# Assessment of Window Energy Transfer Performance in Courtyard Buildings Using DesignBuilder in Tehran's Climate

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**Glazing selection is a key strategy for improving building energy performance; however, its application in heritage buildings with architectural preservation constraints remains to be explored. This study addresses this gap by evaluating 11 glazing configurations, including single, double, and triple-pane systems with varying U-values (0.78–5.82 W/m²K), Solar Heat Gain Coefficients (0.31–0.90), and Visible Transmittance values (0.43–0.91), in a historic courtyard building located in Tehran's hot-dry climate. Dynamic simulations were conducted using DesignBuilder, based on a Typical Meteorological Year (TMY) weather file for Tehran (Mehrabad station). The model was validated using ASHRAE Standard 140 (BESTEST) benchmark cases. Results show a consistent seasonal pattern across scenarios, although significant differences emerged during peak heating and cooling periods. The triple-pane low-E argon-filled glazing (T2) achieved the best performance, reducing annual energy consumption by 12.7% compared to the base case. In contrast, the single-pane low-iron glazing (S3) increased the energy demand by 1.2% owing to higher solar heat gains. The sensitivity analysis of building orientation indicated that the total annual energy consumption varied between approximately 85,847 kWh and 91,967 kWh, with the lowest demand observed at a 180° orientation. The economic analysis showed that the D4 double Low-E glazing system achieved a shorter payback period of approximately 6 years, whereas T2 required about 10.7 years to recover the initial investment. Overall, the findings demonstrate that reducing the U-value and Solar Heat Gain Coefficient is the most effective strategy for improving building energy performance in hot-dry climates, particularly for heritage buildings, where design modifications are limited.**

***Keywords:*** *Building energy modeling, building heating and cooling needs, energy use, window heat features, Tehran weather, window glass.*

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## 1. Introduction

Climate change is a fundamental and enduring global challenge [1]. Consequently, energy efficiency and thermal performance of buildings have become increasingly significant worldwide as the demand for thermal comfort through efficient methods grows. As the focus on energy efficiency increases, evaluating the energy-saving potential of buildings is imperative in construction. An accurate assessment of the energy performance of HVAC systems, materials, designs, and key components is essential [2]. Energy efficiency in urban environments is critical for mitigating climate change, resource depletion, and other environmental challenges such as air pollution. The increasing living standards and urbanization have increased the use of energy-intensive equipment, particularly air-conditioning systems. The expansion of urban building spaces has further increased energy use; therefore, the overall building energy demand is projected to rise in the near future [3]. Excessive solar heat gain through windows often increases indoor temperatures. Managing incoming solar radiation is essential for controlling thermal loads and maintaining comfort, and is a key principle in the design of low-energy buildings. Proper shading limits solar heat gain.

Effective shading strategies can reduce overheating and cooling loads. Careful selection of window details and glazing types enables energy savings from shading devices, reducing reliance on mechanical cooling. In recent years, numerous studies in the field of energy systems and the environment have focused on artificial intelligence, life cycle assessment (LCA) methods, and renewable energy technologies, particularly solar energy systems for building applications [4,5]

One of the key components in designing energy-efficient buildings is the proper selection of window types, as the thermal and optical properties of glazing have a direct impact on heating and cooling loads and, ultimately, on the building's overall energy consumption. The use of high-performance glazing can reduce heat transfer, control the amount of incoming solar radiation, and improve indoor thermal comfort. In recent years, the development of building energy simulation software such as DesignBuilder has enabled detailed investigation of the effects of various glazing types and parameters, including U-value, Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT), on building energy performance. DesignBuilder, which uses the EnergyPlus simulation engine, enables detailed assessment of hourly building energy performance by considering geometry, construction materials, glazing properties, solar gains, HVAC operation, and climatic conditions. Guan conducted one of the earliest significant studies in this field by simulating an office building in Australia. This study demonstrated that windows, owing to their substantial role in heat transfer, are a critical factor in determining cooling and heating loads. The findings indicated that reducing the Shading Coefficient and selecting low-emissivity (Low-E) glazing can directly decrease cooling loads, although the overall impact on total energy consumption may be limited under specific conditions [6]. Faggal et al. examined seven glazing types in the hot-arid climate of Cairo, demonstrating that appropriate glazing selection can reduce energy consumption by up to 18.8%. Utilizing DesignBuilder and empirical field data, the study showed that high-performance glazing not only reduces cooling loads but also enhances the model alignment with real-world conditions [7]. In the same year, Slavkovic focused on industrial buildings in Serbia and investigated the impact of various glazing types during the building retrofitting process. The results indicate that certain glazing products, such as Copilit glass, produce excessive unwanted heat, and replacing them with energy-efficient alternatives can improve building energy performance. The study showed that glazing selection yields different outcomes depending on the climate and building function [8]. Hart et al. evaluated the performance of thin triple glazing in residential buildings located in cold regions of the United States. Their findings revealed a 7–16% reduction in annual energy consumption owing to lower U-values, underscoring the importance of adequate window insulation in regions with severe winters, such as Tehran [9]. In 2021, Altaf and Hill focused on hot semi-arid climates and demonstrated that reducing the Solar Heat Gain Coefficient (SHGC) is the most influential glazing property for lowering energy consumption. SHGC values below 0.3 had the greatest effect on cooling loads. This finding is particularly relevant to Tehran, where cooling loads are predominant in summer [10]. In 2021, El-Eshmawy et al. conducted a comprehensive review of both conventional and advanced glazing technologies. They categorized glazing as either conventional (clear, tinted, reflective, low-emissivity) or advanced (vacuum, gas-filled, nano-gel, PCM-integrated). The review demonstrated that advanced glazing materials provide superior reductions in the SHGC and U-value, resulting in significant improvements in building energy efficiency [11]. Usta and Zengin simulated an office building in Turkey and evaluated four glazing types. Their study demonstrated that optimal glazing selection can reduce the building energy consumption by up to 25%. This research confirmed the combined significance of the thermal and optical properties of glazing in achieving thermal comfort and minimizing cooling loads [12]. Mahmoud’s study in the extremely hot climate of Aswan, Egypt, demonstrated that multilayer glazing systems incorporating nano-gel and argon gas can reduce energy consumption by 3–12%. The results emphasized that window orientation and Window-to-Wall Ratio (WWR) are significant factors influencing the glazing performance [13]. In 2025, Liu et al. investigated the combined effects of Window-to-Wall Ratio (WWR) and glazing type in a temperate monsoon climate in China. Their results indicated that a WWR of approximately 30% combined with double-glazing yielded optimal annual performance, whereas an excessive window area increased both the heating and cooling loads. These findings underscore the necessity of balancing daylight with energy efficiency [14]. As summarized in Table 1, the most prominent studies on glazing technologies have focused on the thermal, optical, and energy-related characteristics of single-, double-, and triple-glazing systems and low-emissivity coatings. Collectively, these studies demonstrate that glazing selection is fundamental to reducing building heating and cooling loads, and that advanced glazing technologies can substantially enhance the energy performance of buildings.

