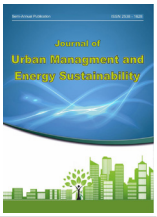
International Journal of Urban Management and Energy Sustainability (JUMES)

Homepage: http://www.ijumes.com



CASE STUDY RESEARCH PAPER

Optimizing Thermal Performance of Double-Wall Systems in Tehran's Climatic Conditions: A Simulation-Based Approach

Ashkan Hassani, Shooka Khoshbakht Bahramani*, Vahid Ghobadian

Department of Architecture, CT.C., Islamic Azad University, Tehran, Iran

ARTICLE INFO

Article History:
Received 2025-04-13
Revised 2025-10-06
Accepted 2025-10-26

Keywords:
Double-wall systems, Thermal insulation, Energy efficiency, Building materials, Tehran city, Simulation analysis

ABSTRACT

Energy efficiency is an essential part of sustainable urban development strategies, especially in cities with wide temperature ranges like Tehran, where a significant amount of energy is consumed to maintain occupants' comfort. Double-wall systems with an air cavity can minimize reliance on mechanical heating and cooling sources; however, there are few quantitative studies of insulation materials in Tehran's climatic conditions. In this study, we use a simulation-based approach utilizing the DesignBuilder program and EnergyPlus engine to evaluate the thermal performance of eight insulation materials (polystyrene, PVC, rock wool, fiberglass, polyurethane, glass wool, polyurethane foam, and extruded polystyrene) in double wall systems, with insulation thickness ranging from 5 to 15 cm, for a typical residential unit located in Tehran, using the actual climate data to analyze heat transfer .The results showed that both the insulation type and thickness play an important role in energy efficiency. Polyurethane and polyurethane foam delivered the best performance in this study with approximately a 30% reduction in heat transfer at 12 cm thickness. Other materials also exhibited more energy efficiency than a non-insulation process, although performance improvement was limited as thickness increased. The study concludes that high-performance insulation, particularly polyurethane at 12 cm, can effectively enhance thermal efficiency in Tehran's residential buildings. This research provides a technical basis for optimizing wall systems in urban environments. Future studies should incorporate cost, environmental impacts, and advanced insulation technologies to develop more comprehensive strategies for sustainable building design in Tehran and comparable climates.

DOI: 110.22034/IJUMES.2024.711844

Running Title: Thermal Performance of Double-Wall Systems in Tehran's Climatic Conditions

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
30	28	03

*Corresponding Author:
Email: *shooka.khoshbakht@iau.ac.ir*
Phone: +989121712023
ORCID: https://orcid.org/0000-0002-6987-9987

INTRODUCTION

In accordance with the rapid development of urbanization, enhancing building energy efficiency has been accounted for as a key factor in sustainable development. Buildings represent one of the most consuming sectors all around the world, particularly in expanding cities such as Tehran, where urban construction has escalated (Farahani et al., 2022). Among various strategies in building improvement energy performance, the use of double-wall systems has been considered an influencing method for enhancing thermal insulation usage and reduction of overall building energy demand (Malbila et al., 2021b). By considering air between two wall layers, double walls act as insulating barriers that reduce heat transfer between indoor and outdoor environments in a significant way (Jamal et al., 2020). With the aim of developing a conceptual foundation, the current research employs a comprehensive framework that integrates principles of heat transfer, thermal behavior of composite walls, and modern insulation materials. This model unifies theory and practice, guiding both academic and professional applications for optimizing wall systems to achieve higher energy efficiency. Tehran's distinct climate which is considered hot in summers and cold in winters, makes wall insulation vital for building designers to increase thermal comfort and make reductions in energy consumption. Despite its vitality, limited quantitative investigation has examined the thermal behavior of double-wall systems under Tehran's climatic conditions. This lack of localized, data-gathering studies highlights a considerable research gap.

The present research follows this gap by quantitatively analyzing the thermal performance of different sorts of double-wall materials used in Tehran with the thermal insulation. Applying mathematical and simulation-based approaches, it evaluates material effectiveness under different conditions. This study makes a contribution to developing efficient construction methodologies that are suitable for Tehran's climate, which suggests a novel quantitative framework for sustainable architectural practices.

