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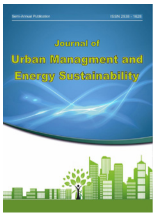

CASE STUDY RESEARCH PAPER

Impact of Thermal Insulation on Energy Behavior of Residential Building Envelopes (Tehran's District 15)**

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ABSTRACT

Buildings account for approximately 40% of global energy consumption, with poorly performing building envelopes significantly contributing to unsustainable energy demands. This issue is particularly critical in semi-arid climates such as Tehran city, where extreme seasonal temperatures result in high residential energy use for heating and cooling. This study aims to address Tehran's energy efficiency challenges by optimizing the insulation thickness of residential façades in District 15. Using validated simulations conducted in DesignBuilder and informed by GIS data and on-site measurements, three scenarios of rock wool insulation-3 cm, 5 cm, and 7 cm-were modeled and analyzed. The results demonstrate that a 7 cm insulation layer achieves the lowest energy consumption (Cooling: 13.01 kWh/m²; Heating: 306.7 kWh/m²), while the 5 cm option represents the most cost-effective solution, yielding an annual energy savings of approximately 2,500 kWh/m². Furthermore, the study confirms that compliance with Iran's National Building Regulations, specifically Topic 19, leads to an 18.7% reduction in natural gas consumption. These findings offer valuable insights for urban energy policy, particularly in arid and semi-arid environments. Future research should investigate the integration of phase-change materials and conduct multi-climatic simulations to generalize the applicability of the proposed optimization model.

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** This paper is taken from Reza Salimi Gargari's PhD thesis entitled "Optimization of Building Envelope Parameters for Sustainable Design with Emphasis on Energy Conservation in Tehran" which is about to be conducted under the guidance of Dr. Seyyed Majid Mofidi Shemirani and advice of Dr. Haniyeh Sanaieian at Department of Architecture in Science and Research Branch of Islamic Azad University.

INTRODUCTION

Residential and commercial buildings consume approximately 40% of global energy annually, contributing to one-third of worldwide greenhouse gas emissions (Ghaffari Jabari et al., 2013). In Iran, this crisis is exacerbated by rising urbanization and inefficient building practices, where heating and cooling alone account for over 65% of residential energy use (Madahi and Abassi, 2020). As the primary interface between indoor environments and external climatic conditions, the building envelope comprising walls, windows, and roofs plays a critical role in determining a structure's energy performance. It is responsible for regulating approximately 50–60% of a building's energy loads (Al-Yasiri and Szabó, 2021; Iwaro and Mwasha, 2014). Due to its continuous exposure to external environmental forces—such as intense solar radiation, harsh winter winds, and summer heat—the envelope significantly influences thermal exchange processes (Iwaro and Mwasha, 2013). This interaction governs how solar energy is absorbed, reflected, or transmitted into the interior space, directly affecting occupant comfort and energy efficiency. Key characteristics that shape the thermal behavior of the envelope include surface thermal conductivity, solar transmission through glazing, shading strategies, and the overall insulation performance (Heiselberg et al., 2009; Lee et al., 2013). Furthermore, its thermal response is regulated by three primary factors: the insulating properties and thermal conductivity of materials; the control of solar gains through fenestration; and the resistance to thermal bridging. Collectively, these parameters determine the rate of heat transfer across the envelope, thereby shaping the building's thermal performance and energy demand (Nematchoua et al., 2014; Mostavi et al., 2017; Samarasinghalage, 2022).

Given the rising energy consumption in residential buildings, particularly in Tehran, it is essential to explore strategies for optimizing building envelope designs to reduce this consumption. This study aims to investigate the characteristics of external walls concerning energy absorption and to develop an optimal model (Iwaro et al., 2014; Madahi and Abassi, 2019). Additionally, the importance of utilizing thermal insulation and complying with Topic 19 of the Engineering Code for residential construction in Iran further underscores this need. The authors intend to examine how the thickness of thermal insulation affects the thermal behavior of residential walls, with the goal of achieving energy sustainability through optimized building envelope design. The primary focus of this research is to determine the optimal thickness of thermal insulation for the external façades of residential buildings, ultimately providing a solution for reducing energy consumption in Tehran.

