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Original Research Article

Assessing Façade Thermal Performance for Sustainable Urban Development: The Case of Village Tourist Complex, Mashhad

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Abstract

Background and Objectives: In recent decades, inadequate attention by designers to the thermal performance of commercial building façades has resulted in significant thermal inefficiencies in such complexes. This study aims to precisely evaluate the thermal performance of façade materials in the Village Tourist Commercial Complex in Mashhad, using Fourier's Law of Heat Conduction, within the framework of sustainable urban development.
Methods: This research adopts a quantitative approach, employing Fourier's heat conduction law, the overall heat transfer coefficient, total building heat load, envelope load, and solar radiation analysis. To validate the results, simulation modeling was performed using Design Builder and Fluent software.
Findings: The thermal performance assessment of the Village Tourist Commercial Complex façade in Mashhad reveals that the total building heat load, reaching approximately 2.5 MW, is predominantly influenced by solar gains (59% of the total), caused by extensive glazing areas with high heat transfer coefficients. This results in substantial cooling demand during summer, whereas in winter, reduced solar radiation enables partial passive heating yet still necessitates efficient heating systems.
Conclusion: The façade design, as a critical determinant, significantly affects the trajectory of sustainable urban development in Mashhad. The observed patterns of unsustainability, such as increased carbon and greenhouse gas emissions, highlight the environmental implications of current façade performance.

Running Title: Façade Thermal Performance in Cold– Dry Mashhad

NUMBER OF REFERENCES	NUMBER OF FIGS	NUMBER OF TABLES
36	3	5

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Introduction

In recent decades, the rapid expansion of commercial complexes, driven by increasing demand for modern, multifunctional spaces, has led to high energy consumption in these buildings. A major share of this consumption arises from inefficient façade design and insufficient consideration of environmental adaptation. These shortcomings result in consequences such as increased thermal loads, inefficiency of heating and cooling systems, and reduced thermal comfort for occupants. The building façade, as the primary interface between indoor and outdoor environments, plays a vital role in controlling heat transfer through conduction, radiation, and convection, potentially influencing up to 60% of total energy consumption (Shyamal and Rashmi, 2020).

However, common façade designs, characterized by extensive use of glass panels and materials with high thermal transmittance, often lead to increased heat loads and higher energy use. This trend contributes to the urban heat island effect, which negatively impacts sustainable urban development by undermining energy efficiency and environmental quality. It is noteworthy that heat transfer through building façades occurs via three main mechanisms: conduction, radiation, and convection (Oliveira Neves *et al.*, 2017), all of which significantly influence thermal performance and energy efficiency (Ma *et al.*, 2024). In conductive, radiative, and convective heat transfer, the heat flux depends on the overall heat transfer coefficient (U-value), the façade surface area, and the temperature difference between indoor and outdoor environments (Shyamal and Rashmi, 2020; Wang *et al*., 2024).

Conductive heat transfer, governed by the U-value and surface area of the materials, directly affects the building's energy demand (Wang *et al.,* 2024). Radiative heat transfer, particularly significant in glazed façades, is influenced by the Solar Heat Gain Coefficient (SHGC), which can increase summer heat loads by up to 50% in buildings with large window areas (Liu and Wu, 2022). Convective heat transfer, driven by air movement near the building envelope, can be controlled through proper design of openings and the use of natural or mechanical ventilation systems, thereby reducing ventilation loads by up to 30% (Evola and Lucchi, 2024). Optimizing these heat transfer mechanisms enhances façade durability and supports urban ecosystem health by mitigating the urban heat island effect, improving environmental quality, reducing pollution, and promoting biodiversity all contributing to sustainable urban development (Firoozi *et al.,* 2025).

Accordingly, the thermal performance of the building envelope—which involves optimizing thermal resistance, heat transfer coefficients, solar heat gain factors, and the use of high thermal capacity materials (Zhang *et al.,* 2024), can be evaluated using Fourier's Law of Heat Conduction. As one of the fundamental principles of heat transfer, Fourier's Law provides the basis for calculating conductive heat transfer through façade materials (Karlsson, 2012) and plays a key role in optimizing thermal performance and reducing energy consumption. The law, commonly expressed as ($Q=A\times U\times \Delta T$) describes conductive heat transfer through materials (Talib Mahdi *et al.*, 2025) and is used in façade design to estimate the conductive heat load of building materials (Wang and Wang, 2022). Moreover, solar load analysis plays a crucial role in understanding the impact of solar radiation on a building's thermal load (Samuelson *et al.*, 2025) and is considered one of the main factors influencing both cooling and heating demands (Selvakumar *et al.*, 2022).

The solar angle and façade orientation also have a significant effect on solar gains, with south-facing façades in the Northern Hemisphere receiving the highest exposure (Kumar Kirme and Kapse, 2023). In the developing cities of the world, the issue of sustainable urban development has become increasingly dependent on optimizing the thermal performance of building façades (Schram and Shirazi, 2025). In general, the thermal performance of façades plays a vital role in achieving sustainable urban development by creating a positive feedback cycle that reduces greenhouse gas emissions, improves residents 'quality of life, and accelerates economic revitalization (Yu *et al.*, 2025). According to the International Energy Agency (IEA, 2024), the building façade, as the primary boundary for heat exchange, has the potential to manage up to 40% of total heating and cooling energy demand. However, it is important to note that climatic conditions play a critical role in determining the thermal performance of building envelopes and, consequently, in achieving sustainable urban development. In the cold and dry climate of Mashhad, characterized by hot summers and cold winters, the thermal performance of commercial building façades is essential for sustainable urban growth. High temperature fluctuations require passive design strategies capable of reducing both summer cooling and winter heating loads, resulting in energy savings and lower CO_2 emissions.

