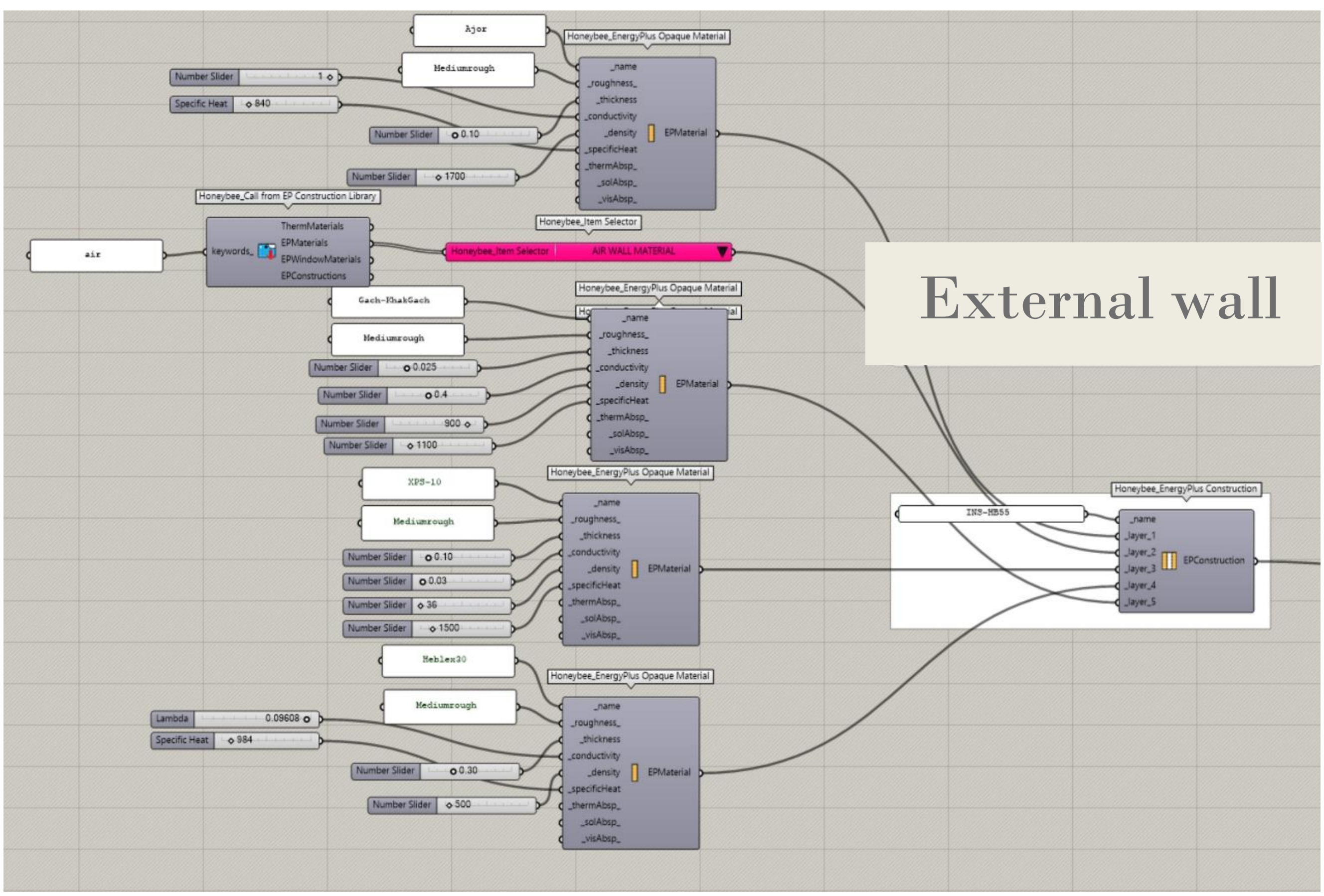


Fig. 5: contd….

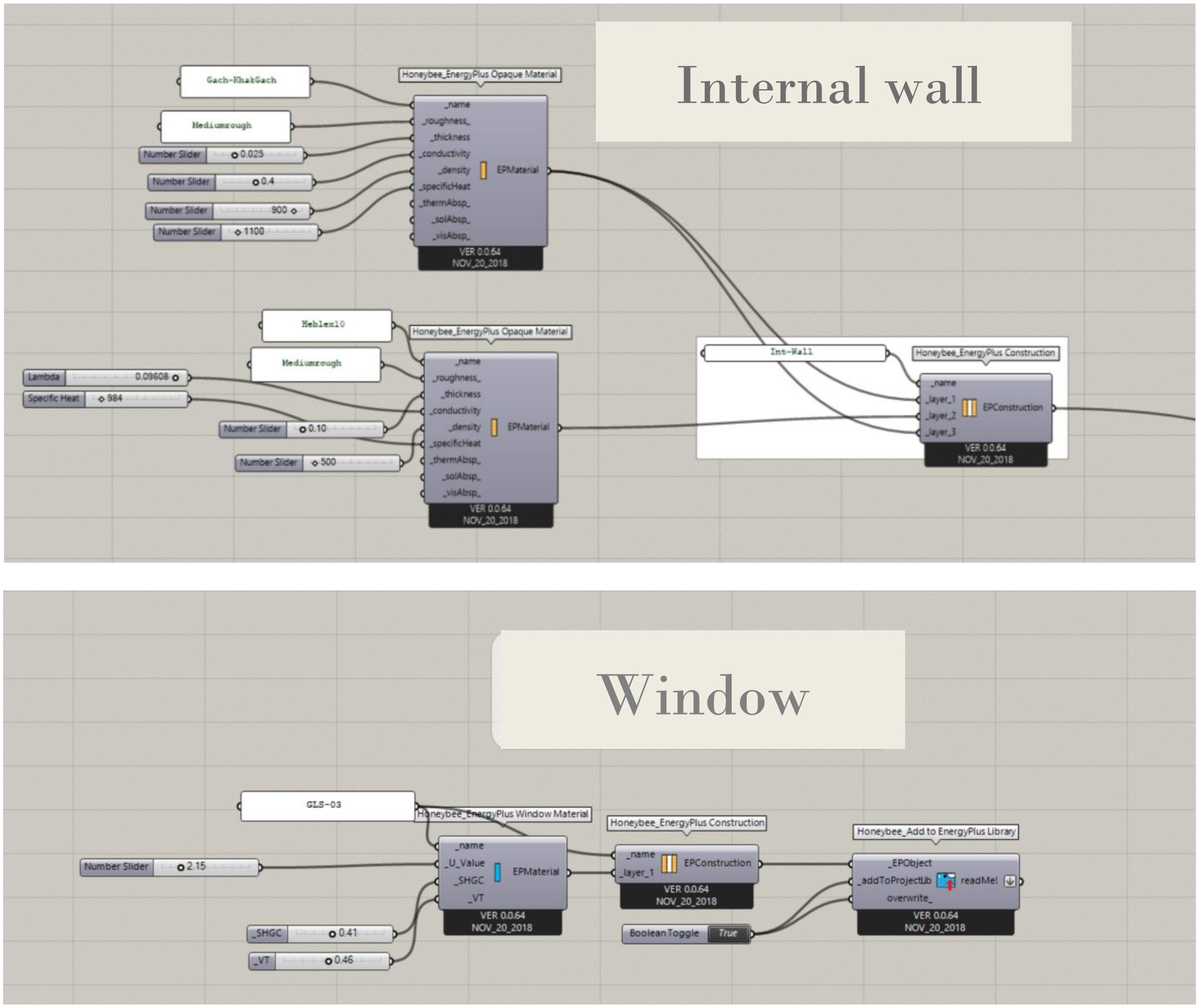


Figure 5: Algorithms for material definition in Grasshopper.