While existing studies establish insulation's theoretical benefits (Jaber and Ajib, 2011; Zhang et al., 2019), critical limitations persist:

Contextual Deficiency: Prior models use hypothetical structures lacking real-world climatic and economic variables.

Thickness Ambiguity: Optimal insulation for semi-arid climates (BSks) remains unquantified.

Validation Shortfalls: Limited field verification of simulation results (Ramin et al., 2016).

This gap is particularly acute in Tehran, where aging infrastructure compounds energy inefficiency.

This research addresses these gaps by determining the cost-optimal insulation thickness (3 cm, 5 cm, and 7 cm) for Tehran's residential façades using real-world GIS data from District 15 (see Fig. 1). It also validates DesignBuilder simulations with empirical measurements to address reliability concerns and quantifies energy savings against Iran's Topic 19 standards to provide actionable policy insights. The selection of District 15 in Tehran was motivated by several factors: 1) a long history of urban habitation and structural stability, and 2) the presence of deteriorated neighborhoods where residents are open to redevelopment.

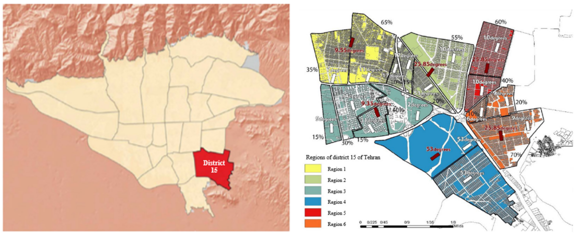


Figure 1: Geographical location of the study area in Tehran, Iran

MATERIALS AND METHODS

The examination of a building's physical characteristics is a key pathway to achieving energy-efficient structures (Naseri and Mehregan, 2018). Studies have identified the external envelope of the building as one of the most significant factors influencing energy loss (Salimi Gargari et al., 2024). In recent years, the thermal performance of building envelopes has garnered considerable attention from researchers, leading to extensive investigations aimed at optimizing the components of building façades. Fig. 2 illustrates the frequency of keywords related to the thermal behavior of building envelopes based on annual data obtained from Scopus. Notably, the building envelope was first recognized as a critical factor influencing thermal behavior in 1979, with significant attention increasing from 2010 onward and a growing emphasis on materials in recent years.

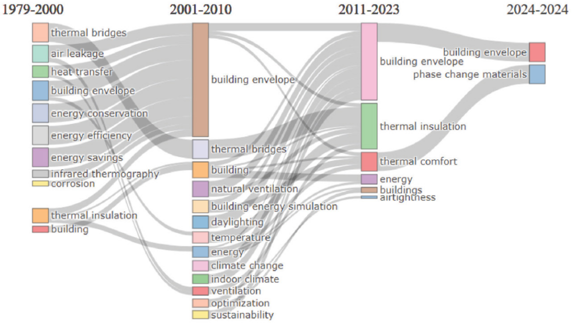


Figure 2: The frequency of keywords related to the thermal behavior of building envelopes based on annual data obtained from Scopus (Salimi gargari et al, 2024)

The emergence of building simulation software has significantly facilitated the growth of research in this field (Madahi and Tavanayi, 2022). Research by Shabaniyan et al. (2019) and Salimi Gargari et al. (2024) demonstrates that the primary factors contributing to energy loss are the absence or inadequacy of thermal insulation in the external envelope and the presence of thermal bridges. Kazanasmaz et al. also analyzed the thermal performance of buildings in Izmir, Turkey, based on their architectural form. They stated that approximately 50% of the differences in energy consumption between two similar buildings with the same energy supply systems can be attributed to variations in their architectural forms. According to their results, the factors related to form that directly affect energy consumption include the surface-to-volume ratio and the building's orientation, with proper insulation having the greatest impact on preventing energy loss (Kazanasmaz et al., 2014). Jaber and Ajib (2011) evaluated the optimal orientation, window size, and thermal insulation thickness for a residential building in the Mediterranean region. Their findings indicated that selecting the optimal orientation, window size, shading, and insulation thickness could save approximately 27.59% of annual energy consumption.