These strategies contribute to mitigating the Urban Heat Island (UHI) effect, improving urban air quality, and enhancing climate resilience, objectives that align with Mashhad's sustainable urban development goals. In this context, Bano and Sehgal (2018), in their study "Evaluation of Energy-Efficient Design Strategies: A Comparative Study of Thermal Performance in High-Efficiency Office Buildings in Composite Climates", used experimental and simulation methods in Energy Plus software and concluded that optimized façades (e.g., with Low-E glazing) can reduce energy consumption by 15–25%. Similarly, Huynh *et al.* (2021), in "Energy Efficiency Requirements for Building Envelopes in Cold-Climate Residential Areas", employed a comparative research method and simulations in Design Builder, finding that façade insulation requirements in cold climates reduce heating loads. In Iran, Mirshojaeian Hosseini *et al.* (2021) conducted a study titled "Design of Conventional High-Rise Buildings with Energy Optimization through Façade Modification in Cold and Dry Climates: A Case Study of Mashhad". Using simulation methods in Design Builder, they found that modifying the façade and using materials with lower thermal transmittance reduced annual energy consumption in high-rise buildings by 25–35%. Pakdel and Alemi (2024), in "Enhancing Thermal Efficiency of Building Envelopes Using Natural Fiber-Based Nonwoven Composites", employed analytical–descriptive research and simulation with Grasshopper software. Their findings indicated that nonwoven natural fiber composites could improve thermal performance by 12.7%, reducing heat transfer between indoor and outdoor spaces. Finally, Nazarboland *et al.* (2024), in their study "Assessing the Impact of Urban Block Form and Orientation on the Thermal Performance of High-Rise Building Envelopes" using Design Builder simulations, reported that optimizing façade geometry and orientation reduced energy loss in various façade components by 5–39%. In addition, Vakilinezhad and Kabir (2023), in "Thermal and Energy Performance Evaluation of Cool Coatings in Low-Rise Residential Buildings in Hot Climates", utilized simulation with Energy Plus software and concluded that applying cool coatings on façades can reduce heat loads by up to 14%. Evola and Lucchi (2024), in their study titled "Thermal Performance of Building Envelopes: Novel Methods and Advanced Solutions", employed an experimental methodology and HFM simulations, concluding that innovative assessment approaches can reduce heat loss by up to 40%. Their findings emphasized that thermal bridge control within façade systems is critical for improving performance in cold climates. Similarly, Ahmad *et al.* (2024), in "Thermal Analysis of a Building Envelope in a Hot and Dry Climate: A Detailed Study", used an experimental research approach and heat transfer equations. They found that sun-exposed façade components account for approximately 60% of the total cooling load, and that applying advanced insulation materials and shading devices can reduce cooling energy consumption by up to 40%. Based on the reviewed literature, the distinctive contribution and innovation of the present study lie in its focused analysis of a real commercial complex located in the cold and Dry climate of Mashhad, and in the integration of Fourier's Law with Design Builder and Fluent simulation data to evaluate façade heat loads.

In contrast to previous studies—most of which have either generally examined façade optimization in high-rise buildings or focused on hot and dry climates and residential façades this research specifically investigates a commercial façade within the cold-Dry climate context of Mashhad. Another innovation of this study is the introduction of an effective overall heat transfer coefficient for the commercial complex façade under Mashhad's climatic conditions. This coefficient aligns with local standards, such as Iran's National Building Code, Part 19, and supports pathways toward sustainable urban development.

The city of Mashhad, capital of Khorasan Razavi Province, is located in northeastern Iran and covers an area of approximately 35,147 hectares. According to the third comprehensive urban plan approved in 2016, the city's buffer zone extends to about 86,500 hectares (Fig 1). Geographically, Mashhad lies at 36.27° N latitude and 57° E longitude, at an elevation of 999 meters above sea level (Maddahi and Tavanai, 2019). The city experiences a variable but predominantly cold and dry climate, characterized by hot and dry summers and cold, occasionally humid winters (Noohi Bezenjani and Nikpour, 2022). Overall, Mashhad's cold– dry climate exhibits considerable temperature fluctuations, with summer temperatures reaching up to 41 °C and winter temperatures dropping to −9 °C (Mashhad Synoptic Organization, 2024). These conditions significantly increase cooling loads during summer due to high solar radiation and heating loads during winter, caused by thermal losses through the building envelope.

The objective of this study is to conduct a precise evaluation of the thermal performance of the façade materials of the Village Tourist Commercial Complex using Fourier's Law and solar radiation data. The study aims to determine the impact of façade materials (glass and composite) on building heat loads, with a focus on promoting sustainable urban development in Mashhad. The Question of the present study is to determine how the thermal performance of the façade of the Village Tourist Commercial Complex in the cold and dry climate of Mashhad affects the building's heat load, considering the principles of sustainable urban development.

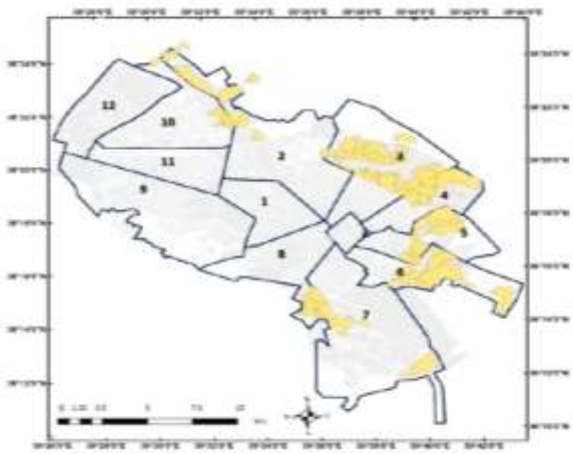
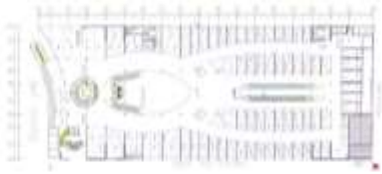


Fig 1: Map of the city of Mashhad
Source: (Baghban and Minaei, 2022)

The case study of this research is the Village Tourist Commercial Complex located in the city of Mashhad, at the end of Vakil Abad Boulevard, near the beginning of Torqabeh Road. The complex consists of six floors, excluding the parking levels, and is situated at the entrance of the Torqabeh recreational corridor. The structural system of the Village Tourist Commercial Complex is steel-framed, featuring double-glazed glass panels with aluminum frames connected to the steel atrium structure. The façade envelope comprises dark gray double-glazed glass combined with light gray aluminum composite panels. It is noteworthy that the building lacks external insulation and shading devices on its façade surfaces. The architectural and structural specifications of the building are presented in Table1.