MATERIALS AND METHODS

Building Double Walls Thermal Transmittance

Double-wall systems affect heat retention and building energy efficiency considerably in comparison with single walls. Studies highlight features like material thickness, air layer, and surface emissivity, which influence thermal transmittance and energy demand (Aketouane et al., 2016) (Jamal et al., 2020). Advanced thermal insulation materials, such as flexible hollow polymer fibers, enhance resistance and design flexibility (Knapczyk-Korczak et al., 2024).

Thermal insulation categorized as nanomaterials, including vacuum insulation panels and silica aerogels, also demonstrates outstanding performance with minimal thickness (Koebel et al., 2017), (Jaber Abdulhameed et al., 2023). The group of investigations on material optimization continues through thermal imagery, eco-friendly materials like rice straw bales (Marques et al., 2020), and studies of thermal break strips for light steel frames (Sadhukhan et al., 2020), (Santos et al., 2020).

Overall, thermal efficiency in double walls depends on material properties, especially air cavity thickness and emissivity, which shape the basics of simulation optimization.

Thermal Balance of Building Double Walls

Air cavities and insulation methods such as polystyrene beads, which lessen heat transfer significantly compared to single walls (Malbila et al., 2021b). (Al Fakhoury et al., 2024). Composite multi-layered systems emphasize the key role of material type, layer thickness, and insulation placement in thermal behavior (Vučenović et al., 2022). In the category of phase change materials like expanded graphite (EG), the fluctuation and heating loads are reduced by over 15% (Yang et al., 2021). Likewise, bio-based materials such as wood–plastic composites (WPC) offer sustainable alternatives (Yu et al., 2021). The thermal balance conceptual model makes an assessment based on the equilibrium of heat flux as it transverses through the layers, focused on storage, release, and optimization in simulations.

Building Double Walls Façade

As a useful sort of building elevation, double-skin façades (DSFs) use two glass layers separated by an air cavity to enhance energy efficiency and indoor comfort (Nastri, 2023). Research articles show performance improvement in brick façades, where U-values correlate with solar radiation response (Penić et al., 2014). Double-wall systems reduce heat transfer by 47–90% in comparison with single-skin elevation (Malbila et al., 2021b). Alternative materials such as compressed earth blocks and recycled textile waste improve insulation by up to 33% (Paiva et al., 2011). Optimal air cavity thickness (5–6 cm) and low emissivity make an improvement in energy performance (Jamal et al., 2020), (Kareem Abdullah et al., 2022). Various case studies in Morocco reflect a reduction in energy usage of up to 63% when there is hemp concrete in an integration with an air cavity (Dlimi et al., 2023). Though double-stud walls as a cellulose-insulated base express a risk of condensation, especially in cold climates, field studies show minimal damage (Ueno et al., 2015). In another type of facade, timber-based walls with air layers achieved suitable U-values as low as 0.18 W/m²K (Bucklin et al., 2023). Moreover, research in Iran pointed out the benefits of smart concrete reducing heating demand by 22.5% (Boroumand, 2023) and integrated wall–window designs reducing the energy consumption costs by over 33% (Awad, et al., 2020). Traditional Iranian passive designs in a similar way demonstrate the efficiency of thick thermal mass and controlled airflow in cold local areas (Hajali Zadeh, 2022). In equivalent research, integrated approaches in Kashan demonstrated energy savings of up to 27% when wall and window upgrades were combined, cutting annual costs by more than 33% (Awad, et al., 2020), (Abdul Nasir and Hassan, 2020).

Foundation of the Theoretical Framework

The underlying premise of this study is founded on double-wall building systems that consist of layers of insulation and air cavities which will yield superior thermal performance by restricting heat transfer and minimizing energy demand. The research model is based on establishment of empirical literature and re-contextualized in the context of the weather and climate of Tehran.

Theoretical Concepts Core and Supporting Theories

- Heat Transfer Reduction through Multi-Layered Wall Assemblies (Transmittance Theory)

Based on classical heat transfer theory, overall thermal transmittance (U-value) decreases as a factor of the number of layers in the transmission walls and lower surface emissivity. Reflective and insulating materials minimize heat gain and los significantly (Aketouane et al., 2016; Jamal et al., 2020).