The window properties (U-value 2.15, SHGC 0.41) represent typical local construction standards and intentionally provide a suboptimal baseline to highlight the potential benefits of façade adaptation. Although this study does not include economic cost-benefit analysis or control algorithms of dynamic systems, these aspects are acknowledged as future research directions. The simulation environment was established using Grasshopper, Ladybug, and Honeybee, which act as visual scripting interfaces for the EnergyPlus and Radiance engines. This parametric workflow allows full integration of geometry modeling, material definitions, climate inputs, and simulation results in a single environment [61]. All energy simulations were conducted using Honeybee (v0.0.64), which generates EnergyPlus input files automatically based on the building geometry and parameters defined in Grasshopper.

The reason for using this workflow rather than standalone energy modeling tools (such as DesignBuilder or OpenStudio) was its superior compatibility with adaptive façade geometry manipulation and rapid parametric variation. The flexibility of this approach facilitated the comparison of multiple façade configurations in a consistent and efficient manner. However, we acknowledge that while this setup provides valuable insights into the impact of form and envelope changes, it inherently simplifies some operational aspects such as HVAC system dynamics or cost estimations. These limitations are noted as potential areas for future model enhancement.

4.2. Deeper Design Implications

The baseline simulation results show that heating demand (72.76 kWh/m²) dominates the building's total annual energy consumption (81.2 kWh/m²), while cooling demand (8.44 kWh/m²) remains relatively low. This confirms Bojnord's heating-dominated climate, as previously shown in the psychrometric analysis, and justifies the emphasis on strategies that reduce winter energy losses and maximize passive solar gains. The window system of the base model has relatively high U-values and uniform SHGC across all orientations.

These choices were deliberate to reflect common construction practice and to serve as a neutral base for comparison. Prior research suggests that even moderate improvements in glazing performance or orientation-based SHGC optimization can significantly reduce heating loads in cold-dry climates. However, this study focused primarily on façade morphology and WWR variation, and therefore did not modify insulation levels or introduce advanced thermal mass strategies, to preserve clarity in isolating geometric effects. This decision aligns with our goal to evaluate adaptive vs. static façade geometries under consistent thermal properties.

5. Results and Discussion

5.1. Changing the Variation of WWR

The impact of varying WWR on building energy performance was investigated by simulating four distinct WWR percentages: 20%, 40%, 60%, and 80% (Table **5**). According to the simulation results, the façade with a 20% WWR demonstrated the best performance in reducing both cooling and heating loads. This configuration yielded the lowest cooling load (10.60 kWh/m²), effectively minimizing summer heat gain, and concurrently exhibited the lowest heating load (66.60 kWh/m²), implying superior heat retention in winter. In contrast, the façade with an 80% WWR consistently showed the highest cooling and heating loads.

Table 5: Energy consumption in the first façade design strategy (WWR variation).

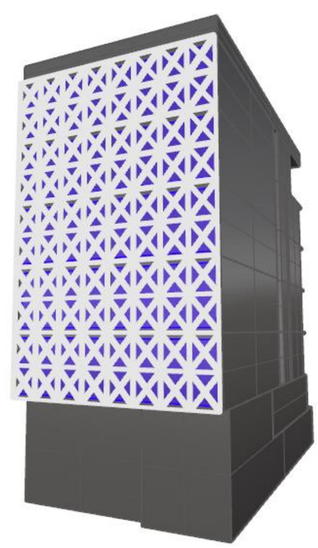
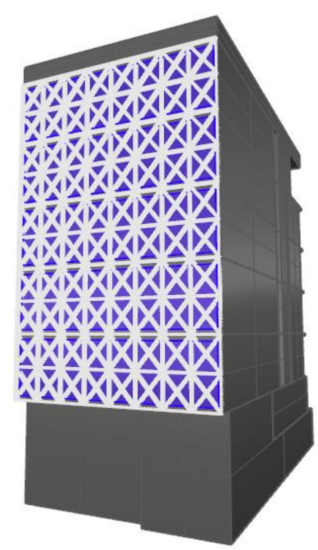
	WWR: 20%		WWR: 40%		WWR: 60%		WWR: 80%	
								
	Cooling (kWh/m2)	Heating (kWh/m2)	Cooling (kWh/m2)	Heating (kWh/m2)	Cooling (kWh/m2)	Heating (kWh/m2)	Cooling (kWh/m2)	Heating (kWh/m2)
January	0.00	20.66	0.00	19.99	0.00	19.31	0.00	18.44
February	0.00	13.62	0.00	13.05	0.00	12.49	0.00	11.84
March	0.01	8.77	0.02	8.37	0.03	8.00	0.05	7.58

Table 5: contd....

April	0.09	3.20	0.12	3.03	0.14	2.90	0.19	2.73
May	0.64	0.31	0.69	0.29	0.73	0.27	0.79	0.25
June	1.75	0.00	1.82	0.00	1.87	0.00	1.95	0.00
July	2.73	0.00	2.81	0.00	2.87	0.00	2.95	0.00
August	2.32	0.00	2.41	0.00	2.49	0.00	2.59	0.00
September	1.13	0.01	1.25	0.01	1.35	0.01	1.49	0.01
October	0.22	1.62	0.31	1.51	0.411	1.43	0.55	1.34
November	0.00	10.91	0.00	10.41	0.01	9.93	0.03	9.41
December	0.00	16.97	0.00	16.36	0.00	15.74	0.00	15.01
Total	8.90	76.80	9.42	73.03	9.90	70.07	10.66	66.60
	84.97		82.45		79.97		77.21	
Energy consumption reduction compared to the base model	4.56%		1.54%		-1.52%		-4.92%	
Heating load reduction compared to the base model	4.56%		0.37%		-3.69%		-8.46%	
Cooling load reduction compared to the base model	5.43%		11.61%		17.25%		25.64%	

Overall, the optimized performance of the 20% WWR façade resulted in the highest energy savings. Its total energy consumption was 77.21 kWh/m², marking a 4.92% reduction compared to the base model (81.2 kWh/m²). Other WWR configurations tested showed varied total energy consumption, including a 1.52% reduction (79.97 kWh/m²), a 1.54% increase (82.45 kWh/m²), and a 4.56% increase (84.97 kWh/m²). This superior performance of the 20% WWR is primarily attributed to its effectiveness in minimizing unwanted heat gain during summer and reducing heat loss in winter (Fig. **6**).