Table 1: Specifications of Village Tourist Commercial Complex

Image	Architectural Features of the Base Model	Plans
 	Location: Mashhad City Structural System and Core Type: Steel Plan Geometry: Rectangle Plan Proportions: 1:4 Façade Materials: Glass and Composite Percentage of Glazed Area: 60% Number of Floors: 6 Floor Height: Approximately 5 m HVAC System: Direct-Fired Absorption Chiller for Cooling and Hot Water Coil for Heating Ventilation: Natural and Mechanical Thermal Comfort Range: Temperature Range: 20.3–26.7 °C; Relative Humidity: 30–50%	 Ground Floor Plan  Floor Plans

Materials and Methods

The present study employs a quantitative, computational, and simulation-based approach. Data collection was conducted through library research and field studies. In the first stage, the technical, architectural, and mechanical specifications, including floor plans, façade details, and sectional drawings, of the *Village Tourist Commercial Complex* were obtained from the building's mechanical department, located on the fifth floor. Subsequently, the thermal load calculations were performed using the following equations.

1) Heat Transfer through the Building Envelope (Fourier's Law of Heat Conduction)

$(A.K\text{-}=Q=\frac{\Delta T}{\Delta x})$

Q = Rate of heat transfer (W)

k = Thermal conductivity of material (W/m·K)

A = Surface area of the envelope (m^2)

ΔT = Temperature difference between indoor and outdoor air (°C)

Δx = Thickness of the envelope (m)

This formula was used to calculate the heat transfer through different façade materials, including composite panels and insulated glazing. Technical data such as window surface areas, façade dimensions, thermal conductivity of materials, and façade thickness were obtained from the mechanical engineers at the administrative department of the Village Tourist Complex.

Material properties used in the calculations are as follows:

- Double-glazed glass: U-value = 1.8 $W/m^2·K$
- Composite panel (with 4 mm polystyrene insulation): U-value = 0.4 $W/m^2·K$
- Total façade area (A): 10230 m^2
- Temperature difference (ΔT): 20 K (for peak summer and winter conditions)
- Glazed surface area: 6138 m^2

2) Overall Heat Transfer Coefficient (U-value)

To evaluate the thermal performance of the building envelope, the overall heat transfer coefficient (U-value) was calculated using the following equation:

$$\frac{1}{iR\sum} = U$$

U = Overall heat transfer coefficient ($W/m^2·K$)

R_i = Total thermal resistance, including surface resistance and the resistance of each layer of the façade assembly

3)Total Building Heat Load

The total heat load of the building was computed using the following relation:

Qtotal =Qconduction +Qsolar +Qventilation +Qinternal

Where:

$Q_{(conduction)}$ = Heat transfer through the envelope (conduction)

$Q_{(ventilation)}$ = Heat load due to natural ventilation

$Q_{(solar)}$ = Heat load from solar radiation

$Q_{(internal)}$ = Internal heat gain (from mechanical equipment, lighting, and occupants)

4) Envelope Heat Load

Given the focus of this study on the façade and envelope of the Village Tourist Commercial Complex, the heat load from conduction and solar radiation through the façade and roof was analyzed. Internal and ventilation loads (including stack effect) were neglected in this stage.
Thus, the envelope heat load was determined as follows: $Q_{envelope} = Q_{conduction} + Q_{solar}$.
5) Solar Radiation

To evaluate the amount of solar radiation incident on the façade of the *Village Tourist Commercial Complex*, the following equation was applied:

$Q_{solar} = SHGC \times I \times A$

Where:
$Q_{(solar)}$ = Solar heat gain (W)
A = Glazed area (m²) = 6,138
I = Solar radiation intensity (W/m²) = 600
SHGC = Solar Heat Gain Coefficient = 0.4

To validate the analytical results, the simulation was performed using Design Builder and ANSYS Fluent software.
The default simulation assumptions were as follows:

Indoor thermal comfort range based on the ASHRAE standard (American Society of Heating, Refrigerating, and Air-Conditioning Engineers): 21.5–27°C

Closed and fixed façade openings during simulation

Double-glazed windows with a U-value of 1.8 W/m²·K

Composite panels with polyurethane insulation, $U_{(C)}$ = 0.5 W/m²·K.

Material properties and thermal parameters were obtained from Iran's National Building Regulations, Chapter 19 (Energy Conservation).
Subsequently, the analytical calculations were performed first, followed by the simulation modeling in Design Builder and Fluent. The International Weather for Energy Calculations (IWEC) climate data set was used to model the baseline climatic conditions for Mashhad

Results and Discussion

The analysis of the calculated heat transfer rate for the façade envelope of the Village Tourist Commercial Complex in Mashhad reveals the thermal performance of the building's outer shell against heat transmission. According to the presented calculations, the total heat transfer rate (Total Q) through the façade envelope is 261,888 W, consisting of two main components: heat transfer through the glazing (220,968 W) and heat transfer through the composite façade sections (40,920 W). These values were obtained using the formula $\dot{Q} = U \times A \times \Delta T$ where U is the overall heat transfer coefficient (W/m²·K), A is the façade surface area (m²), and ΔT is the temperature difference between the indoor and outdoor environments (20 °C).
For the glazing, with U=1.8W/m² and an area of 6,138 m², the calculated heat transfer rate is 220,968 W, accounting for approximately 84.4% of the total heat transfer, indicating the dominant role of glass in thermal energy loss. This is primarily due to the higher thermal transmittance (U-value) of the glass compared to the composite panels and its larger surface coverage within the façade.
In contrast, the composite sections, with an area of 4,092 m² and a lower thermal transmittance (U=0.5 W/m², contribute only 40,920 W (about 15.6% of the total heat loss), demonstrating their greater thermal resistance and more efficient insulation performance compared to the glazing.
Based on the presented data, the calculation of the heat transfer rate is as follows:
$-\dot{Q}_{Total} = (U_g.A.\ \Delta T) + (U_c.\ A.\ \Delta T)$
$-\dot{Q}_{Total} = (1.8.6138.20) + (0.5.4092.20)$
Calculation of heat transfer through the glass façade of the building:
$-Q = 1.8 \times 6138 \times 20 = 220968W$
Calculation of heat transfer through the composite façade:
$-Q = 0.5 \times 4092 \times 20 = 40920W$
Total heat transfer:
$-Q = 220968W + 40920W = 261888W$

The net conductive heat transfer rate through the building envelope, under both summer and winter peak conditions assuming a temperature difference of ΔT = 20 °C, is calculated as:

$$-Q \approx 261.89Kw$$

This value represents the heat load that the building experiences solely through conductive heat transfer of the façade components.