- Thermal Balance in Composite Wall Systems

This theory focuses on the heat flux balance in the wall layers. The type of material, its thickness, or the configuration of the material will demonstrate how heat is stored and released, but simulations can formulate optimization to enhance the overall performance (Malbilia et al. 2021b), (Vu\renović et al. 2022).

- Air Layer in Envelope Design

Air cavities act as passive zonal insulators. Cavity width of 5–6 cm has been demonstrated to significantly lower heat transmittance (Kareem Abdullah et al., 2022), (Jamal et al. 2020).

- Novel Insulation Materials and Nanotechnology Theory

Nanomaterials, which include vacuum insulating panels and silica aerogels, improve thermal resistance with thinner insulation which contributes benefits in design relating to working in confined spatial applications (Koebel et al. 2017), (Jaber Abdulhameed et al., 2023).

- Dynamic Façade Performance Theory (Double-Skin Facades)

Double-skin façades adapt to environmental conditions, improving thermal and acoustic regulation and optimizing heating, cooling, and daylight (Nastri. 2023), (Penić et al. 2014).

Overall Theoretical Model

By synthesizing and integrating these theories, this research also produces a solid framework for assessing and evaluating double wall systems for the multiple thermal conditions of the city of Tehran, and to justify the theoretical imperatives from an ecological and sustainable design perspective.

Methodology

This study takes a positivist quantitative approach using a simulation-based case study to assess thermal transmittance and energy consumption as considerable factors in residential buildings in Tehran. The study relies on Tehran's climatic data and DesignBuilder/EnergyPlus use as the mail simulation tools, allowing precise evaluation of wall configurations. The research process is comprehensively summarized in Table 2.

In accordance with this research, it is noticeable to design a more comprehensive method that covers the various aspects of building double-wall thermal transmittance and heat consumption. So, a simulation-based approach will be considered, and it will be followed based on a quantitative approach.

The methodology is designed to quantify in which method double-wall configurations affect thermal performance and heat flow based on real climatic condition data. The process includes case study selection, modeling, material assignment, climate data integration, simulation, and optimization.

In this part, different sections of methodology are being introduced step-by-step:

- Building modeling: The first phase involved two-dimensional building modeling using the The first stage involved two-dimensional modeling in AutoCAD 2020, followed by 3D modeling in DesignBuilder. The 2D plans are illustrated in Figs. 1–2. The building layout was divided into distinct thermal zones (Table 1), with Zone 1 as the main simulation area.
- Double-Wall Configuration: After building planning, the building walls are modeled as double-wall systems, as shown in Fig. 3.
- Material property assignment: Material property assignment: Ten wall configurations (Types 1–10) were simulated by various insulation materials and thicknesses, which reflect common Tehran construction practices. Each configuration's layer thickness and heat balance (kW) are expressed in Table 4. Each configuration's layer thickness and heat balance (kW) are expressed in Table 4.
- Climate zone selection: Simulations are conducted for Tehran's climatic situation, considering specific temperatures, humidity, and solar radiation. Table 3 presents these details.
- Insulation layer configuration: Multiple simulations are currently running with different insulation layer setups. This includes varying the type, thickness, and layer placement of insulation materials within the wall structure.

DISCUSSION AND FINDINGS

Simulation Platform: The finalized models were simulated using DesignBuilder, powered by the EnergyPlus engine, to analyze overall energy performance and U-value reductions across wall types. The insulation properties are summarized in Table 3.

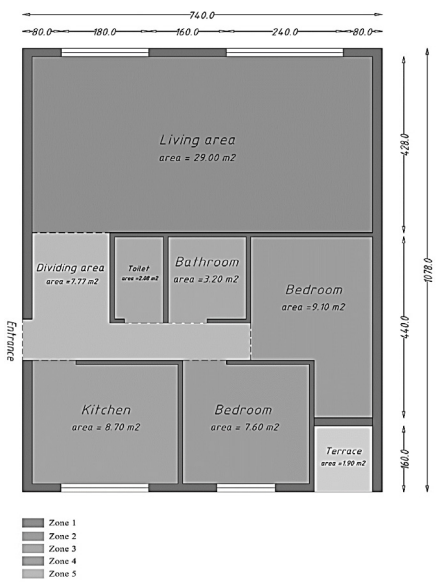


Fig. 1: building plan zoning (source: author)