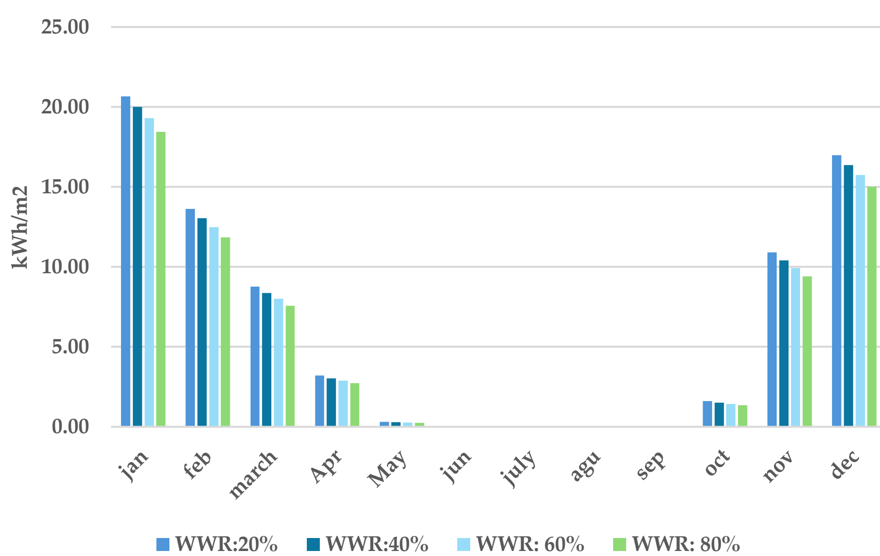


Fig. 6: contd....

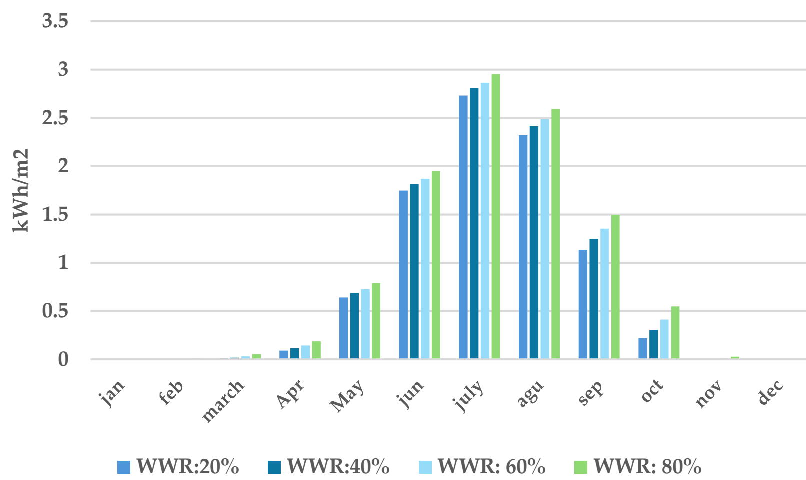


Figure 6: Comparison of heating load (above) and cooling load (below) in façades with different WWR percentages.

5.2. Air Insulation Layer and Shading System (DSF)

This strategy investigated the use of a DSF with an air insulation layer and a shading system. Three different configurations were analyzed: DSF with horizontal shading, DSF with vertical shading, and DSF with both horizontal and vertical shading systems (Table **6**).

Table 6: Energy consumption in the 2nd façade design strategy (DSF).

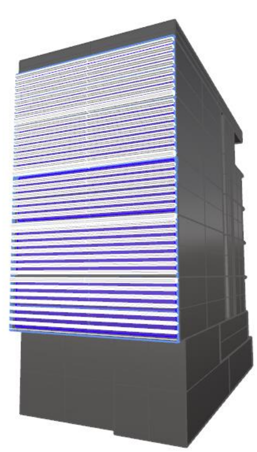
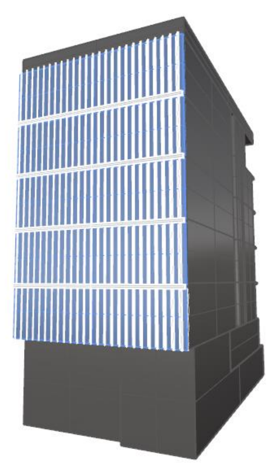
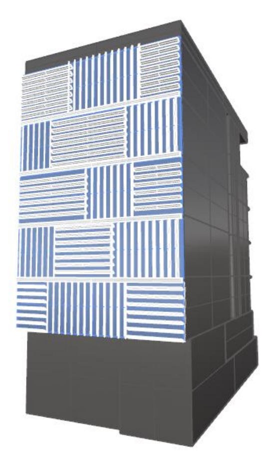
	DSF with Horizontal Shading		DSF with Vertical Shading		DSF with Horizontal and Vertical Shading	
						
	Cooling (kWh/m2)	Heating (kWh/m2)	Cooling (kWh/m2)	Heating (kWh/m2)	Cooling (kWh/m2)	Heating (kWh/m2)
January	0.00	19.38	0.00	19.51	0.00	19.12
February	0.00	12.84	0.00	13.01	0.00	12.20
March	0.00	8.32	0.00	8.36	0.00	8.32
April	0.06	2.53	0.06	2.64	0.06	2.06
May	0.58	0.21	0.58	0.24	0.58	0.18
June	1.64	0.00	1.64	0.00	1.63	0.00
July	2.64	0.00	2.64	0.00	2.62	0.00

Table 6: contd….

August	2.22	0.00	2.22	0.00	2.20	0.00
September	0.96	0.01	0.95	0.01	0.95	0.01
October	0.11	1.34	0.09	1.41	0.10	1.25
November	0.00	10.25	0.00	10.38	0.00	10.12
December	0.00	16.15	0.00	16.25	0.00	16.08
Total	8.21	71.03	8.19	71.81	8.15	69.34
	79.24		80.00		77.48	
Energy consumption reduction compared to the base model	-2.42%		-1.48%		-4.58%	
Heating load reduction compared to the base model	-2.38%		-1.31%		-4.70%	
Cooling load reduction compared to the base model	-2.72%		-2.93%		-3.47%	

According to the results, the DSF with horizontal shading showed the best overall energy performance, primarily due to its effectiveness in reducing cooling loads (Fig. **7**).