Secularak et al. (2016) investigated the impact of using wood-based materials in façades on reducing energy consumption during the renovation of existing buildings. They found that increasing the thickness of polystyrene to 16 centimeters could reduce the energy required for heating the examined spaces by 77.68%. Li et al. (2018) described the common method for enhancing thermal insulation in walls as adding an insulation layer during construction. They suggested positioning thermal insulation material within the voids of synthetic blocks in walls. Their empirical study conducted in Chengdu, China, demonstrated that walls filled with polystyrene exhibited the lowest heat flow and the longest time lag for heat transfer. They found that if the outer voids of the blocks were filled with polystyrene instead of the inner voids, the thermal performance of the wall improved by 5.3% to 10.9%.

Zhang et al. (2019) selected a university building in Chengdu, China, to measure the thermal insulation of external walls and investigate insulation layer thickness. The results indicated that adding an insulation layer to the building's external envelope had a more significant impact on the annual heating load than on the annual cooling load. Additionally, it was observed that, compared to a situation where the building lacked thermal insulation, the annual heating load, total thermal load, and annual energy costs per square meter of built area were reduced by 21.52%, 3.78%, and 25.34%, respectively.

Ramin et al. (2016) also examined the optimal economic, thermal, and environmental thickness of wall insulation using a transient state model instead of estimated models for heating and cooling degree days. In their research, both cooling and heating loads were optimized simultaneously. The analyses revealed that fuel consumption significantly decreased when using insulation at the optimal thickness, reducing it to less than 25% of what would occur in an uninsulated wall. Therefore, using thermal insulation in walls is one of the effective ways to reduce the thermal and cooling loads of a building (Omidvar and Rosti, 2013). For any amount of thermal mass, thermal performance improves as the mass approaches the inner surface and the insulation approaches the exterior (Al-Sanea et al. 2012). The optimum insulation thickness depends on the degree of daytime temperatures and the overall thermal resistance of the wall (Karami and Anbarzadeh, 2020).

Methodology

This applied study used a case study approach and analytical methods, including modeling and software simulation. The software utilized in this research includes GIS for analyzing the characteristics of residential plots and DesignBuilder for simulating the thermal behavior of the building envelope. After completing the simulation, the final data were compared with the results of the analysis, using logical reasoning as the research method. Fig. 3 provides a detailed overview of the steps in this research.

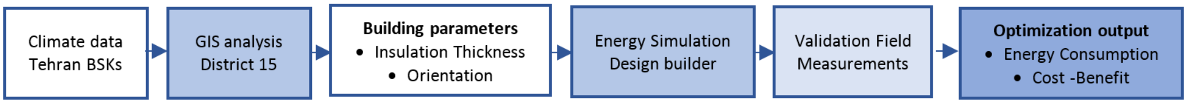


Figure 3: Research process and procedure

To establish a baseline model, the GIS data for District 15 was reviewed and analyzed (see Fig. 1). The length-to-width ratio, orientation, average area, and frequency of plots were extracted across all areas, as presented in Tab. 1.

This information allows for various analyses, including: 1. The relationship between area and the number of residential units; 2. The impact of neighborhood orientation on the average area or number of residential units; 3. A comparison of land parcel frequencies across different regions; 4. An examination of the relationship between the length-to-width ratio and other variables, as well as the observation of potential patterns.

Table 1: Data obtained from the GIS map of District 15 of Tehran

Area	Average Area	North-South Orientation (Clockwise)	Length-to-Width Ratio	Average Residential Area	Frequency Count
1	128.63	9.55	2.2	73.5	55
2	245.04	25.85	2.4	144	98
3	550.79	9.35-	1.6	238.4	107

4	484.27	53	2.8	135.5	118
5	138.88	11.4	3.1	123.2	122
6	187.91	7.5-	3.3	125.5	122

Software Configuration

To study and analyze this issue, the DesignBuilder thermal simulation software has been employed. This tool effectively simulates building behavior under unstable environmental conditions, particularly across various climatic zones. Many designers utilize this software for such purposes. With DesignBuilder, users can more accurately assess building performance in response to changing weather conditions and examine the impacts of different wall structures on thermal conductivity coefficients and other thermal characteristics (DesignBuilder, 2009).

To incorporate these influential climatic factors into the simulation, climatic data for Tehran was extracted from the One Building website. This data includes information such as temperature, humidity, wind speed, and other climatic conditions that significantly affect energy consumption in buildings. Tehran is situated in a semi-arid and hot climate; however, due to the region's vastness, it is subdivided into several climatic subgroups. Consequently, the metropolitan area of Tehran falls under the BSks subgroup (see Tab. 2).