Courtyard buildings represent a traditional architectural typology in hot-arid climates, where the enclosed configuration can moderate solar exposure, promote natural ventilation, and provide partial self-shading to surrounding façades [20, 21]. In such buildings, windows facing the courtyard are influenced by courtyard geometry, orientation, and the degree of self-shading, which can modify their solar heat gain compared with conventional street-facing façades. Therefore, evaluating glazing performance in a courtyard building is important, as window behavior is governed not only by glazing thermal and optical properties but also by the interaction between courtyard geometry and orientation—an aspect that has received limited attention in existing literature. Despite extensive research on glazing systems and building energy performance, limited studies have focused on heritage courtyard buildings in hot-dry climates under strict architectural preservation constraints. In particular, the combined effect of the thermal properties of glazing and building orientation on energy performance has not been sufficiently investigated.

This study addresses this gap by evaluating multiple glazing configurations in a validated heritage courtyard building model using DesignBuilder simulations, under real climatic conditions. The novelty of this study lies in the integration of glazing performance assessment with orientation sensitivity analysis to provide design-oriented insights for the energy-efficient retrofitting of heritage buildings. This study aims to simulate thermal loads and annual energy performance across multiple glazing scenarios and to identify the optimal configuration for reducing energy consumption. The findings can inform the design of similar cultural buildings and the retrofitting of existing heritage structures by supporting energy-efficient glazing selection under architectural preservation constraints.

**Table 1.** Summary of studies on glazing technologies

| Ref. | Authors | Article Title | Brief Description |
|---|---|---|---|
| 15 | Cuce,E.&Riffat,S | A state-of-the-art review of innovative Glazing technologies | This review presents advanced glazing technologies and practical applications related to the improvement of building energy performance. |
| 16 | Rezaei, S.D. et al. | A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment | This study analyzed different types of glazing and coatings in terms of energy performance and optical properties. |
| 17 | Aguilar-Santana, J. L. et al. | Review on window-glazing technologies and future prospects | This study reviews conventional and advanced glazing technologies, focusing on their thermal characteristics. |
| 18 | Feng, F. et al. | A review of fenestration and window system design methodologies for high-performance buildings | This study examined the design approaches and energy performance of window systems in high-performance buildings. |
| 19 | Aruta, G. et al. | Double-skin façades for the refurbishment of historic buildings: Energy-economic feasibility for different types of glazing and ventilation rates | Analysis of various glazing types (single, double, low emissivity, reflective, smart) using EnergyPlus and Design Builder across different climates. |