Next, the overall heat transfer coefficient (U-value) of the Village Tourist Commercial Complex envelope is analyzed based on the given data:

-Glass: Ug=1.8m2·KW

-Glass Area: Ag =6,138 m²

Composite panels with polyurethane insulation: Uc=0.5 W/m2·K

-Composite panel area: Ac =4,092 m²

-Total façade area: Atotal =10,230 m²

These values form the basis for calculating the effective overall U-value of the entire façade.

Based on the overall heat transfer coefficient (U-value) data, the façade envelope consists of two main components:

- Glass: Ug=1.8m²·KW, area = 6,138 m² (~60% of the total façade)

- Composite panels with polyurethane insulation: Uc=0.5 W/m²·K, area = 4,092 m² (~40% of the total façade)

The total façade area is 10,230 m². These data indicate that approximately 60% of the envelope surface is glazed, and due to the high U-value of glass (U_g = 1.8), the majority of thermal losses occur through the glazing. In contrast, the composite panels, with U_c = 0.5, provide better thermal resistance and contribute less to energy loss because of the polyurethane insulation.

The effective overall U-value (U_total) of the entire façade, considering 60% glass and 40% composite panels, is approximately:

UTotal≈1.280048875 W/m²·K

This value indicates that the overall thermal performance of the façade, when weighted by the high proportion of glazing, is close to the U-value of the glass itself (1.8 W/m²·K). This is due to the large share of glazing in the façade area (~60%). The calculation of the overall U-value also represents the average thermal performance of the envelope, which is skewed toward a higher U-value because of the dominant glass component.

In Mashhad's climate, characterized by cold winters and hot summers, this relatively high U-value can lead to increased heating and cooling loads. Overall, these data not only highlight heat loss but also serve as a starting point for sustainable urban development, as the total heat load calculation shows that glazing accounts for approximately 77% of total envelope losses, potentially increasing the building's annual energy consumption by up to 35% above standard values.

This imbalance threatens sustainable urban development by exacerbating the urban heat island effect, since highly conductive glazing at the urban scale raises surface temperatures and CO_2 emissions.

To calculate the heating and cooling energy consumption of the Village Tourist Commercial Complex, the following parameters were considered based on the total heat load formula:

- Skylight height: 36 m
- Atrium shape: elliptical with an approximate diameter of 30 m at the base
- Double-glazed 4 mm glass (high U-value)
- Atrium with no operable openings, equipped with 6 air dampers functioning as exhaust fans for thermal ventilation and enabling natural stack-effect ventilation
- Metal structure with aluminum frame façade
- HVAC ducting across all floors
- Presence of staircases and elevators

Based on these parameters and the extracted data, the following results were obtained:

ConductionQ=261.89

SolarQ=1473.12

InternalQ=306.9

VentilationQ=356.25

TotalQ≈261.89+1473.12+306.9+356.25

TotalQ≈2498.16kW≈2.5MW

-Envelope conductive load (Conduction Q): 261.89 kW

-Envelope solar load (Solar Q): 1,473.12 kW

-Based on the results, the total heat load (Total Q) of the building is approximately 2,498.16 kW (2.5 MW), composed of four main components:

- Conductive load (Conduction Q): 261.89 kW (~10.5% of total)
- Solar load (Solar Q): 1,473.12 kW (~59% of total)
- Internal load (Internal Q): 306.9 kW (~12.3% of total)

- Ventilation load (Ventilation Q): 356.25 kW (~14.3% of total)

The solar load, at 1,473.12 kW, accounts for roughly 59% of the total heat load, primarily due to the use of 4 mm double-glazed high-U-value glass and the large atrium skylight (36 m high, elliptical shape with an approximate 30 m diameter). While this skylight provides ample natural daylight, its high solar heat gain coefficient (SHGC) imposes a significant solar heat load on the building.

The conductive load, at 261.89 kW, arises from heat transfer through the façade materials indicating that conductive losses are relatively minor compared to the solar load. The six air dampers, enabling stack-effect ventilation, help reduce the ventilation load (356.25 kW) but the absence of additional operable openings in the atrium may limit natural ventilation efficiency. The internal load (306.9 kW) reflects the commercial use, including mechanical equipment, lighting, and occupant presence.

Although the metal structure and aluminum frame façade are structurally suitable, their high thermal conductivity could increase the conductive load unless thermal break profiles are used. Overall, the analysis identifies the atrium skylight as the primary weakness in the envelope design, suggesting a need for reconsideration of materials or design strategies to improve energy performance and reduce total energy consumption in Mashhad's hot-cold climate.

The conductive load from glazing (261.89 kW) constitutes only ~15.1% of the peak load, demonstrating the better thermal performance of the polyurethane-insulated composite sections. In Mashhad's climate, characterized by hot summers and cold winters, the peak envelope heat load (1.734 MW) highlights the challenges in designing the façade to control cooling loads. Since this study focuses on heat transfer interaction between the envelope and the environment (façade and roof), the Peak Envelope Load is 1,734.91 kW. This value represents the peak heat load directly penetrating the building through its envelope. It shows that the façade's thermal performance at the Village Tourist Commercial Complex in Mashhad has the potential to influence sustainable urban development, improving environmental and climatic performance by reducing carbon emissions.