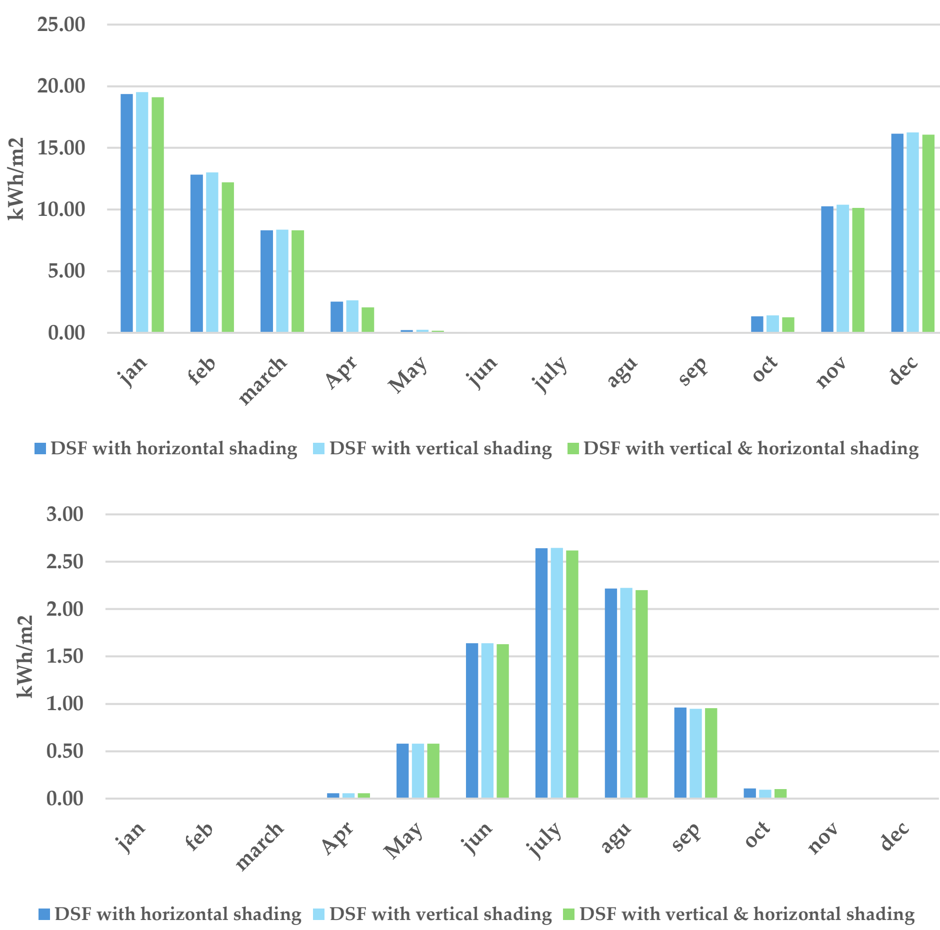
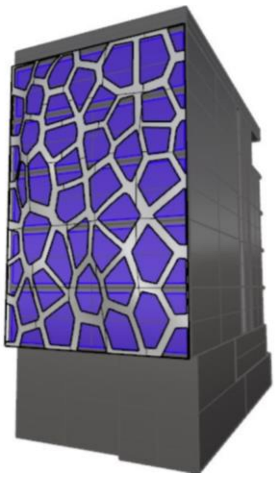
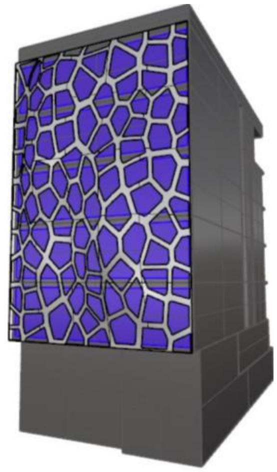
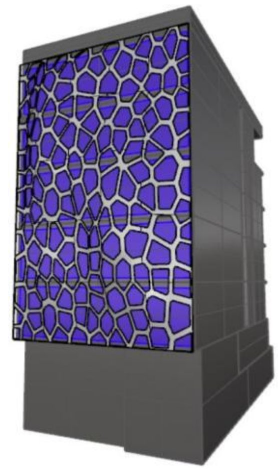


Figure 7: Comparison of heating load (above) and cooling load (below) in different DSF systems.

5.3. Voronoi Façade

The energy performance of a Voronoi façade, characterized by its unique geometric patterns, was investigated through the analysis of three distinct types. The simulated cooling and heating loads for each Voronoi façade type are presented in Table **7** (Cooling and Heating Loads).

Table 7: Energy consumption in the 3rd façade design strategy (Voronoi façade).

	Type 1		Type 2		Type 3	
						
	Cooling (kWh/m2)	**Heating (kWh/m2)**	**Cooling (kWh/m2)**	**Heating (kWh/m2)**	**Cooling (kWh/m2)**	**Heating (kWh/m2)**
January	0.00	19.36	0.00	18.83	0.00	19.85
February	0.00	12.55	0.00	12.32	0.00	12.73
March	0.03	8.06	0.03	8.06	0.03	8.51
April	0.14	2.93	0.14	2.93	0.14	2.76
May	0.71	0.28	0.71	0.28	0.71	0.28
June	1.84	0.00	2.30	0.00	1.38	0.00
July	2.84	0.00	2.75	0.00	2.67	0.00
August	2.46	0.00	2.52	0.00	2.46	0.00
September	1.33	0.01	1.33	0.01	1.20	0.01
October	0.40	1.44	0.40	1.44	0.40	1.44
November	0.01	9.97	0.01	9.97	0.01	10.23
December	0.00	15.78	0.00	14.96	0.00	15.92
Total	9.76	70.38	10.18	68.79	8.99	71.72
	80.13		78.97		80.71	
Energy consumption reduction compared to the base model	-1.31%		-2.74%		-0.60%	
Heating load reduction compared to the base model	-3.27%		-5.46%		-1.43%	
Cooling load reduction compared to the base model	+15.60%		+20.67%		+6.53%	

Regarding total energy consumption, Voronoi Type 2 demonstrated the most efficient performance among the three variations. It recorded a total energy consumption of 78.97 kWh/m², signifying a 2.74% reduction when compared to the base model. Voronoi Type 3 followed with a consumption of 80.13 kWh/m², representing a 1.31% reduction, while Voronoi Type 1 consumed 80.71 kWh/m², a 0.60% reduction. The superior performance of Voronoi Type 2 was primarily driven by its effectiveness in reducing heating loads. However, the overall impact of this Voronoi façade strategy on total energy consumption was relatively modest compared to other strategies investigated in this study (Fig. **8**).