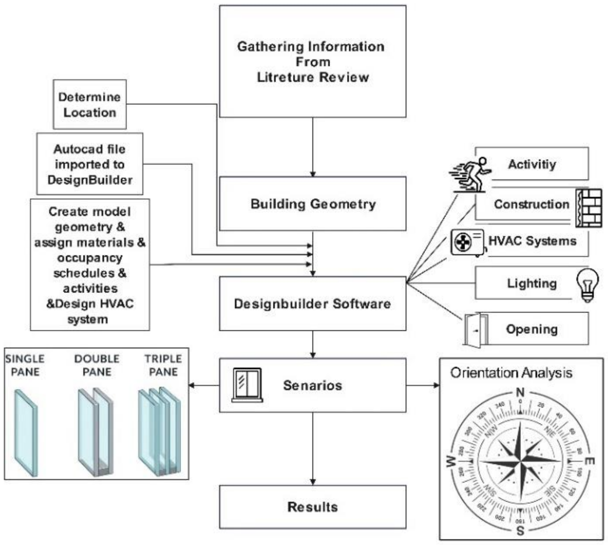


**Fig. 1.** Flowchart of the research

## 2. Methodology

A historic building in Tehran, serving a cultural and administrative function and encompassing approximately 3,000 m², was selected as the case study. Figure 1 presents the research methodology: data collection, modeling, simulation, and results analysis. A Typical Meteorological Year (TMY) weather file for Tehran was used to represent local climatic conditions. The weather data was imported into DesignBuilder and provided hourly climatic inputs for all simulations.A two-dimensional architectural model of the building was created using AutoCAD. As shown in Figure 2, the building is a two-story courtyard complex. In this figure, the upper floor is indicated using a hatch pattern and follows the same spatial configuration as the ground floor. The courtyard is located at the center of the building. The model includes floor plans of interior spaces, walls, openings, and other architectural elements, all developed based on field measurements and documentation of the existing structure. In the subsequent stage, the drafted model was exported in DXF format and imported into DesignBuilder Software. The building orientation was defined based on its actual north alignment in the site plan. The window-to-wall ratio (WWR) was calculated after the geometric modeling process based on the DesignBuilder model outputs. The total window area was 108.75 m², corresponding to a gross WWR of 7.16%. The distribution of window areas across façades is presented in Table 2, showing that the north façade has the highest glazing area (37.61 m²), while the west façade has the lowest (21.06 m²). Within the software, parameters such as three-dimensional geometry, material layer configurations, component thermophysical properties, thermal transmittance coefficients, solar absorptance values, air infiltration rates, and operational schedules were specified. To ensure modeling accuracy, all interior spaces, including office rooms, multipurpose halls, lobbies, classrooms, and service areas, were categorized. Internal loads, including occupant density, lighting, and office equipment, were defined in accordance with ASHRAE standards and assigned to different functional space categories as summarized in Table 3. Occupancy density, equipment power density, and thermal setpoints were specified based on the functional usage of the building, including offices, classrooms, laboratories, kitchens, libraries, and entrance halls. The building was modeled using a split system with separate mechanical ventilation. A fresh air ventilation rate of 4 L/s per person, together with an area-based component, was applied in accordance with ASHRAE guidelines for educational buildings. Heating was modeled using a natural gas-based boiler system, while cooling was provided by an electricity-driven air-conditioning system. The corresponding system performance parameters were defined based on the default simulation settings in DesignBuilder for similar building types. Domestic hot water (DHW) demand was also included in the model and supplied by a dedicated natural gas boiler system. The operational schedules for HVAC and related systems were defined based on typical usage patterns of educational buildings implemented in the simulation environment.

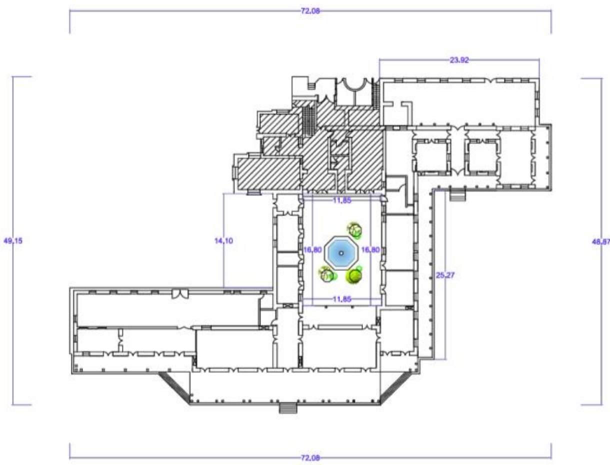

**Fig. 2.** Ground floor and upper floor plans of the case study building

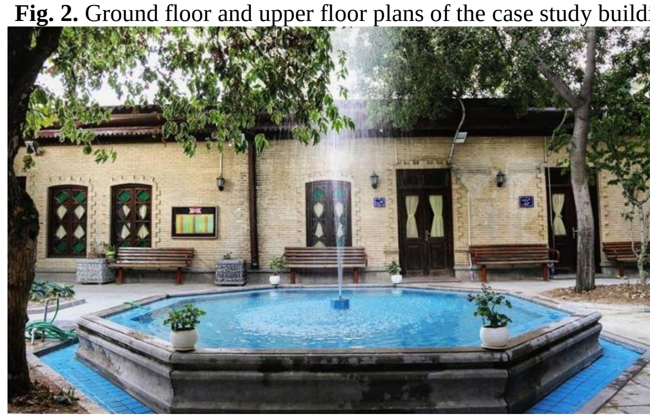

**Fig. 3.** Section of the building façade analyzed in this study

**Table 2.** Window-to-Wall Ratio (WWR)

| Parameter | Total | North | East | South | West |
|---|---|---|---|---|---|
| Gross Wall Area [$m^2$] | 1518.25 | 424.53 | 332.22 | 429.67 | 331.83 |
| Window Opening Area [$m^2$] | 108.75 | 37.61 | 24.78 | 25.30 | 21.06 |
| Above Ground Window-Wall Ratio [%] | 7.16 | 8.86 | 7.46 | 5.89 | 6.35 |

The initial step in the simulation process involved creating the Base Case model with 6-mm clear single glazing, which served as the reference scenario. To assess the impact of various window glazing types, 11 glazing scenarios were incorporated into the model. The scenarios included single glazing (clear, bronze, gray, and low-iron), double glazing (air-filled, argon-filled, and low-E), and triple glazing (clear, low-E, and film-coated). Each scenario was entered into the model with its respective U-value, solar heat gain coefficient (SHGC), and visible transmittance (VT). Figure 3 presents a section of the study building, emphasising the layout and interior spaces utilised in the energy simulation. Table 4 lists the physical and thermal properties of the materials comprising the building envelope, including the exterior, interior, roof, and floor. The material layers are arranged from exterior to interior. The table provides values for density (kg/m³), thermal conductivity (W/m·K), specific heat capacity (J/kg·K), and thickness (m) for each layer.

**Table 3.** Internal loads and thermal setpoint assumptions for different space types

| Space Type | Occupancy ($person/m^2$) | Equipment / Power Density (W/m2) | Heating Setpoint (C) | Cooling Setpoint (C) |
|---|---|---|---|---|
| Office | 0.1 | 4 | | |
| Library | 0.25 | 6 | | |
| Classroom | 0.3 | 5 | 22 | 27 |
| Computer Lab | 0.35 | 12 | | |
| Kitchen | 0.05 | 10 | | |
| Entrance Hall | 0.1 | 0 | 20 | 28 |