The solar load was calculated using SHGC.I.A=solarQ. Where A=6,138 m² (glazed area), I=600 W/m² (reference solar irradiance), SHGC=0.4 (solar heat gain coefficient).This yields a solar load of 1,473.12 kW, highlighting the significant solar heat gain through the glazed envelope, especially the elliptical atrium skylight (36 m high). Despite using 4 mm double-glazing and a relatively low SHGC (0.4) to reduce solar gain, the large glass area still imposes a high heat load on the building.

The peak envelope heat load of the Village Tourist Commercial Complex in Mashhad, resulting from the interaction of the envelope (façade and roof) with the external environment, was calculated as 1,734.91 kW. This value highlights the significant heat transfer through the building envelope, with the majority (~84.9%) attributed to solar gain.

Emphasizing the dominant role of glass in heat transfer, these data show the necessity of reducing SHGC to below 0.3 through Low-E glass, and reducing the window-to-wall ratio in the facade of the Tourist Village commercial complex, in order to reduce the solar load, reduce the urban heat island (UHI) effects in the growing fabric of Mashhad, and reduce carbon emissions from fossil cooling systems. In this way, it can contribute to smart urban growth, energy self-sufficiency, and community participation in national sustainability policies (such as NUP and neighborhood-based projects) to move Mashhad towards environmental, economic, and social sustainability.

These data were subsequently used as input parameters in the façade modeling of the Village Tourist Commercial Complex in Design Builder to validate the study. As shown in **Fig. 2**, the high share of solar load (84.9%) and the continuous peak envelope load during summer (1,734.91 kW) confirm the accuracy of the manual calculations.

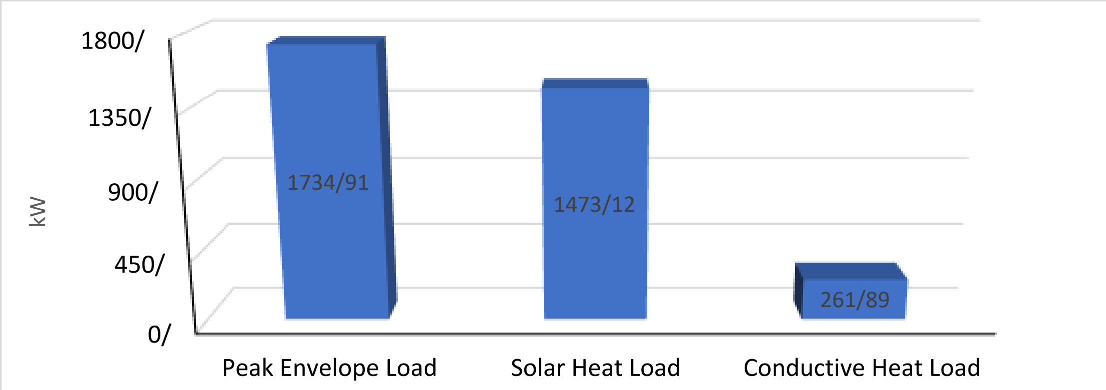


Fig 2: Total envelope heat load of the Village Tourist Commercial Complex modeled using Design Builder.

The simulations conducted in Design Builder for analyzing the envelope heat load of the Village Tourist Commercial Complex in Mashhad confirm the peak envelope load of 1,734.91 kW, primarily composed of:

- Solar load: 1,473.12 kW from the glazed façade
- Conductive load: 261.89 kW from glass (U = 1.8 W/m²·K) and composite panels (U = 0.5 W/m²·K)

As shown in Fig. 3, the solar heat load from the building's glazing during a daily and hourly summer peak (corresponding to July 11th, considering vertical solar incidence) increases from 06:00, reaches its peak at 14:00, and decreases after sunset (around 18:00). Additionally, solar heat gain is zero between 00:00–05:00 and 19:00–23:00. therefore, the maximum solar heat load through the glazing occurs between 12:00 and 14:00, reaching approximately 1,400–1,473.12 kW, with the peak at 14:00, which validates the manual calculations of the solar heat load.

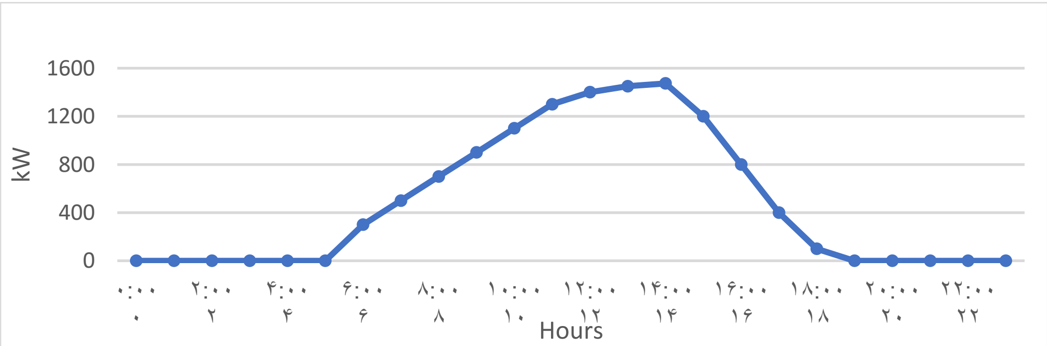


Fig 3: Solar heat load of the envelope for the Village Tourist Commercial Complex in Mashhad during July 2025

Based on the simulation data from Design Builder, the façade of the Village Tourist Commercial Complex in Mashhad generates a peak envelope heat load of 1,734.91 kW, which has a direct impact on energy consumption and sustainable urban development. The majority of this load (~85%) originates from solar radiation through the glazing, reaching its maximum at 14:00. This pattern poses a significant challenge to urban sustainability, as it not only places substantial demand on the electricity grid during peak hours but also conflicts with principles of energy optimization and carbon reduction. From a sustainable urban development perspective, the issue extends beyond energy use. The deployment of extensive glazed façades without consideration of local climatic conditions, coupled with the absence of effective active or passive solar management strategies, results in reduced thermal comfort in indoor spaces, increased reliance on mechanical cooling systems, and consequently higher greenhouse gas emissions. This situation positions the building as a detrimental factor in the urban environment, contributing to urban heat island effects and heightened dependency on municipal energy resources. the hourly solar heat load for a winter day (January 10, Fig. 4) illustrates the effect of Mashhad's cold and dry climate on solar energy gain through the building envelope. According to Fig. 4, the solar load begins at 07:00 with sunrise, reaching a peak of 800 kW at 12:00. Due to the lower sun angle and reduced solar intensity in winter, this value is approximately 54% of the summer peak at 14:00 (1,473.12 kW). The load gradually decreases until 17:00, and is zero during nighttime hours (18:00–06:00) due to the absence of solar radiation. This pattern aligns with Mashhad's winter climatic characteristics, including shorter daylight hours and lower solar intensity.