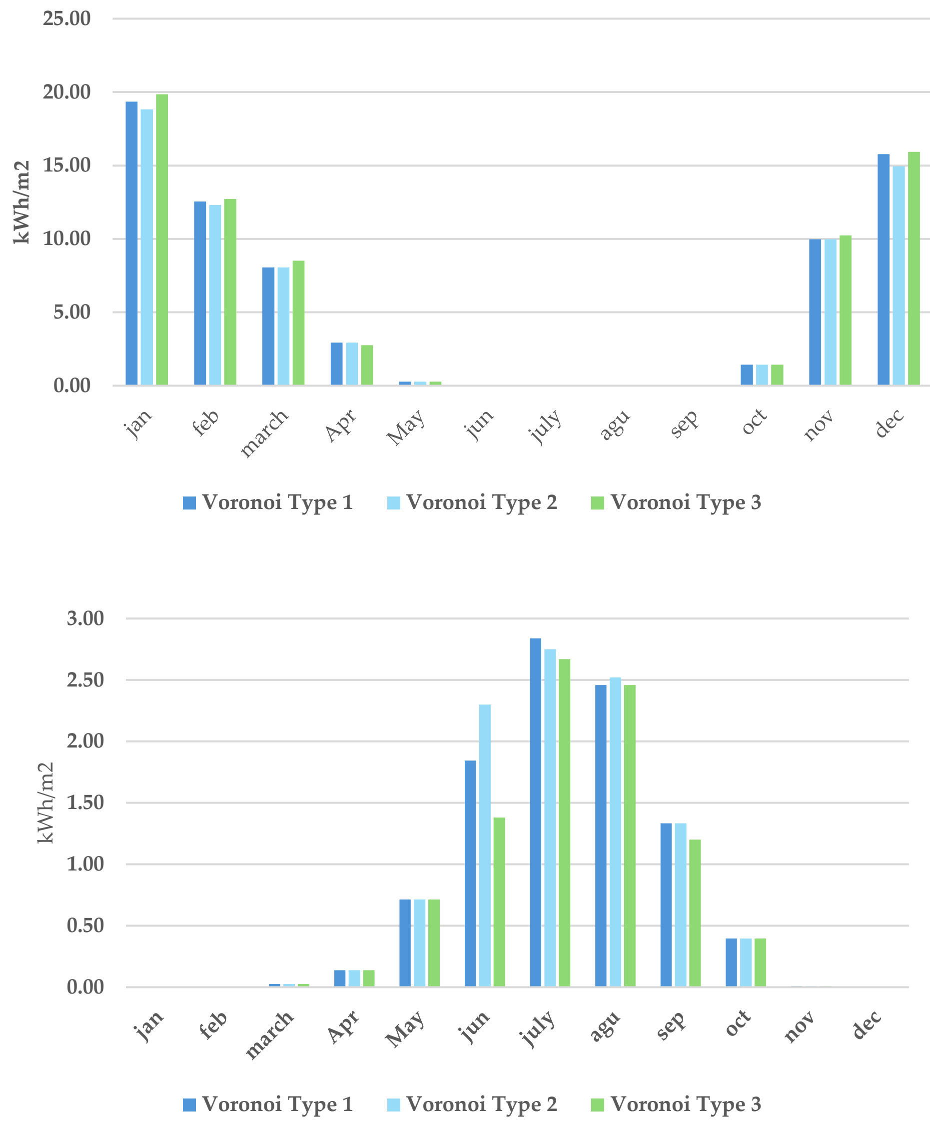
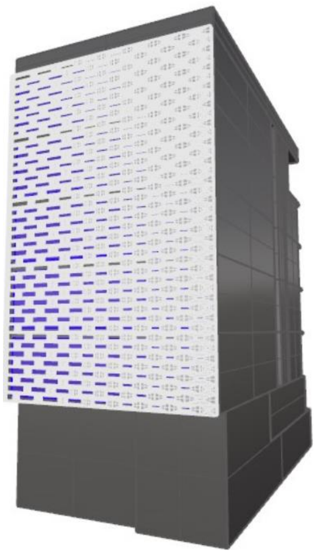
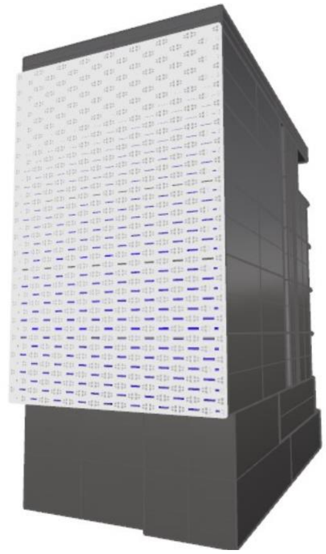


Figure 8: Comparison of heating load (above) and cooling load (below) in different types of Voronoi façades.

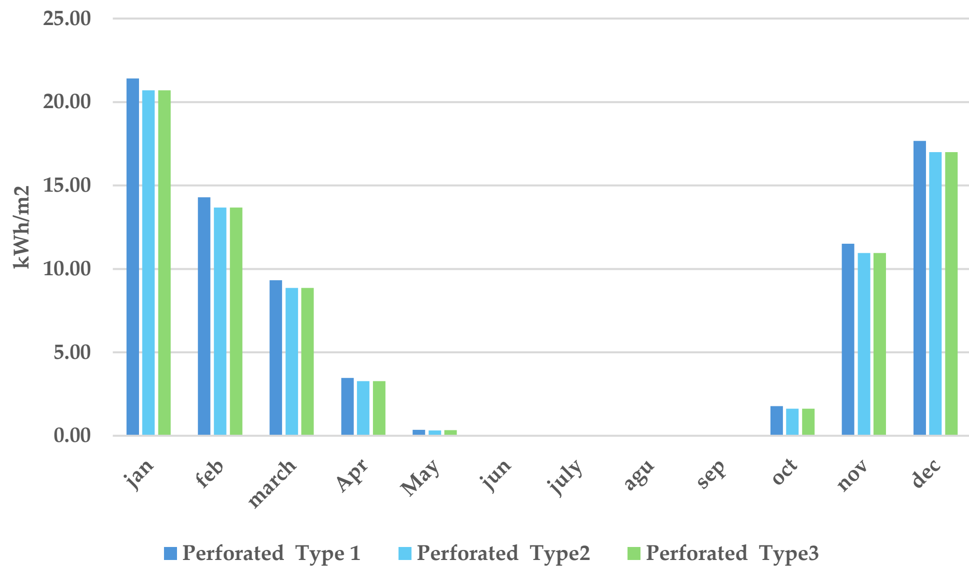
5.4. Perforated Façade

The energy performance of a perforated façade, designed with a pattern of openings to control light and heat, was examined through the analysis of three distinct types. The simulated cooling and heating loads for each perforated façade type are presented in Table **8** (Cooling and Heating Loads). Analysis of the total energy consumption revealed a consistent increase across all investigated perforated façade types when compared to the base model.

Table 8: Energy consumption in the 4th façade design strategy (perforated façade).