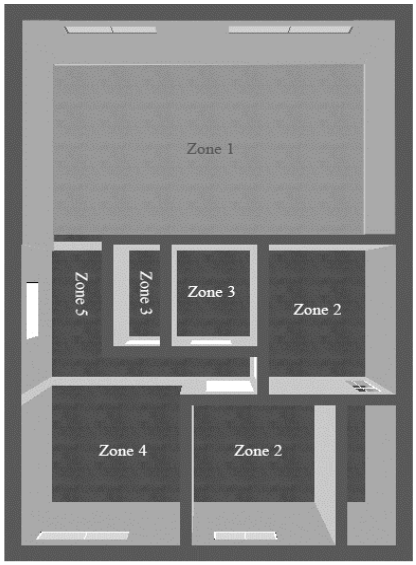


Fig. 2: building plan 2d model zoning (source: author)

Optimization process: Based on the layer configuration (insulation layer) and the simulation reports, an optimization process is implemented to determine the most effective combination of insulation layers to achieve the most efficient thermal performance.

Analysis Method: In this section, the assessment of the simulation results is performed quantitatively for each wall configuration.

Result Factors Introduction

The simulations compare the thermal performance of eight insulation materials—Polystyrene, PVC, Rock Wool, Fiberglass, Polyurethane, Glass Wool, Polyurethane Foam, and Extruded Polystyrene (XPS)—within double-wall systems for Tehran residential buildings. Table 4 summarizes performance under the assumptions presented in the methodology.

Table 1: plan spaces zoning (source: authors)

Number	Categories	Ranking
1	Living area	1
2	Bedroom	2
3	Bathroom – Toilet	3
4	Kitchen	4
5	Dividing area	5

	Step	Description / Simulation Input
1	Research Paradigm & Design	Positivist quantitative approach using a simulation-based case study. Real climatic data and numerical simulations conducted in DesignBuilder/EnergyPlus.
2	Case Study Selection	A typical residential unit in Tehran's hot–dry climate selected. Zones (living, bedroom, kitchen, bath) defined for accurate thermal load estimation.
3	2D and 3D Building Modeling	2D model prepared in AutoCAD 2020; detailed 3D model developed in DesignBuilder with distinct thermal zones (Figs. 1–3, Table 1).
4	Climate Data Input	Tehran's temperature, humidity, and solar radiation data imported into the simulation (Table 2).
5	Wall System Configuration	Building envelope modeled as double-wall systems. Ten wall types (1–10) created by varying insulation materials (0–15 cm) and AAC layer thickness (5–30 cm).
6	Material Property Assignment	Thermal conductivity, density, and specific heat assigned to each wall layer. Insulation properties (EPS, rock wool, etc.) defined (Table 3).
7	Simulation Execution	Simulations run in DesignBuilder (EnergyPlus engine) for all 10 wall types under Tehran's climate. Cooling/heating setpoints: 25 °C / 21 °C.
8	Optimization Process	Results analyzed to identify the optimal AAC and insulation thickness combination minimizing heat transfer and annual cooling demand.
9	Quantitative Analysis	Outputs compared across configurations; heat balance (kW) and annual cooling demand (kWh/year) tabulated. Regression analysis applied for predictive modeling.