**Table 4.** Physical and thermal characteristics of the materials employed

| Application | Material Name | Thickness (m) | Thermal Conductivity (W/m·K) | U-Value (W/m²·K) |
|---|---|---|---|---|
| External Wall | Brick – burned | 0.3 | 0.85 | 1.672 |
| | Gypsum Plastering | 0.03 | 0.4 | |
| Internal Wall | Gypsum Plastering | 0.02 | 0.4 | 2.004 |
| | Brick | 0.1 | 0.72 | |
| | Gypsum Plastering | 0.02 | 0.4 | |
| Roof | Steel Siding (HF-A3) | 0.002 | 45 | 0.194 |
| | MW Stone Wool (rolls) | 0.2 | 0.04 | |
| | Roofing Felt | 0.005 | 0.19 | |
| Floor | Ceramic / Clay Tiles | 0.01 | 0.8 | 1.295 |
| | Mortar | 0.02 | 0.88 | |
| | Concrete Block (Medium) | 0.2 | 0.51 | |
| | Gypsum Plastering | 0.03 | 0.4 | |

Three rose diagrams (wind, temperature, and solar Rose) were generated for the Mehrabad weather station in Tehran to complete the climatic analysis. Figure 4-a (Wind Rose) shows that most annual winds originate from the north and northwest, with average wind speeds generally in the low-to-moderate range. This wind pattern underscores the importance of considering prevailing winds when positioning openings, designing natural ventilation, and controlling dust infiltration through the northern and western façades. Figure 4-b (Temperature Rose) presents the mean dry bulb temperature for each wind direction. The data indicate that warmer air primarily enters from the west and southwest, whereas winds from the north and northeast are cooler and can be utilized for natural cooling during warmer months. Figure 4-c (Solar Radiation Rose) displays the distribution of average horizontal solar irradiance by direction, revealing that the highest radiation levels occurred from the southern hemisphere, particularly between the southeast and southwest. A combined interpretation of these three diagrams yields significant conclusions for climatic design in Tehran. Controlling solar radiation from southern façades through shading devices and appropriate glazing is essential. Additionally, utilizing cool northern winds for natural ventilation can reduce both cooling and heating loads. The implementation of these strategies enhances the thermal comfort of the occupants.

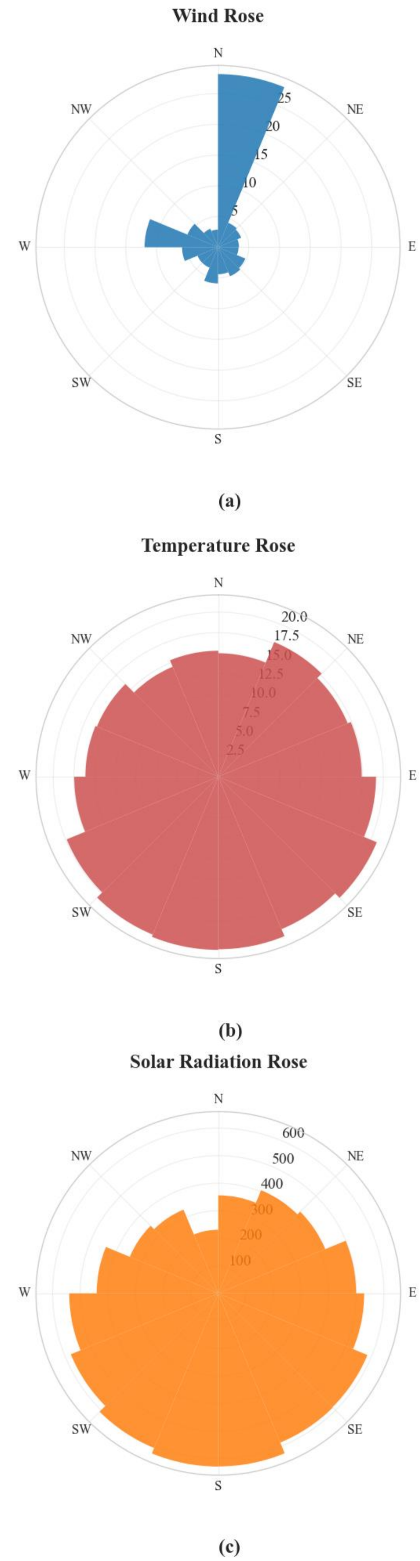


**Fig. 4.** Wind, Temperature, and Solar Radiation Roses for Tehran.

Figure 5 presents the structural differences between the window glazing types. Single glazing exhibited the lowest thermal performance owing to its high rate of heat transfer. In contrast, double-glazed windows incorporate an intermediate air or gas layer that functions as a thermal insulation barrier, significantly reducing heat transfer through the window assembly, leading to approximately a 50% decrease in heat loss compared with single-glazed windows [22]. Furthermore, studies have shown that the heat transfer rate of a double-glazed window is up to 2.5 times lower than that of a single-glazed window, resulting in a 50–67% reduction in heat gain in warm climates [23]. Triple glazing, which contains two intermediate cavities, offers the highest thermal resistance and is thus most appropriate for low-energy buildings. Table 5 presents the thermal and optical properties of the glazing types evaluated in this study, including 11 scenarios with single, double, and triple-glazing. The specifications, including thermal transmittance (U-value), Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT), provide a basis for comparing the energy performance of each simulation scenario. Figure 6 presents the three-dimensional model of the building under study as developed in the DesignBuilder software. All glazing scenarios (11 different configurations, including single, double, and triple glazing) were applied to the same geometric model and simulated to enable a consistent and comparable assessment of how variations in the thermal and optical properties of the glazing affect the energy performance of the building. The position of the openings, their dimensions, and the building orientation were modeled in accordance with the actual project conditions and climate of Tehran. This model served as the basis for all heating, cooling, and energy efficiency calculations across the defined scenarios. An orientation sensitivity analysis was conducted to examine the effect of building rotation on annual energy demand. The whole building model was rotated from 0° to 315° at 45° intervals, while all other simulation inputs, including construction materials, glazing properties, occupancy schedules, HVAC settings, infiltration rate, internal loads, and weather data, were kept constant. For each orientation, annual heating, cooling, and total energy consumption were extracted using the same DesignBuilder/EnergyPlus simulation settings. This procedure allowed the influence of orientation to be isolated from other design variables and compared with the impact of glazing properties. The validation of the simulation model was carried out using the ASHRAE Standard 140 (BESTEST) procedure, as described in the following section.