	Type 1		Type 2		Type 3	
						
	Cooling (kWh/m2)	**Heating (kWh/m2)**	**Cooling (kWh/m2)**	**Heating (kWh/m2)**	**Cooling (kWh/m2)**	**Heating (kWh/m2)**
January	0.00	20.70	0.00	21.40	0.00	20.69
February	0.00	13.68	0.00	14.29	0.00	13.68
March	0.01	8.86	0.01	9.31	0.01	8.86
April	0.08	3.27	0.06	3.47	0.08	3.28
May	0.61	0.33	0.56	0.36	0.60	0.33
June	1.69	0.00	1.63	0.00	1.68	0.00
July	2.67	0.00	2.60	0.00	2.66	0.00
August	2.27	0.00	2.18	0.00	2.26	0.00
September	1.10	0.01	1.00	0.01	1.10	0.01
October	0.21	1.63	0.14	1.78	0.21	1.63
November	0.00	10.95	0.00	11.51	0.01	10.95
December	0.00	17.00	0.00	17.66	0.01	17.00
Total	8.64	76.42	8.18	79.80	8.61	76.43
	85.06		87.98		85.04	
Energy consumption reduction compared to the base model	+4.76%		+8.34%		+4.73%	
Heating load reduction compared to the base model	+5.03%		+9.67%		+5.04%	
Cooling load reduction compared to the base model	+2.36%		-3.10%		+2.03%	

Perforated façade Type 1 recorded a total energy consumption of 85.06 kWh/m², representing a 4.76% increase. Similarly, perforated façade Type 3 showed an energy consumption of 85.04 kWh/m², a 4.73% increase. The highest consumption was observed in perforated façade Type 2, reaching 87.98 kWh/m², which translates to an 8.34% increase. These findings suggest that, for the climate of Bojnord, the perforated façade strategy generally leads to elevated energy consumption, indicating it may not be the most suitable design approach for energy optimization in this specific climatic context (Fig. **9**).



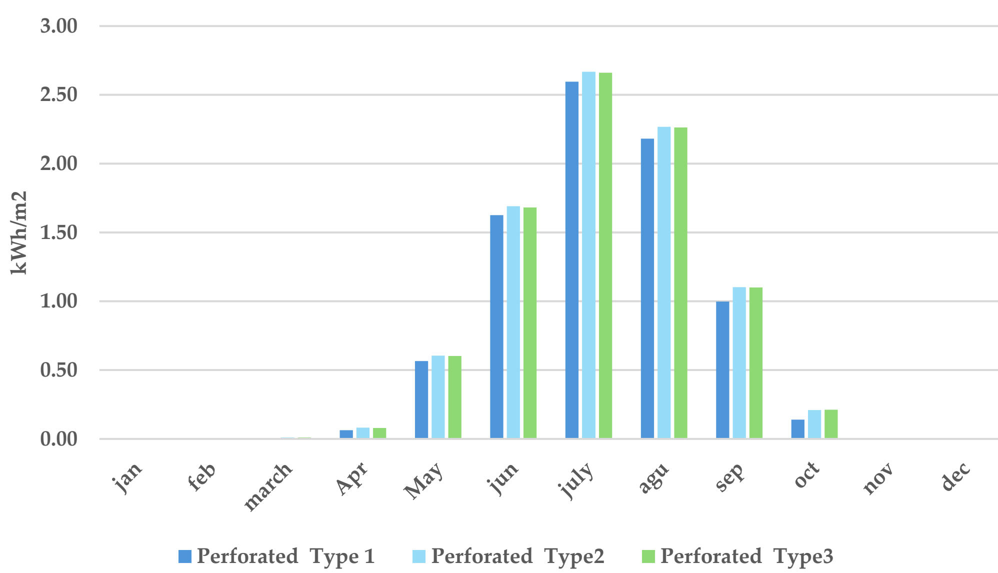
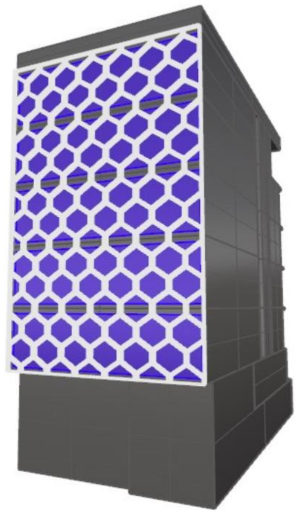
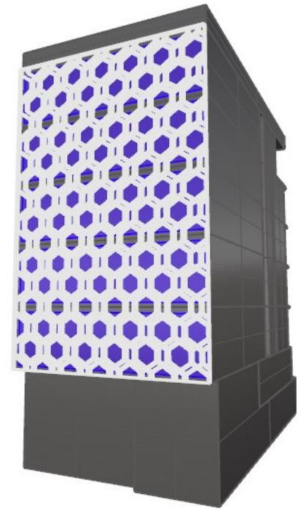
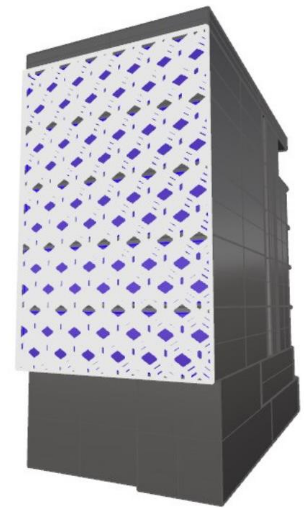


Figure 9: Comparison of heating load (above) and cooling load (below) in different types of perforated façades.

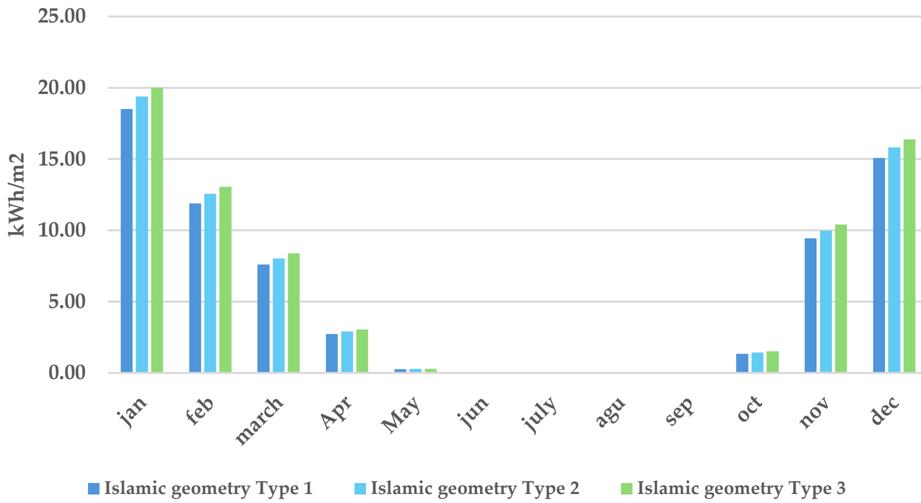
5.5. Perforated Façade with Islamic Geometry

The energy performance of façades designed with Islamic geometric patterns, incorporating three distinct porosity levels, was thoroughly evaluated. The comprehensive cooling and heating load profiles for each porosity configuration are detailed in Table **9** (Cooling and Heating Loads).

Table 9: Energy consumption in the 5th façade design strategy (perforated façade with Islamic geometry).