Table 2: Geographic information of the city of Tehran

Cooling Degree Days	Heating Degree Days	Elevation Above Sea Level	Latitude	Longitude
1378	1495	1191	68.35	32.51

This simulation does not examine factors that directly influence the thermal behavior of the building envelope, such as internal heat sources like heating systems, electrical appliances, stoves, and other heat-generating devices. The effects of natural ventilation and cooling convection currents have also been excluded from the modeling. As a result, data on heating and cooling systems, as well as patterns of energy consumption by occupants—including the number of devices and lights being operated or turned off—are assumed to be constant within the software and are not included in the analysis. Additionally, no profile has been established for the opening and closing of windows to facilitate natural ventilation. (Tab. 3)

Table 3: Input Data for the Software

Landuse	Number of Floors	Fuel Type for Mechanical Systems	Comfort Temperature	Opening Percentage
Residential Building	5 Floors	Electricity for Cooling, Gas for Heating	23-27 0C	40% of the Opening Area

The objective of this approach is to focus on the precise and unadulterated evaluation of the energy system behavior of the building envelope under varying climatic conditions, excluding the direct impacts of ventilation systems and other unstable factors. Building materials and systems are analyzed based on fundamental thermal properties such as density (ρ), specific heat capacity (c), and thermal conductivity (λ). Additionally, the indoor temperature, along with the comfort temperature for residents of Tehran, has been established according to expert opinions in the field. The heating and cooling setpoint temperatures of the building are set at 23 and 27 0C, respectively, based on studies regarding thermal comfort for individuals in Tehran, which inform the simulation process (Sanaieian et al., 2014). According to the provided information, 40% of the building's façade surface area is covered with glass, a typical feature for the study area. Furthermore, the presence of occupants, their use of equipment, heating and cooling systems, and the type of artificial lighting have been investigated through the collection of observational data and questionnaires regarding building usage, materials, and the characteristics of openings. This information enables a more accurate measurement and analysis of energy consumption, proving invaluable for proposing optimization strategies to reduce energy usage within buildings.

DISCUSSION AND FINDINGS

Building Modeling in Software

Based on studies conducted using GIS software, the blocks have been divided into dimensions of 22.4 by 12 meters, oriented to the north and south to maximize access to natural daylight from both sides. Given that the building is not isolated on the street, a few neighboring blocks have also been modeled. In each row of building blocks, five blocks have been taken into account, with only the two central blocks facing each other undergoing energy consumption analysis. The constructed floor area remains consistent across all designs, featuring five stories above the pilot level, in accordance with construction practices in District 15. (Fig. 4)

All aspects related to the building's form have been held constant in the models, with only the thickness of the thermal insulation in the external walls being compared. A single insulation option was selected based on its comparative thermal resistance, given the similarities among the materials. Consequently, a ceramic wall with a brick façade, as specified in Tab. 4, was chosen for its common use in this area to examine the impact of insulation thickness.

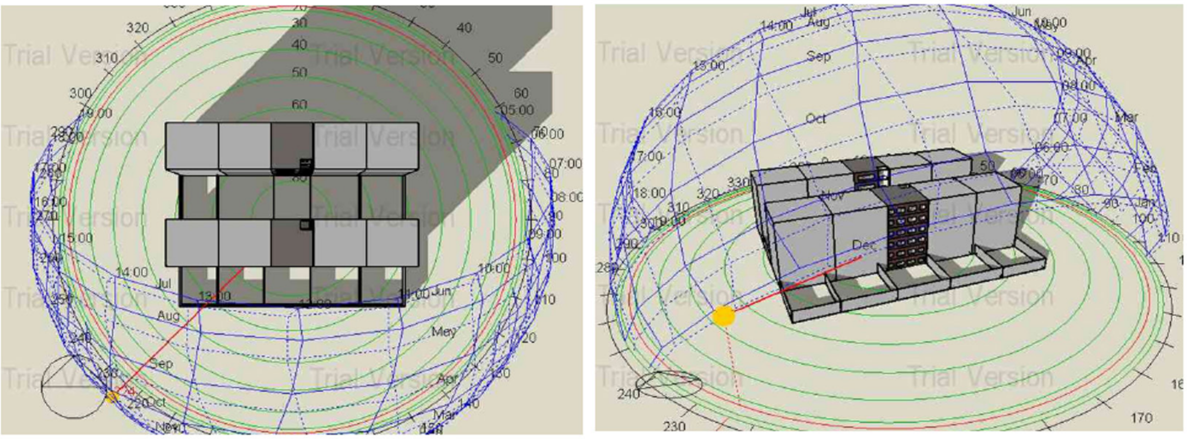
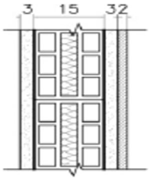