**Table 5.** Thermal and Optical Properties of Glazing Types

| Scenario | Description | U value (W/m2K) | SHGC | VT |
|---|---|---|---|---|
| Base | Single Clear 6 mm | 5.778 | 0.819 | 0.881 |
| S1 | Single Bronze 6 mm | 5.778 | 0.62 | 0.534 |
| S2 | Single Grey 6 mm | 5.778 | 0.602 | 0.431 |
| S3 | Single Low-Iron 5 mm | 5.816 | 0.898 | 0.91 |
| D1 | Double Clear 6mm / 13mm Air | 2.665 | 0.497 | 0.473 |
| D2 | Double Clear 6mm / 13mm Argon | 2.511 | 0.495 | 0.473 |
| D3 | Double Low-Iron 5mm / 13mm Argon | 2.526 | 0.818 | 0.834 |
| D4 | Double Low-E (e2=0.2) 6mm / 13mm Argon | 1.689 | 0.635 | 0.721 |
| T1 | Triple Clear 3mm / 25mm Air | 1.948 | 0.679 | 0.738 |
| T2 | Triple Low-E (e2=e5=0.1) 3mm / 13mm Argon | 0.78 | 0.474 | 0.661 |
| T3 | Triple LoE Film (55) Clear 6mm / 13mm Air | 1.202 | 0.31 | 0.455 |

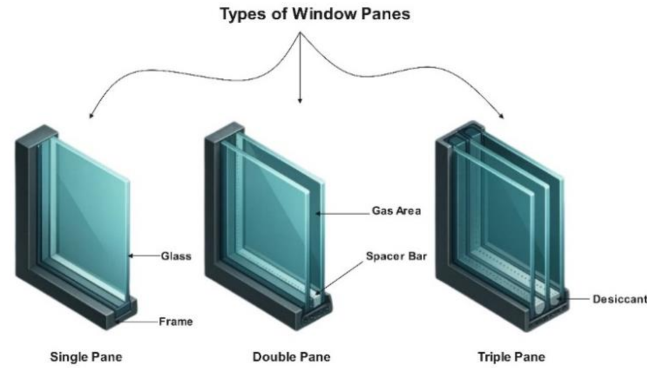


**Fig. 5.** Structural comparison of single, double, and triple glazing systems.

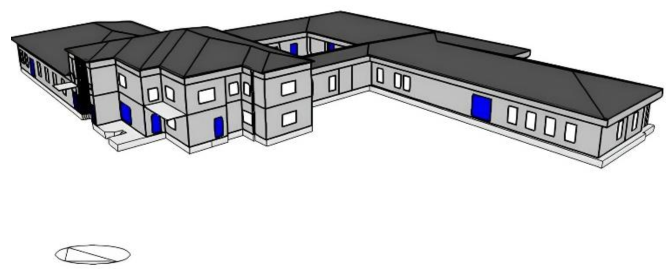

**Fig. 6.** A three-dimensional building model generated using DesignBuilder.

### 3. Validation

The ASHRAE Standard 140 (BESTEST) procedure was used to validate the simulation model [24]. This standard examines two reference cases: Case 600, representing a lightweight building without shading devices, and Case 610, representing a lightweight building with a 1-meter horizontal overhang above the south wall. The simulation results from DesignBuilder, specifically the annual heating and cooling loads, were compared with the ASHRAE reference values and benchmark ranges defined in the standard. The comparison indicated that the heating loads in both cases were within the reference range. Although the cooling loads were approximately 9%–12% lower than the EnergyPlus reference value, they remained within the standard's acceptable limits. These results demonstrate that the simulation model developed in this study successfully passed the ASHRAE 140 validation test and possessed sufficient accuracy and reliability for use in the main analyses. Table 6 presents the results of this comparison, including minimum, maximum, reference, and simulated values. The assessment confirmed that the model outputs

**Table 6.** Validation results of the model using the ASHRAE 140 standard

| Case | Metric | Min-Max | Ref Avg (EnergyPlus) | Your Result |
|---|---|---|---|---|
| 600 | Annual Heating (MWh) | 4.298-5.709 | 4.498 | 4.663 |
| 600 | Annual Cooling (MWh) | 6.137-7.964 | 6.918 | 6.289 |
| 610 | Annual Heating (MWh) | 4.355-5.786 | 4.53 | 5.032 |
| 610 | Annual Cooling (MWh) | 3.915-5.778 | 4.9 | 4.431 |

for both cases fell within the defined standard ranges. Therefore, the simulation model used in this study is considered valid, and the results derived from the primary research model are regarded as reliable.

## 4. Results and discussion

Figures 7–9 illustrate the monthly energy variations for the various glazing scenarios. In all scenarios, energy consumption demonstrated a clear seasonal trend: usage peaked during colder months owing to increased heating requirements and declined during warmer months as thermal demand decreased. Although this general pattern is consistent, differences in performance among the scenarios become more evident during the peak heating and cooling periods. Glazing types with superior performance, such as D4 and T2, exhibited lower energy consumption during the warm months, reflecting reduced solar heat gain and improved thermal properties of the building envelope. Conversely, scenario S3, characterized by a higher Solar Heat Gain Coefficient (SHGC), resulted in higher winter heating loads and greater summer cooling loads.