	Type 1		Type 2		Type 3	
						
	Cooling (kWh/m2)	**Heating (kWh/m2)**	**Cooling (kWh/m2)**	**Heating (kWh/m2)**	**Cooling (kWh/m2)**	**Heating (kWh/m2)**
January	0.00	18.52	0.00	19.40	0.00	20.00
February	0.01	11.89	0.00	12.56	0.00	13.06
March	0.05	7.60	0.03	8.04	0.02	8.39
April	0.19	2.74	0.14	2.90	0.11	3.05
May	0.79	0.25	0.73	0.27	0.68	0.29
June	1.96	0.00	1.87	0.00	1.80	0.00
July	2.96	0.00	2.87	0.00	2.80	0.00
August	2.59	0.00	2.49	0.00	2.40	0.00
September	1.49	0.01	1.35	0.01	1.24	0.01
October	0.54	1.35	0.40	1.43	0.30	1.51
November	0.00	9.45	0.01	9.99	0.00	10.42
December	0.00	15.07	0.00	15.82	0.00	16.37
Total	10.60	66.86	9.89	70.41	9.36	73.09
	77.46		80.30		82.45	
Energy consumption reduction compared to the base model	-4.61%		-1.11%		+1.54%	
Heating load reduction	-8.11%		-3.23%		+0.46%	
Cooling load reduction compared to the base model	+25.55%		+17.16%		+10.88%	

Among the analyzed options, Type 3 emerged as the most energy-efficient solution. It achieved a total energy consumption of 77.46 kWh/m², signifying a notable 4.61% reduction compared to the base model. This superior performance was primarily attributed to its efficacy in mitigating heating loads. While Type 2 also demonstrated energy savings, recording a total consumption of 80.30 kWh/m² (a 1.11% reduction), Type 1 resulted in an increase in consumption, reaching 82.45 kWh/m², which represents a 1.54% rise over the base case (Fig. **10**).



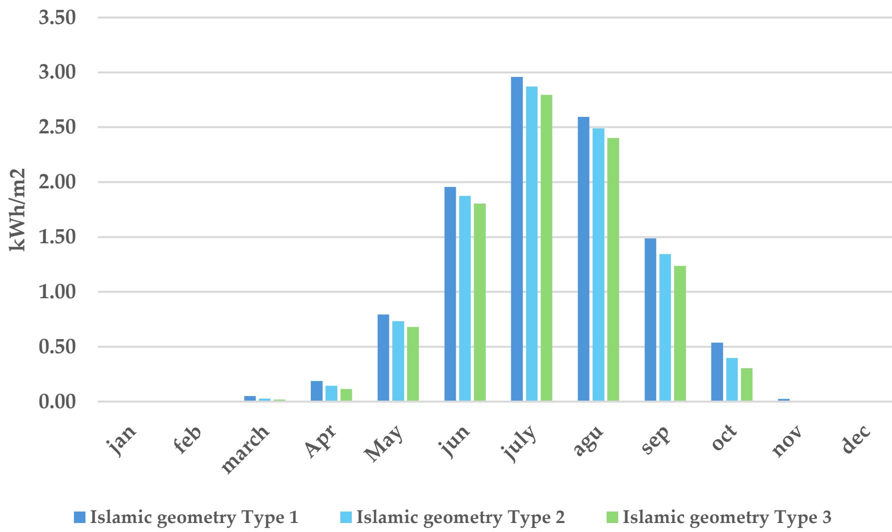


Figure 10: Comparison of heating load (above) and cooling load (below) in different types of perforated façades with Islamic geometry.

5.6. Overall Comparative Analysis of Fixed Strategies

Comparing the five fixed strategies investigated, the façade with 20% WWR and the DSF with air insulation and horizontal/vertical shading demonstrated the most significant energy savings. The façade with 20% WWR resulted in a 4.92% reduction in total energy consumption, while the DSF with horizontal shading achieved a 4.58% reduction. In contrast, perforated and Voronoi façades generally showed less favorable results or even increased energy consumption. This analysis indicates that among fixed strategies, optimizing WWR to 20% is the most effective solution for reducing energy consumption in Bojnord.

However, a significant point to consider is that any façade exhibiting the lowest heating energy consumption and, consequently, the lowest total energy consumption, tends to have a proportionally higher cooling energy consumption. Given the high heating demand in Bojnord and its cold, mountainous climate, prioritizing the reduction of the heating load is crucial. Nevertheless, the ultimate objective of this paper would undoubtedly be the design of an envelope capable of simultaneously reducing both heating and cooling loads. Therefore, the subsequent section will focus on implementing intelligent controls for some of these façade systems (Table **10**).

Table 10: Comparison of fixed façade strategies.

Façade Strategy	Total Energy (kWh/m²/Year)	Reduction Compared to Base (%)	Heating Load (kWh/m²)	Cooling Load (kWh/m²)
Base model	81.20	-	72.76	8.44
WWR: 20%	77.21	4.92 ↓	66.60	10.60
DSF (Horizontal Shading)	77.48	4.58 ↓	69.34	8.15
Islamic Pattern (Type 3)	77.46	4.61 ↓	66.86	10.60
Voronoi (Type 2)	78.97	2.74 ↓	68.79	10.18
Perforated (Type 1)	85.06	4.76 ↑	76.42	8.64

5.7. Smart Façade Strategies

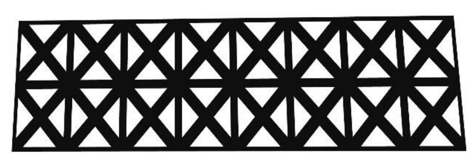
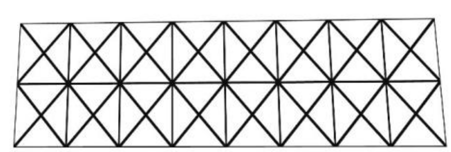
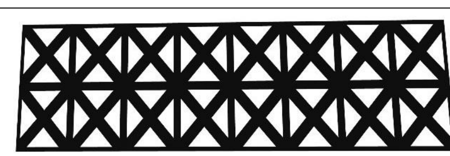
This section examines smart façade strategies, their operational mechanisms, and their energy consumption reduction results.

5.7.1. Smart Façade with Changing WWR

The implementation of a smart façade with a dynamically adjustable WWR was investigated for its energy performance. This system's operational mechanism allows it to transition between a 20% WWR (optimized for minimizing heat loss during winter) and an 80% WWR (designed to maximize daylight and heat gain in moderate seasons). By actively adjusting façade modules based on environmental conditions, this approach aims to optimize natural light ingress and control heat gain and loss throughout various times of the day and across seasons. As mentioned in previous studies [62], the mechanism of changing the opening percentage (COP) is one of the most effective methods for movement in CABFs for the BSk climate.

The application of this variable WWR smart façade yielded significant energy savings. The total energy consumption was recorded at 74.92 kWh/m², representing a substantial 7.73% reduction compared to the base model (81.2 kWh/m²). This performance positions the smart façade with variable WWR as one of the most efficient strategies for reducing overall energy consumption within Bojnord's climate (Table **11**).