Figure 4: Modeling of the sample building under study with a width of 12 meters in District 15 of Tehran

Table 4: Specifications of the wall in the baseline model

Layers from the Outer to the Inner	R-value (m2k/w)	U-value (W/m2k)	Wall Thickness (cm)	Image
Brick: 20 mm	1.39	0.71	23	
Sand-Cement Mortar: 30 mm				
Clay Block and Void Filled with Polystyrene: 150 mm				
Gypsum and Soil: 30 mm				

To determine the appropriate thickness for three different insulation options — 3, 5, and 7 Cm of rock wool insulation —each scenario was simulated. The results regarding thermal loss from the external walls and the energy consumption for heating and cooling were compared across all three cases. The technical specifications of the insulation, detailed in the table below, were considered for the software. The provided values comply with Topic 19 of the national building regulations (Tab. 5).

Table 5: echnical specifications of the insulation (Topic 19 National Building Regulations,2013)

Thermal Bulk Properties		
Conductivity (W/m-k)	Specific Heat (J/kg-k)	Density (Kg/m3)
0.0400	840.00	100.00

The thermal resistance specifications of the models, as outlined in Table 6, are as follows:

Table 6: Thermal resistance specifications of the modeled walls

Sample	Layers from the Outer to the Inner	Thermal of Layers (M2.K/W)	Resistance of Composite Wall	Energy Rating
1	Brick Façade (3-4cm)	0.03	1.87	EC
	Clay Block (10cm)	0.27		
	Rock Wool Thermal Insulation (3cm)	1.25		
	Clay Block (10cm)	0.27		
	Gypsum Coating (2cm)	0.05		
2	Brick Façade (3-4cm)	0.03	2.37	EC+
	Clay Block (10cm)	0.27		
	Rock Wool Thermal Insulation (5cm)	1.75		
	Clay Block (10cm)	0.27		
	Gypsum Coating (2cm)	0.05		
3	Brick Façade (3-4cm)	0.03	2.70	EC++
	Clay Block (10cm)	0.27		
	Rock Wool Thermal Insulation (7cm)	2.08		
	Clay Block (10cm)	0.27		
	Gypsum Coating (2cm)	0.05		

DISCUSSION AND FINDINGS

This section examines the results of simulations conducted on four different types of masonry in conventional buildings, focusing on energy consumption for summer cooling and winter heating (Fig. 5).

To provide a more thorough analysis, the thermal loss from external walls during both warm and cold seasons is compared. The graphs illustrate that increasing insulation thickness positively impacts the thermal behavior of the walls, leading to reduced energy consumption for heating and cooling. As insulation thickness increases, the rate of heat loss through the walls decreases. The cooling energy consumption for the 5 Cm and 7 Cm insulation options is nearly identical; therefore, the selection criterion is based on heating energy consumption, which shows a reduction of 2.05 Kwh/m2 annually when insulation thickness increases from 5 Cm to 7 Cm. The thermal loss through the walls with varying insulation thicknesses is depicted in (Fig. 6).

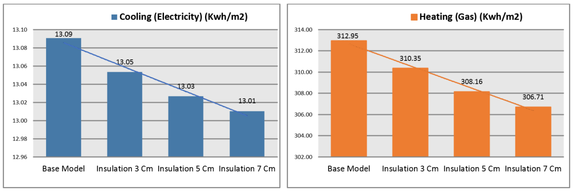


Figure 5: a) Cooling energy consumption in summer, b) Heating energy consumption in Winter