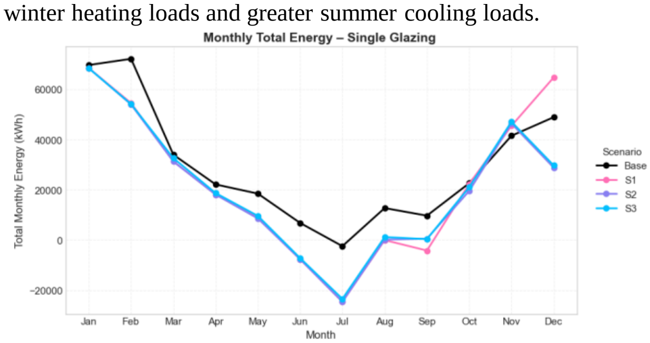


**Fig. 7.** Monthly energy consumption for single-glazing scenario.

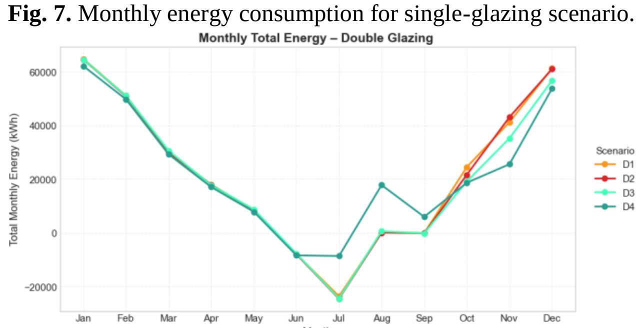


**Fig. 8.** Monthly energy consumption for double-glazing scenarios.

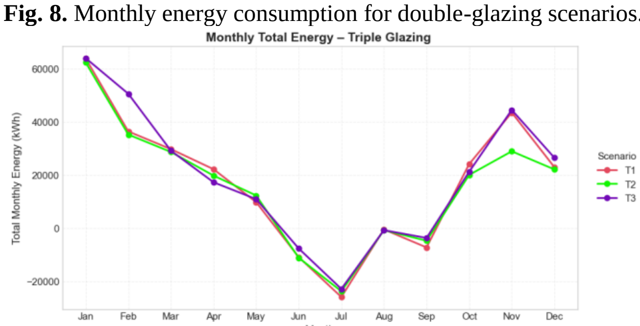


**Fig. 9.** Monthly energy consumption for triple-glazing scenarios.

Figure 10 illustrates the percentage change in annual energy consumption for each scenario relative to the Base Case. The results indicate that, except for the single-glazing scenarios, all double and triple glazing configurations reduce energy consumption. Scenario T2 achieves the greatest improvement, with a 12.7% reduction compared to the Base Case, followed by scenario D4 with a 10.9% decrease. Other high-performance options, including D3, T1, and T3, also showed reductions of 6%–9%. In contrast, scenario S3, owing to its high solar heat gain coefficient (SHGC), resulted in a 1.2% increase in energy consumption. This demonstrates that lower U-values and effective solar control improve the energy performance of buildings.