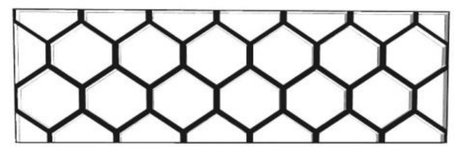
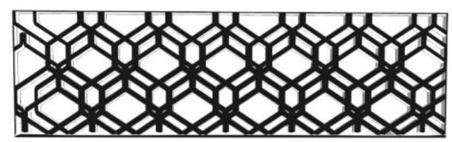
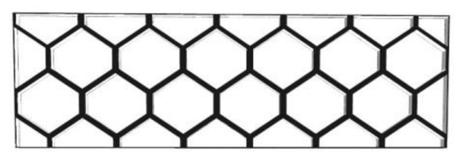
Table 11: Energy consumption in a smart façade with changing WWR.

Month	Energy consumption (kWh/m2)	WWR	Smart façade pattern
January	18.44	80%	
February	11.84		
March	7.58		
April	2.73		
May	0.64	20%	
June	1.75		
July	2.73		
August	2.32		
September	1.13		
October	1.34	80%	
November	9.41		
December	15.01		
Total	74.92 (kWh/m2)		

5.7.2. Hollow Smart Façade (Voronoi/Perforated with Islamic Geometry)

This façade is designed to actively adjust its transparency and porosity, thereby enabling controlled light penetration and creating a dynamic visual effect. By varying its degree of porosity, the system can effectively respond to differing solar radiation conditions and interior daylighting needs. Simulation results for this hollow smart façade demonstrated notable improvements in energy performance. Its total energy consumption was recorded at 75.52 kWh/m², representing a significant 6.99% reduction compared to the base model. This enhanced performance, particularly when contrasted with fixed Voronoi and perforated façade designs, underscores the considerable potential of adaptive approaches in these façade types for optimizing building energy efficiency (Table **12**).

Table 12: Energy consumption in hollow smart façade.

Month	Energy consumption (kWh/m2)	WWR	Hollow smart façade pattern
January	18.52	Type 1	
February	11.89		
March	7.60		
April	2.74		
May	0.68	Type 3	
June	1.80		
July	2.80		
August	2.40		
September	1.24		
October	1.35	Type 1	
November	9.45		
December	15.07		

Type of Annual Energy Consumption	Energy Consumption (kWh/m²)	Energy Consumption Reduction Compared to the Base Model
1	77.46	-2%
3	82.45	-8%
Optimal energy consumption (kWh/m2)	75.52	

5.7.3. Smart Façade with Air Insulation and Shading Systems

The implementation of a DSF system was investigated, characterized by an insulating air cavity between its two layers to mitigate heat transfer. This design incorporates adaptive horizontal and vertical shading systems that dynamically adjust to the sun's angle, strategically blocking direct sunlight in summer and allowing its penetration in winter. This system's ability to reconfigure throughout the day and year is intended to optimize energy efficiency.

The simulation results confirmed the effectiveness of this adaptive double-skin façade in reducing energy consumption. In summer, the total energy consumption was recorded at 75.96 kWh/m², representing a 6.45% reduction compared to the base model (81.2 kWh/m²). Similarly, in winter, total energy consumption was 76.18 kWh/m², achieving a 6.18% reduction. These findings collectively demonstrate that the smart façade, with air insulation and adaptive shading, effectively reduces both heating and cooling loads, particularly through its dynamic operational capabilities.

Based on the comprehensive comparison, the smart façade with changing WWR (specifically with dynamic optimization between 20% and 80% WWR) was identified as the most effective strategy for reducing energy consumption in Bojnord's climate, demonstrating a 7.73% reduction in total energy consumption. This strategy effectively controls both heat gain in summer and heat loss in winter, which is crucial for achieving thermal comfort and reducing energy consumption in this climate. The hollow smart façade also performed very well, with approximately a 7% reduction in energy consumption (Table **13**).

Table 13: Comparison of smart façade solutions.

Smart Façade Solution	Total Energy Consumption (kWh/m²/year)	Reduction in Energy Consumption Compared to the Base Model
Base model	81.2	-
Smart façade with changing WWR	74.92	7.73%
Hollow smart façade	75.52	6.99%
Smart façade with air insulation and shading (Summer)	75.96	6.45%
Smart façade with air insulation and shading (morning)	76.18	6.18%

6. Study Limitations and Future Directions

While this study provides valuable insights into the adaptive geometric behavior of façade systems, it is important to acknowledge certain limitations that may affect the generalizability of the findings. Firstly, the focus of our research was intentionally narrowed to the modulation of window-to-wall ratios and shading configurations in response to climatic variables. As a result, critical factors such as insulation levels, airtightness, and thermal mass were not included in our analysis. This selective approach was based on our previous findings in Mashhad [62], where we identified that geometry-driven adaptability offered significant energy-saving potential.

By isolating the effects of adaptive fenestration geometry, we aimed to provide a clearer understanding of its performance without the confounding influence of other envelope parameters. However, this methodological choice means that the thermal performance of the building envelope, particularly regarding insulation and airtightness, remains unexamined in this study. The exclusion of these elements is a notable limitation, as they play a crucial role in overall energy efficiency and occupant comfort. We recognize that a comprehensive assessment of thermal performance should ideally encompass these factors. Future research will aim to integrate these variables into a more holistic optimization framework, allowing for a more thorough evaluation of façade performance in relation to energy efficiency and sustainability.

7. Conclusion

This study investigated the optimization of residential building envelopes in the cold and semi-arid climate of Bojnord, Iran, through comprehensive simulations. Detailed analysis of climatic data revealed that Bojnord is a heating-dominated climate, characterized by cold winters and over 100 frost days annually, with annual heating loads approximately nine times higher than cooling loads. This underscores the critical importance of strategies that reduce heat loss and maximize passive solar heat gain in envelope design. Simulation results demonstrated that among fixed strategies, optimizing the WWR to 20% was the most effective solution, yielding a 4.92% reduction in total energy consumption. This ratio provides an optimal balance between daylight provision and heat transfer control throughout the year. However, the investigation into smart façade strategies revealed significantly higher potential for energy savings. The smart façade with dynamic WWR adjustment was identified as the most optimal solution, achieving a 7.73% reduction in total energy consumption compared to the base model. This system's adaptability in responding to varying climatic conditions, particularly in controlling heat gain and loss, proved its superiority. The hollow smart façade also demonstrated notable performance, with a 6.99% reduction in energy consumption. This paper makes a significant contribution to the body of knowledge in sustainable architecture, particularly by offering specific quantitative insights for building design in cold and semi-arid regions. These insights contribute to the development of more resilient and energy-efficient urban environments. The detailed analysis of climatic data and simulation results provides a robust foundation for design decisions aimed at reducing the environmental impact of buildings and enhancing occupant comfort.

Conflict of Interest

The authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported herein.

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