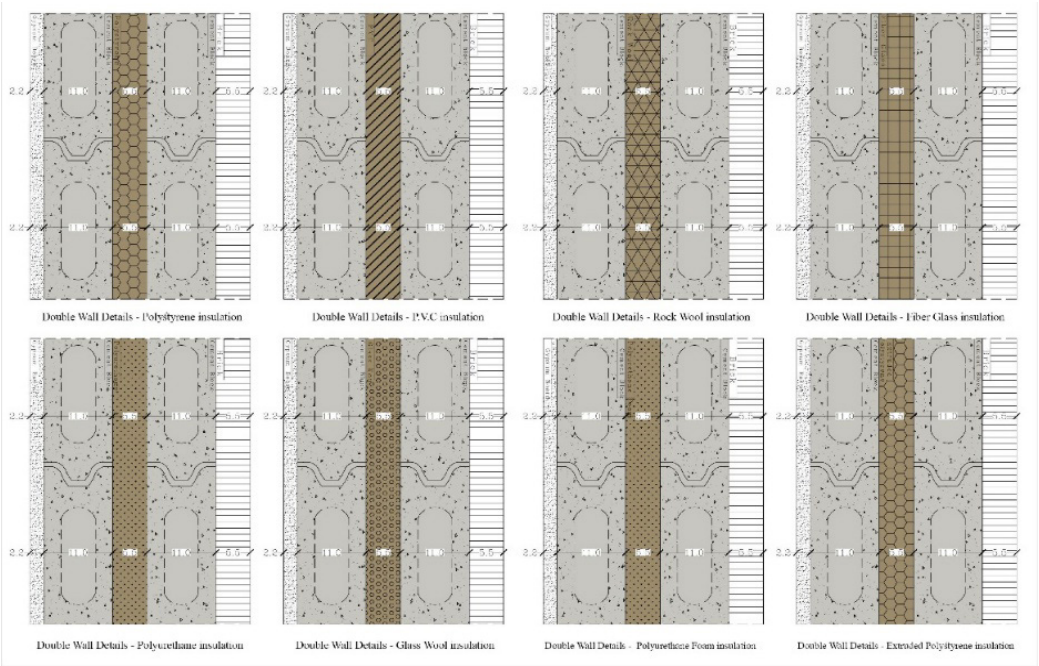


Fig. 3: Eight wall types with different insulation materials (source: authors)

Table 2: Research Process and Simulation Steps (source: authors)

	1.Activity Template	
1	Template	Domestic Lounge
2	Sector	Residential space
3	Zone type	Standard
4	Include zone in thermal calculation	+
5	Include zone in Radiance daylighting calculation	+
	2.Floor Areas and Volumes	
6	Floor area (m2)	25.63
7	Zone volume (m3)	71.77
8	Inner surface mode	Deflation
	3.Occupancy	
9	Occupancy density (people/m2)	0.0188
10	Schedule	Dwell_Dom-Lounge_Occ

Table 3: activity, area and volume (source: authors)

Wall types

Wall types and insulation materials are presented in Table 3 each tested at several thicknesses. This categorization provides a way to systematically evaluate material behavior in double-wall calculations.

Heat Balance

Heat balance, measured in kilowatts (kW), indicates thermal energy transfer through the wall. As it presents in Table 4, results indicate that greater insulation thickness generally improves thermal performance, as reflected in less negative heat balance values.

Heat Balance Change Ratio

The ratio measures how heat transfer varies as thickness increases to determine when incremental gains become negligible and for the consideration of insulation performance..

Thickness and Heat Balance Diagram

The ratio measures how heat transfer varies as thickness increases to determine when incremental gains become negligible and for the consideration of insulation performance. 4.1.4. Thickness and Heat Balance Diagram - As previously discussed, Table 4 and the related diagrams represent the relationships of thickness to performance. While all materials improve with thickness, the rate of efficiency varies, offering insight into optimal selection.

CONCLUSION AND RESULTS

This section brings together the results of the simulations and identifies thermal insulation behavior in relation to the materials considered.

5.1 General Analysis

Both insulation type and thickness strongly influence thermal balance. Thickness enhances efficiency, though with diminishing returns.

- PVC: Strong at lower thicknesses with limited potential gains at higher thicknesses. Ideal for constricted space.
- Polyurethane and Polyurethane Foam: Most efficient at greater thicknesses and with less deviation, high safety factor, and high reliability.
- Rock Wool and Fiberglass: Steady through the range, choice often is based on cost or availability or based on sustainable approach.
- Polystyrene and Extruded Polystyrene: Less efficient than Polyurethane options, but offer cost benefits; XPS is more stable but has weak efficiencies.

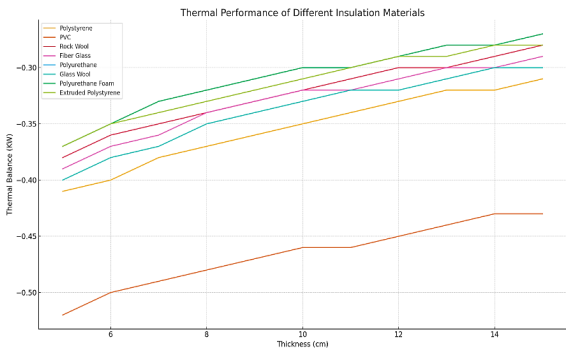


Diagram 1: Wall types simulation results (source: authors)

Specific Analysis

This section interprets the performance of different wall types with specific insulation materials, based on incremental thermal efficiency gains across thickness variations.