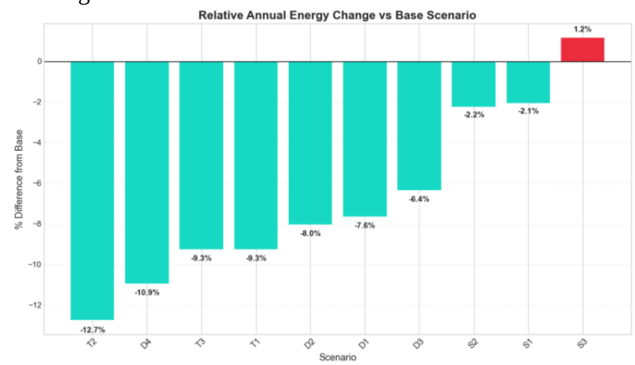


**Fig. 10.** Percent change in annual energy consumption relative to the base case

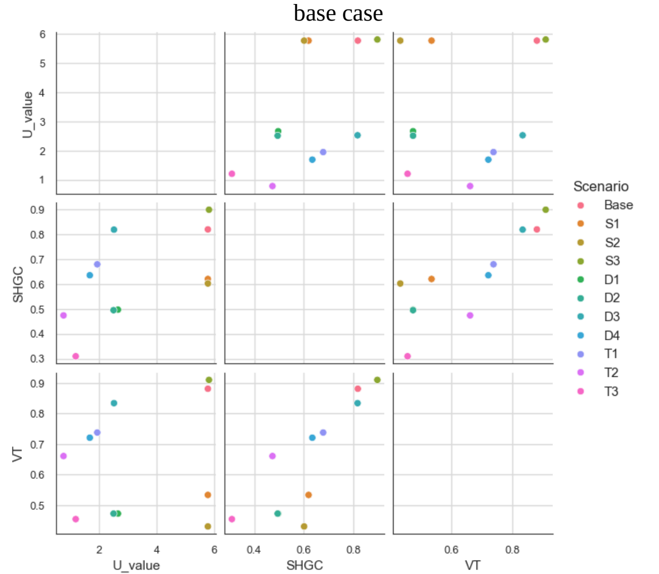


**Fig. 11.** Comparative analysis of the thermal and optical properties of various window glazing types

Figure 11 illustrates the distributions and correlations among the three principal glazing indicators (U-value, SHGC, and VT). Single-glazing types cluster at high U-values and therefore exhibit weaker thermal performance, whereas double- and triple-glazing, particularly low-E scenarios such as D4 and T2, fall within the low U-value range and demonstrate superior efficiency. Furthermore, scenarios with high SHGC values (S3 and D3) have greater potential to increase cooling loads, whereas low-E glazing types such as T2 and T3 provide more effective control of solar radiation. These patterns clearly distinguish high-performance glazing systems from conventional ones. Figure 12 illustrates the contribution of different components to the annual energy consumption across all glazing scenarios. In every case, heating accounts for the largest share of energy use, indicating the predominance of thermal demand in the studied climate. Lighting exhibits a nearly constant share across scenarios, as artificial lighting was modeled using a fixed lighting power density governed by occupancy schedules, with no daylighting control system implemented. Consequently, changes in glazing type do not produce a significant effect on lighting energy demand. The main differences among the scenarios are observed in cooling loads and internal equipment consumption. Scenarios D4 and T2 demonstrate the lowest cooling energy demand, due to their lower thermal transmittance (U-value) and Solar Heat Gain Coefficient (SHGC). Consequently, unwanted heat transfer and solar-induced thermal loads are effectively minimized. Conversely, scenario S3 shows the highest heating and cooling loads. This is due to its relatively higher SHGC, which increases thermal loads during both the cold and warm seasons. Overall, the figure shows that glazing selection has the greatest impact on the thermal components of energy consumption (heating and cooling), whereas fixed loads such as lighting and DHW remain largely unchanged. This finding underscores that improving the thermal performance of glazing, particularly in scenarios such as D4 and T2, can play a pivotal role in reducing the annual energy consumption of buildings.

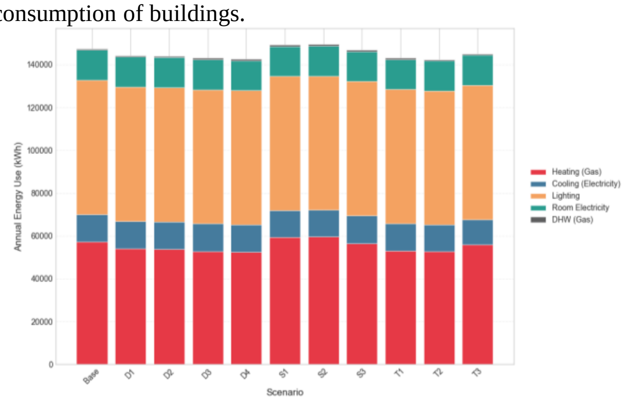


**Fig. 12.** Annual energy consumption distribution by usage type across all-glass scenarios.

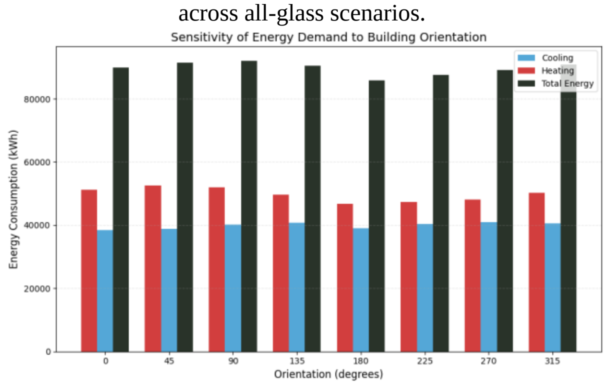


**Fig. 13.** Sensitivity of Building Energy Consumption to Orientation.

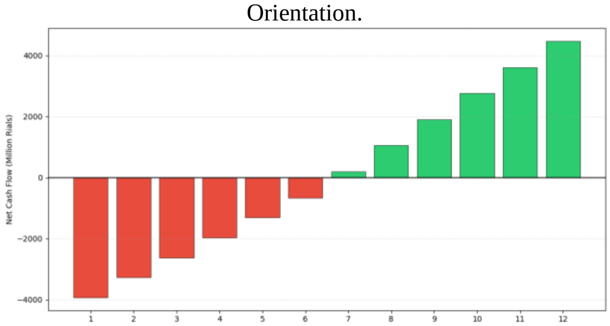


**Fig. 14.** Payback Period Analysis of the D4 Glazing System.

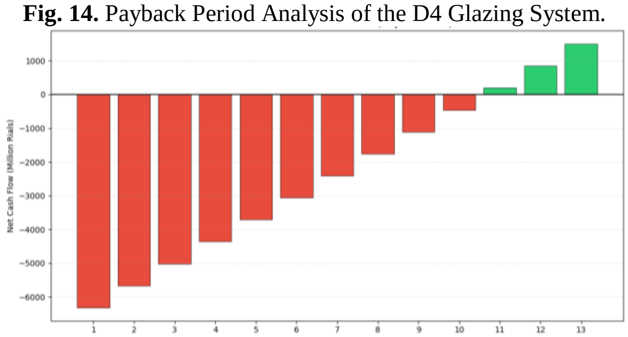


**Fig. 15.** Payback Period Analysis of the T2 Glazing System.

The sensitivity analysis results indicated that building orientation had a noticeable but moderate impact on annual energy consumption. Across the tested orientations, the total energy demand varied between 85,847 and 91,967 kWh. Compared with the original 0° orientation, the minimum energy demand observed at 180° represents an energy reduction of approximately 4.4%. The minimum energy consumption was observed at 180°, whereas higher values occurred at orientations near 45° and 90°. The heating demand decreased by approximately 11% when the building was rotated to 180°, whereas the cooling demand increased by approximately 6%, indicating an inverse relationship between the heating and cooling loads owing to variations in the solar exposure on the building envelope. Overall, the results show that orientation influences the balance between heating and cooling demands; however, its impact on the total annual energy consumption remains moderate compared to that of glazing properties. The results of the sensitivity analysis for the different building orientations are presented in Table 7 and Figure 13.