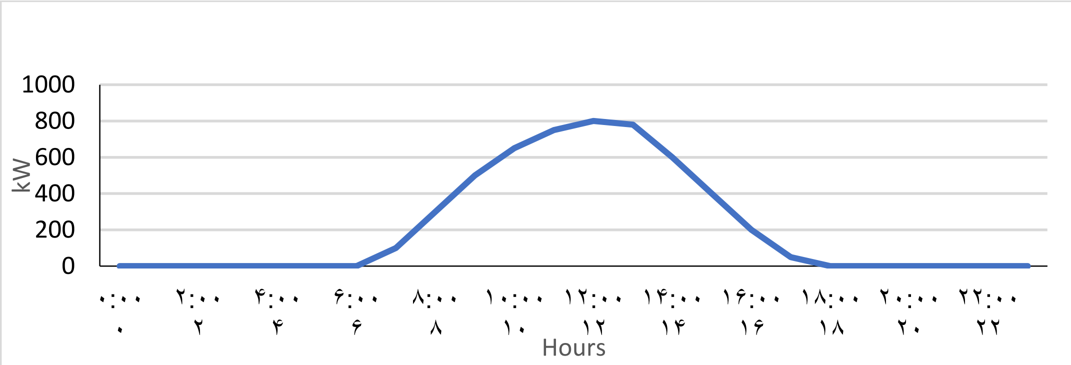


Fig 4: Solar heat load of the envelope for the Village Tourist Commercial Complex in Mashhad during January 2025

The Heat Balance data from Design Builder was further analyzed. According to Fig. 5, the distribution of thermal loads through the glass and composite façade of the Village Tourist Commercial Complex in Mashhad on July 11th, 2025 shows that the total conductive load peaks at 261.89 kW at 14:00, which aligns with manual calculations. Approximately 60% of this load is attributed to glass, with its higher U-value, and 40% to the composite panels. The conductive load begins to rise at 06:00 with increasing outdoor temperatures, reaches its peak between 12:00 and 14:00, then gradually decreases until sunset (18:00), and drops to zero between 18:00 and 23:00 due to minimal temperature difference. From the perspective of sustainable urban development, this cyclical pattern of energy loss exacerbates urban instability. During the peak heat of the day (12:00–14:00), the complex transfers significant energy from the façade to the environment, unnecessarily increasing cooling demand and imposing substantial pressure on the city's electricity distribution network. This heightened demand pushes the grid toward low-efficiency, polluting power plants, resulting not only in higher carbon emissions but also in increased urban pollution.

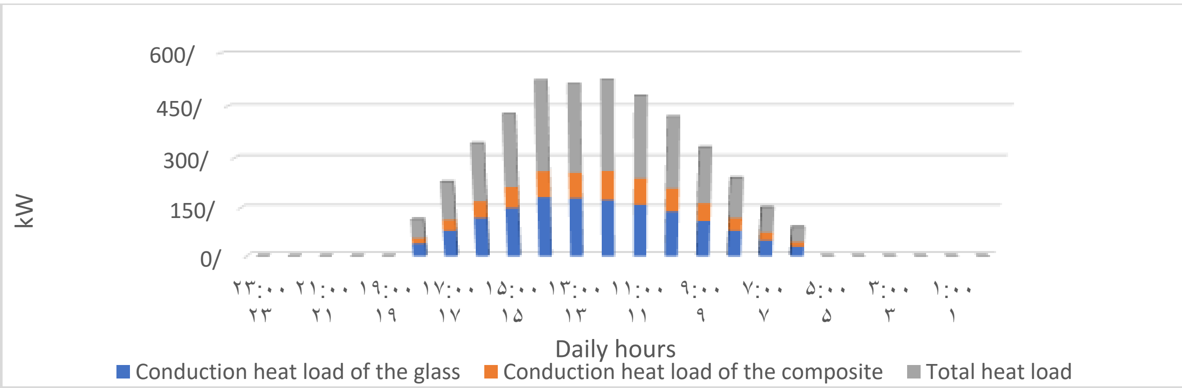


Fig 5: Thermal load of the façade of the Village Tourist Commercial Complex in Mashhad in July 2025

As shown in Fig. 6, the total conductive load reaches a peak of 130 kW at 13:00, which, due to the lower outdoor temperatures in winter compared to summer, is only about 50% of the summer peak (261.89 kW). This load remains low (around 28 kW) during the early morning (00:00–06:00) and evening hours (19:00–23:00) due to the smaller temperature difference between inside and outside and increases during the mid-day hours as outdoor temperatures rise. Based on the available data, the envelope load pattern in winter—with its 130 kW peak at 13:00 and lower levels during night hours—highlights the importance of intelligent façade design for achieving urban sustainable development goals. This type of energy consumption directly impacts the three main pillars of sustainability: environment, economy, and society. From an environmental perspective, the 50% reduction in thermal load compared to summer, although a positive step, still indicates significant energy loss, which contributes to increased fossil fuel consumption in power plants and consequently higher greenhouse gas emissions. Economically, this energy loss equates to wasted financial resources, raising the building's long-term operational costs. Socially, low-energy-efficiency buildings fail to provide adequate thermal comfort to occupants, reducing urban quality of life. To achieve true sustainable development, it is essential to consider the building envelope not as a static element but as a dynamic system capable of adapting to variable climatic conditions.