- Wall type 1 - Insulation – Polystyrene: As shown in Diagram 2, efficiency increases by 0.01–0.02 kW when thickness increases from 5 cm to 7 cm, after which the gain stabilizes at 0.01 kW. The optimal range is therefore 5–7 cm.
- Wall type 2 - Insulation – Polyvinyl Chloride: Diagram 3 demonstrated an initial gain of 0.01–0.02 kW as thickness rose from 5 cm to 6 cm, followed by stabilization at 0.01 kW. The most efficient thickness is 6 cm.
- Wall type 3 - Insulation – Rock wool: According to Diagram 4, performance improves by 0.01–0.02 kW between 5 cm and 6 cm, stabilizing thereafter. The optimal thickness is 6 cm.
- Wall type 4 - Insulation – Fiberglass: Diagram 5 demonstrates efficiency growth of 0.01–0.02 kW up to 8 cm, with stable performance afterward. The effective range is 6–8 cm.
- Wall type 5 - Insulation – Polyurethane: Diagram 6 shows growth of 0.01–0.02 kW between 5 cm and 7 cm, after which performance stabilizes. The most efficient point is 7 cm.
- Wall type 6 - Insulation – Glass Wool: As shown in Diagram 7, performance increases by 0.01–0.02 kW between 5 cm and 8 cm, leveling at 0.01 kW thereafter. The effective range is 6–8 cm.
- Wall type 7 - Insulation – Polyurethane Foam: Diagram 8 highlights efficiency gains of 0.01–0.02 kW between 5 cm and 7 cm, with stabilization beyond this. The optimal point is 7 cm.
- Wall type 8 - Insulation – Extruded Polystyrene: Diagram 9 shows gains of 0.01–0.02 kW from 5 cm to 6 cm, stabilizing afterward. The most efficient thickness is 6 cm.