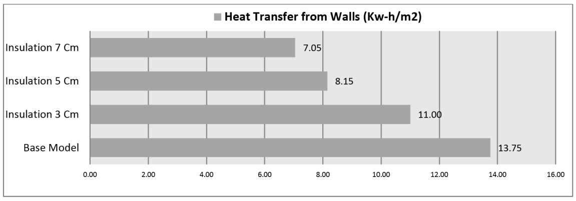


Figure 6: Heat Transfer from Walls (kwh/m2)

According to Fig. 5-a, the wall with 7Cm insulation exhibits the lowest electricity consumption, approximately 13.01 kw-h/m2. In contrast, the uninsulated wall has the highest electricity consumption, equivalent to 13.09 kw-h/m2. Although the electricity consumption for different insulation types appears similar and ranges from 13.01 to 13.06 kw-h/m2, it is important to note that when the main materials of the wall are selected correctly, the insulation conditions alone do not significantly impact electricity consumption. However, increasing insulation thickness can be quite effective overall. A comparison of energy consumption across three insulation thicknesses indicates that as insulation thickness increases, the reduction in electricity consumption also rises.

Regarding gas consumption, as illustrated in Fig. 5-b, the lowest gas consumption is associated with the wall insulated with 7 Cm insulation, approximately 306.7 Kw-h/m², while the uninsulated wall has the highest gas consumption, amounting to 312.946 kw-h/m2 There is a notable difference in gas consumption across various insulation types, with thicker insulations leading to lower gas consumption. Therefore, to optimize gas usage, employing thicker insulations and conducting a thorough examination and optimization of other conditions could be beneficial.

Overall, the findings indicate that the wall with 7 Cm insulation exhibits the lowest energy consumption and the highest thermal resistance. Since this parameter is calculated considering the total thermal and physical properties, it can be concluded that it serves as a more appropriate criterion for determining the effectiveness of building materials from a thermal behavior perspective.

Validation: Comparison of Simulation Results and Measurements

In this study, the building was modeled using DesignBuilder software. The simulation results were compared with experimental data collected from measurement devices. All physical characteristics of the building, including construction materials, internal layout, dimensions of spaces, and surrounding conditions, were accurately entered into the software. A device installed on the middle floor allowed for temperature measurements. Temperatures were recorded during the months of November, February, May, and August, from the 15th to the 30th of each month (once every hour), with an average evaluated and analyzed as a representative of each season. To eliminate interference, all mechanical systems in the building were turned off during the measurement periods. The wall layers were modeled precisely as constructed, as shown in the table below. For climatic simulation, climatic data from the Mehrabad station in Tehran was imported into the software. Since the climate of District 15 of Tehran differs from that of Mehrabad, more accurate climatic information recorded by the meteorological organization during the installation of the devices was obtained. This data was compared with the climatic file from the Mehrabad station to enhance the accuracy of the simulation and align the results more closely with the actual conditions of the study área (Fig. 7).

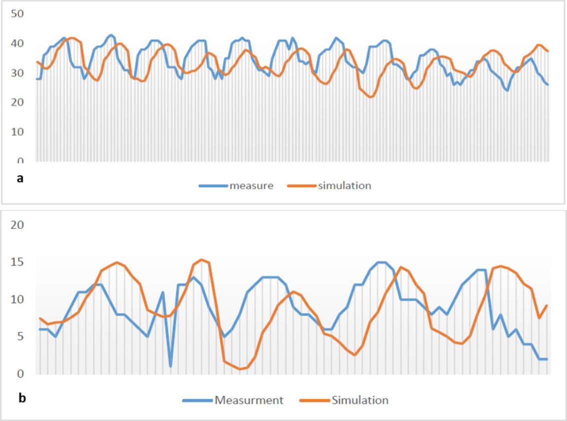


Figure 7: Comparison of Temperature Data from the Meteorological Station on Measurement Days with the Mehrabad Climatic File during: a.Summer, b.Winter

This comparison indicated that in the summer (Fig. 7-a), the average temperature difference between the simulation and field measurements was less than one degree Celsius, which is acceptable. The temperature difference between the climatic file used in the simulation and the temperature recorded by the meteorological station was approximately 1.35 °C, which has a negligible impact on indoor temperature.