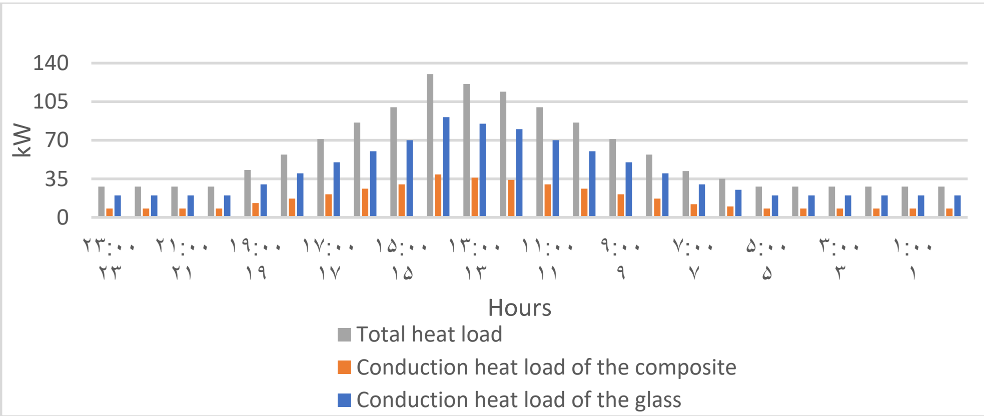


Fig 6: Envelope thermal load of the Vilage Tourist Commercial Complex in Mashhad In October 2025

To enhance data validation, Fluent software was used. The Fluent simulation results for internal temperature distribution through the envelope of the Village Tourist Commercial Complex in summer, considering the solar and conductive loads for the cold and dry climate of Mashhad (solar peak load 1473.12 kW and conductive load 261.89 kW in summer), illustrate temperature differences between floors due to the impact of thermal loads.

As shown in Fig. 7, the first to third floors, with internal temperatures of 28–33.06 °C, receive less solar heat due to the glass façade acting as a shading element, keeping them cooler. This is consistent with the estimated solar peak load (1473.12 kW at 13:00), as the glass envelope (attached façade) likely reduces direct radiation and moderates the conductive heat transfer through the glass (U = 1.8 W/m²·K). in contrast, the upper floors, including the fifth floor beneath the atrium, experience temperatures of 41–44.81 °C due to heat accumulation in the atrium, receiving higher solar and conductive loads, which explains the elevated temperatures. This temperature gradient highlights the greater influence of solar gains (up to 60% of the total thermal load) and glass conduction on the upper floors compared to the lower ones, aligning with the conductive load analysis (60% glass, 40% composite).

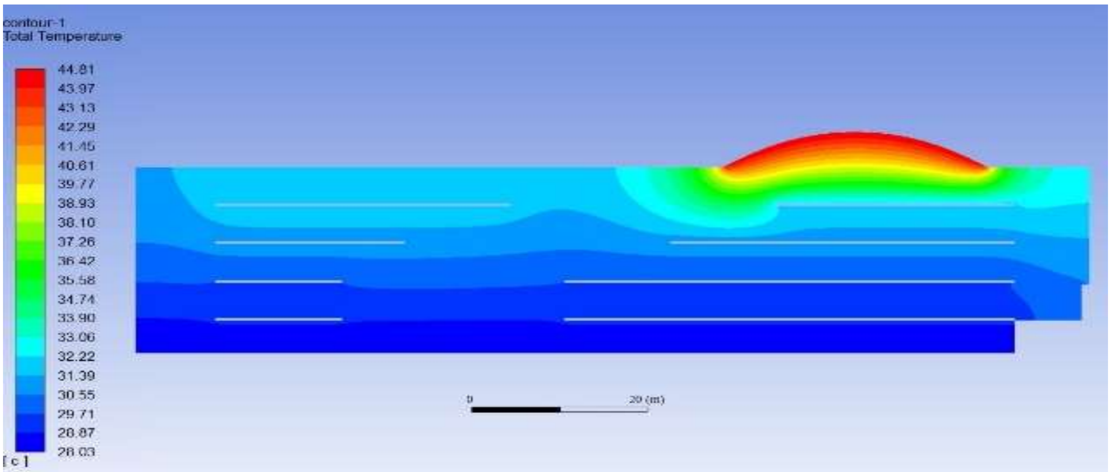


Fig 7: Thermal profile of the envelope of Village Tourist Commercial Complex In July 2025

Fig. 8 also shows that the basement and first floors, with temperatures ranging from 24.05 to 25.51 °C, experience the lowest thermal loads due to better insulation and their lower position, which aligns with the lower conductive load in winter (around 28 kW between 9:00 and 11:00 PM). Floors 1 to 3 (26.10 to 28.14 °C), having larger glass surfaces, receive higher solar and conductive loads, consistent with the solar peak load (800 kW at 12:00 PM) and the 60% glass contribution to the conductive load (91 kW at 14:00). The top two floors (28 to 29.90 °C), with more composite panels, show higher temperatures due to the lower U-value of the composite, yet they remain influenced by solar gain. Under the atrium roof (26 to 27 °C), the polyurethane-insulated roof and six air dampers contribute to a more balanced temperature by enhancing ventilation and reducing heat accumulation. These patterns correspond with the reduced solar and conductive loads in winter compared to summer (1,473.12 kW and 261.89 kW, respectively).