The economic analysis was conducted using current glazing market prices and 2025 energy tariffs. It should be noted that glazing costs may vary due to market fluctuations, supplier differences, and bulk purchasing conditions, while energy prices are based on regulated national tariffs. A sensitivity range of ±20% was considered for the initial investment cost to account for pos sible variations in market conditions. The results indicate that although the absolute payback periods are sensitive to cost changes, the relative ranking of the systems remains unchanged. The economic comparison focused on the best-performing glazing systems rather than the cheapest alternatives; therefore, lower-cost options may yield shorter payback periods but with lower energy-saving performance. Under the baseline conditions, the D4 configuration (double Low-E glazing) results in a payback period of approximately 6 years, while the T2 configuration (triple Low-E glazing) requires about 10.7 years to recover the initial investment. Even under cost variation scenarios, D4 consistently demonstrates a faster return on investment compared to T2, confirming its superior economic performance and feasibility for retrofit applications in hot-dry climates. The cumulative cash flow and payback behavior of both configurations are presented in Figures 14 and 15, respectively, providing a clear comparison of long-term economic performance. The superior performance of D4 and T2 can be mainly attributed to their lower U-values and controlled SHGC values. In Tehran's hot-dry climate, glazing systems need to balance two competing thermal requirements: reducing heat losses during the heating season and limiting excessive solar heat gains during warmer periods. The use of Low-E coatings and gas-filled cavities contributes to this balance by reducing conductive and radiative heat transfer through the glazing system. As a result, T2 achieved the highest annual energy reduction, with a saving of 12.7%, followed by D4 with 10.9%. By contrast, S3, which had both a high U-value and the highest SHGC among the tested scenarios, showed weaker thermal performance and increased annual energy consumption by 1.2%.

**Table 7.** Annual Heating, Cooling and Total Energy Consumption

| Orientation (deg) | Heating (kWh) | Cooling (kWh) | Total Energy (kWh) |
|---|---|---|---|
| 0 | 51279 | 38522 | 89801 |
| 45 | 52603 | 38761 | 91364 |
| 90 | 51880 | 40087 | 91967 |
| 135 | 49636 | 40722 | 90358 |
| 180 | 46811 | 39035 | 85847 |
| 225 | 47240 | 40270 | 87510 |
| 270 | 48075 | 40980 | 89055 |
| 315 | 50180 | 40640 | 90820 |

From a design and retrofit perspective, the findings indicate a clear trade-off between energy performance and economic feasibility. Although T2 provided the greatest annual energy savings, its payback period was approximately 10.7 years. D4, on the other hand, achieved slightly lower energy savings but offered a considerably shorter payback period of about 6 years. Therefore, D4 may represent a more practical retrofit option for heritage courtyard buildings where budget limitations are significant, while T2 may be more suitable when maximum long-term energy reduction is the main priority. Given that major façade alterations, changes in window-to-wall ratio, and the addition of external shading devices are often restricted in heritage buildings, upgrading glazing systems can be considered a practical and relatively non-intrusive retrofit strategy.

Several limitations should be considered when interpreting these findings. The simulations were conducted using a TMY weather file for Tehran, which may not fully capture future climatic variations or extreme weather conditions. Moreover, occupancy schedules, internal heat gains, HVAC operation, and infiltration rates were defined based on standard assumptions and typical building-use patterns rather than long-term measured data. Although the model was validated using ASHRAE Standard 140 benchmark cases, empirical calibration against measured energy consumption of the case-study building was not possible due to the lack of monitoring data. Therefore, the results should be interpreted as comparative, scenario-based findings rather than exact predictions of actual operational energy use.

## 5. Conclusions

The findings of this study demonstrate that glazing type plays a decisive role in controlling thermal exchanges across the building envelope and managing heating and cooling loads in the climate of Tehran. Simulation results indicate that although the overall pattern of energy consumption across scenarios is similar, the differences in thermal performance among glazing types become clearly evident during peak heating and cooling months. Annual consumption analysis showed that the triple-pane Low-E argon-filled glazing (T2) is the most efficient option, achieving a 12.7% reduction in energy use compared to the base case. Scenarios Double Low-E argon-filled glazing (D4), triple clear air-filled glazing (T1), triple clear glazing with applied Low-E film (T3), double clear air-filled glazing (D1), and double clear argon-filled glazing (D2) also produced substantial reductions (6–11%) relative to the base case. also produced substantial reductions (6–11%) relative to the base case. These improvements are primarily attributed to lower U-values, reduced cooling loads, and more effective control of solar heat gain. In contrast, the single-pane Low-Iron glazing (S3) exhibited the weakest performance, with a 1.2% increase in energy consumption—an outcome linked to its higher SHGC and increased solar heat absorption. The disaggregated energy analysis further revealed that the largest share of annual consumption is due to heating loads, which are directly influenced by glazing type, whereas components such as lighting show little variation across different glazing configurations. Overall, the results indicate that simultaneously reducing U-value and SHGC constitutes a key criterion in selecting appropriate glazing for Tehran's climate. The use of Low-E double- and triple-glazing can be an effective strategy for enhancing building energy efficiency and reducing annual thermal loads. This underscores the importance of informed decision-making in glazing selection as a fundamental component of sustainable climatic design.

In addition, the sensitivity analysis of building orientation indicated that total energy demand varies moderately with changes in orientation, with the lowest energy consumption observed at 180°. Compared with the original 0° orientation, the 180° orientation reduced total annual energy use by approximately 4.4%. However, compared with glazing properties, the influence of orientation on overall energy performance remains relatively limited.

In terms of economic performance, D4 showed a shorter payback period of approximately 6 years, compared with about 10.7 years for T2.

Overall, the findings highlight that optimizing glazing properties is more critical than orientation adjustment in improving energy efficiency in the studied context. For similar heritage courtyard buildings in hot-dry climates, D4 double Low-E glazing is recommended as a cost-effective retrofit option because it provides substantial energy savings with a relatively short payback period. T2 triple Low-E glazing may be selected when maximum long-term energy reduction is prioritized, although its longer payback period should be considered. High-SHGC single glazing, such as S3, should be avoided because it can increase annual energy demand. Since WWR modification and additional external shading devices may be constrained in heritage buildings, glazing replacement represents a practical and less intrusive retrofit strategy.

Future research should include empirical calibration using measured energy data, broader climate comparisons, detailed daylighting-control analysis, and more comprehensive life-cycle cost and environmental assessments.

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