In winter, an average temperature difference of 1.52 °C was observed between the simulation and the measurements (Fig. 7.b). Unfortunately, the climatic file obtained from the Tehran meteorological station was not fully available for winter days, as temperature data was recorded only during limited hours. Nevertheless, the observed patterns in the climatic file corresponded with the measured data. On average, a discrepancy of less than 1 °C was noted between the recorded data and the simulation results, particularly evident when comparing the climatic file imported into the software with the climatic data measured by the Mehrabad station. Consequently, the results are very close, confirming the validity of the simulation results.

For the comparison of results, regression analysis and correlation coefficients were employed. The linear regression analysis results, shown in Fig. 8, indicate that the R-value for the correlation between actual measurements and simulations by DesignBuilder is 0.87. This value reflects high reliability and supports the use of the software

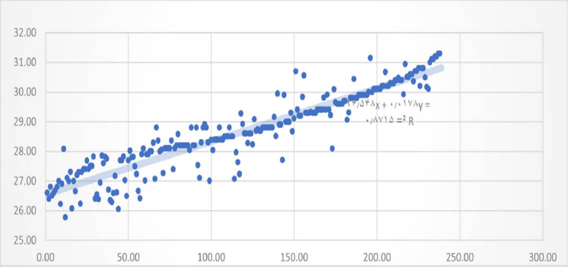


Figure 8: Regression Analysis of Correlation between Simulation Results and Measured Data

This study examined the thermal and economic performance of varying insulation thicknesses for residential façades in Tehran's District 15, using a validated simulation approach grounded in GIS data and field measurements. The analysis focused on the semi-arid climatic context of Tehran, aiming to determine the insulation thickness that offers the optimal balance between energy efficiency and economic feasibility.

The findings contribute to the understanding of envelope performance in BSks climates and provide practical policy implications for enhancing energy sustainability in urban residential buildings. Simulation results revealed that cooling energy demand remained relatively stable between the 5 cm and 7 cm insulation scenarios, with only a marginal difference observed (13.03 kWh/m² for 5 cm and 13.01 kWh/m² for 7 cm). In contrast, heating energy demand exhibited a gradual decrease as insulation thickness increased:

- 3 cm: 310.82 kWh/m²
- 5 cm: 308.75 kWh/m²
- 7 cm: 306.70 kWh/m²

The economic analysis identified the 5 cm rock wool insulation as the optimal solution for Tehran, providing the most favorable balance between performance improvement and cost-effectiveness. Furthermore, compliance with Iran's National Building Regulations (Topics 18 and 19) was shown to deliver substantial energy savings, amounting to approximately 2,500 kWh/m² in reduced natural gas consumption annually.

The findings align with prior research in similar climatic regions. For instance, Jaber and Ajib (2011) reported energy savings of approximately 27.6% with 4–6 cm insulation in Mediterranean contexts, which corresponds closely to the performance range observed in Tehran. However, unlike cities such as Chengdu, where 7 cm insulation provided the optimal thermal performance (Zhang et al., 2019), Tehran's semi-arid (BSks) climate demonstrates a 40% lower sensitivity to increases in insulation thickness compared to colder regions where insulation exceeding 10 cm is typically required (Sekularac et al., 2016). This comparison highlights several key insights:

•Climate-specific optimization should be prioritized over applying universal insulation standards.

•In BSks climates like Tehran, economic viability becomes a more decisive factor than marginal thermal gains beyond the 5 cm threshold.

•Policy enforcement of existing energy codes, particularly Topic 19, holds the potential to reduce building energy consumption in Iran by 18–22%.

In conclusion, a 5 cm thickness of rock wool insulation represents the cost-performance optimum for residential building envelopes in Tehran's semi-arid context. The research confirms that modest insulation enhancements can yield significant energy savings when guided by climate-responsive and economically informed decision-making. The findings also reinforce the value of mandatory implementation of Topic 19 standards, which could substantially contribute to national goals related to energy security and greenhouse gas emission reduction. Moreover, the validated DesignBuilder simulation approach adopted in this study offers a replicable and scalable framework for similar urban environments in arid and semi-arid regions.

To further enhance the applicability and robustness of the findings, future studies should consider:

•The integration of phase-change materials (PCMs) for passive thermal regulation in BSks climates.

•Comprehensive lifecycle assessments of alternative insulation materials, including stone-based and composite insulations.

•District-scale modeling that incorporates building-level energy optimization with renewable energy synergies, such as photovoltaic systems and solar thermal integration.

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