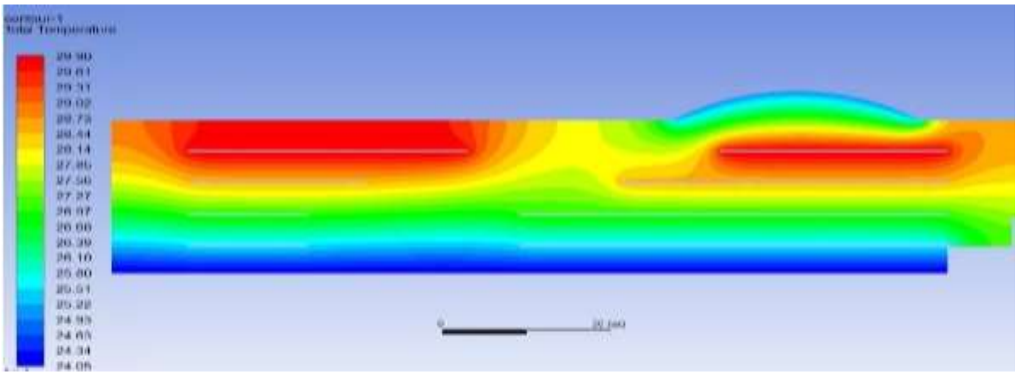


Fig 8: Thermal profile of the envelope of Villages Tourist Commercial Complex in In October 2025
Source: (Fluent software output)

Conclusion

The analysis of the thermal loads on the building envelope of the Villages Tourist Commercial Complex in Mashhad, located in a cold and dry climate, using Fourier's law and simulated solar and conduction heat load data, highlights the significant impact of façade design and materials on building thermal performance and the potential for advancing urban sustainability through optimized thermal management. During summer, the peak solar load (1473.12 kW at 14:00) and conductive load (261.89 kW at 13:00) are primarily attributed to the use of double-glazed glass in the façade, which accounts for approximately 60% of the envelope surface. In winter, the reduced solar intensity (peak 800 kW at 12:00) and conduction load (peak 130 kW at 13:00) result in interior temperatures ranging from 24.05–25.51 °C in basement and lower floors, 26.10–28.14 °C in middle floors, and 28–29.90 °C in upper floors, while the polyurethane-insulated atrium roof with six ventilation dampers maintains balanced temperatures of 26–27 °C. The results of this part of the study are consistent with research by Zhang *et al*., (2024) and Liu & Wu, (2022), which found that buildings with large windows increase the summer heat load by up to 50%. In general, these results, validated by Fluent simulations and Fourier-based calculations, emphasize the importance of using materials with lower thermal transmittance (e.g., polyurethane-insulated composite panels with U = 0.5 W/m²·K) to reduce heat loads, mitigate UHI effects in Mashhad, and improve air quality. The analysis further reveals that glass plays a dominant role in heat transfer due to its high U-value, highlighting the need for proper insulation or high-performance glazing to reduce heat loads. The data also suggest potential for passive heating during midday, which could enhance thermal performance through the envelope in Mashhad's cold-dry climate. On an urban scale, this can reduce fossil fuel dependence, improve indoor environmental quality (IEQ), and support national building codes, steering the city toward environmental, economic, and social sustainability. The results of this part of the research are consistent with the research of Firoozi *et al*., (2025) and Schram & Shirazi, (2025), which acknowledged that the thermal load of the building through the building shell increases the lifespan of the shell and improves the urban ecosystem, and determines the development of urban sustainability.

Overall, the thermal performance analysis of the Villages Tourist Commercial Complex envelope demonstrates significant challenges in managing heat loads in Mashhad's climate. The total building heat load reaches approximately 2.5 MW, with solar heat contributing 59% due to the large glass area with high thermal transmittance, generating substantial cooling loads in summer. In winter, reduced solar radiation allows for some passive heating, though efficient heating systems are still required. Composite panels with better thermal resistance due to polyurethane insulation contribute less to heat transfer and perform better in reducing heat loads. The atrium design, despite providing natural daylight, exacerbates thermal loads in summer due to its large area and relatively high solar heat gain coefficient (SHGC). Six ventilation dampers improve natural ventilation but are limited by the absence of additional openings. These findings underscore the need to reconsider façade design to optimize energy consumption. Glass is identified as the main weakness in the current façade design; strategies such as double glazing, low-emissivity (Low-E) coatings, reducing the window-to-wall ratio (WWR), and using low U-value composite materials can help reduce heat transfer. Further optimization through façade geometry adjustments, advanced insulation, movable shading devices, and additional atrium openings can reduce summer heat loads and enhance natural ventilation. In winter, passive heating via the atrium can reduce energy consumption, provided insulation and ventilation systems are properly designed. Given Mashhad's climate, characterized by hot summers and cold winters, optimizing the building envelope is crucial for reducing total heat loads. This result is consistent with the results of the study Qing *et al*., (2025). by the way the 16 °C temperature variation between floors (28–44 °C), caused by differing thermal responses of envelope components to solar and conductive loads, not only indicates energy losses and reduced thermal efficiency but also reflects urban instability. This temperature heterogeneity increases upper-floor cooling demand, reduces mechanical system efficiency, and creates inequities in occupant thermal comfort, all contrary to urban sustainability principles. The current building envelope lacks adaptive capabilities for local climatic conditions and functions as a source of energy waste and additional load on the urban energy network. To align such buildings with sustainable development goals, the envelope should be redefined as a dynamic system capable of actively managing heat exchanges through advanced technologies such as smart glazing, dynamic shading systems, and double-skin façades. Such measures can reduce energy consumption while promoting thermal equity across all building levels.

Suggested solutions

1. The use of Low-E glass and composites with a U value lower than 0.3 W/m^2K, in addition to reducing solar load by 30 to 40 percent, allows for energy savings in the building and has a significant effect on reducing carbon emissions in the city. This measure is fully consistent with green building standards in Iran (similar to LEED and BREEAM) and can be considered as an effective model for other commercial complexes in Mashhad to help reduce the phenomenon of urban heating (UHI).

2. Installing solar thermal panels on the roof for passive heating reduces dependence on fossil fuels and is in line with Mashhad's strategic sustainability model (such as smart transportation) to move the city towards reducing pollution.

3. Adding a green roof on or near the atrium reduces summer heat load and helps integrate urban agriculture into Mashhad's planning. This approach improves air quality and achieves urban sustainability goals.

4. Reducing the glass surfaces in the facade of the commercial complex reduces the cooling load and complies with national regulations for energy efficiency (such as EC+ codes), leading to economic savings in the city's energy grid.

Author Contributions

D. Zarean Shahraki, the corresponding author, has contributed in Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Writing original draft and editing. A. Akbari has contributed in Conceptualization, Data curation, Validation, and editing. J. Soheili contributed in Conceptualization, Resources, Supervision, Validation, Writing – review and editing.

Conflict Of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

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