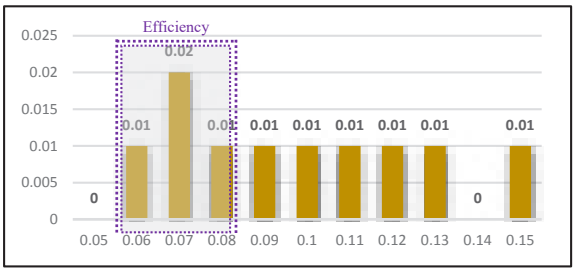
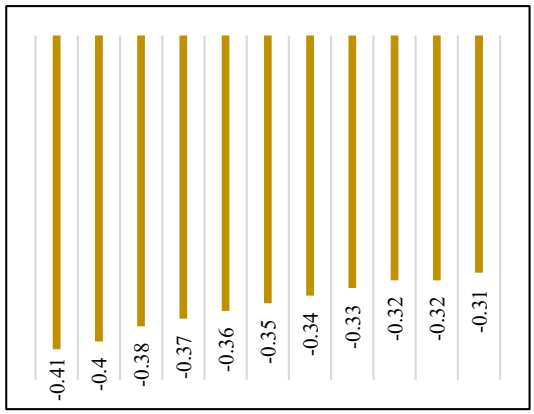
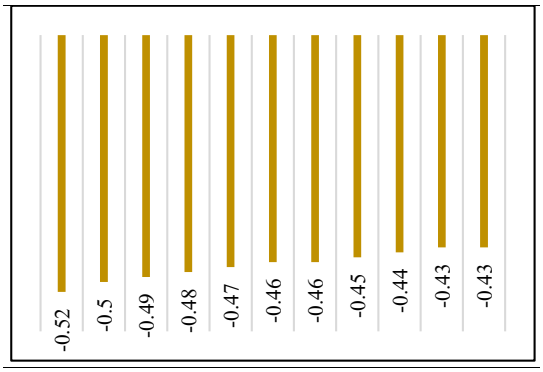
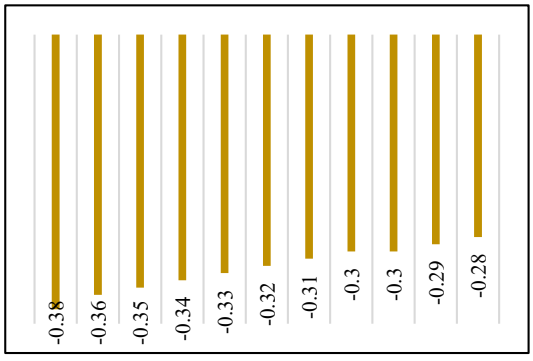
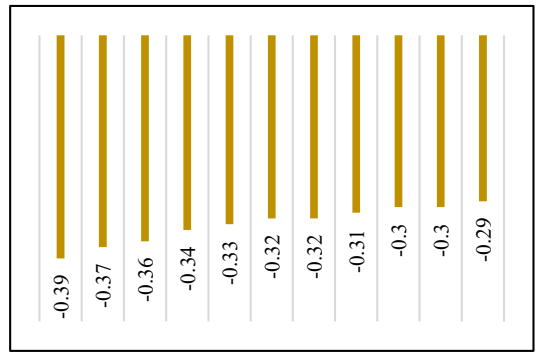
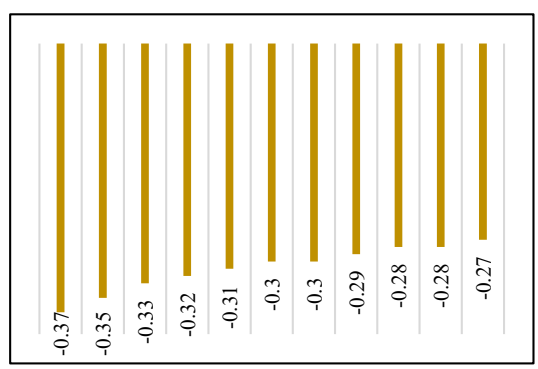
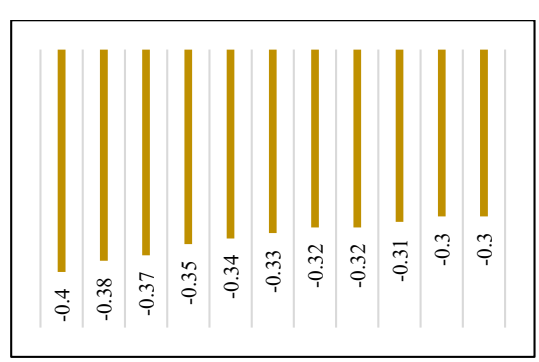
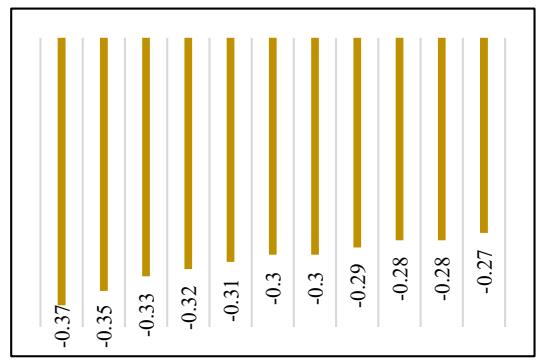


Diagram 2: Polystyrene Heat Balance Change Ratio

Diagram 1: illustrates these trends, showing optimal cost–performance at around 10–12 cm, beyond which improvements diminish.

	Insulation	Thickness (m)	Heat balance (KW)	Heat balance changes ratio (KW)	Thickness and Heat balance diagram
Wall type 1	Insulation – Polystyrene	0.05	-0.41	-	
		0.06	-0.40	+0.01	
		0.07	-0.38	+0.02	
		0.08	-0.37	+0.01	
		0.09	-0.36	+0.01	
		0.10	-0.35	+0.01	
		0.11	-0.34	+0.01	
		0.12	-0.33	+0.01	
		0.13	-0.32	+0.01	
		0.14	-0.32	0	
		0.15	-0.31	0.01	
Wall type 2	Insulation – Polyvinyl Chloride	0.05	-0.52	-	
		0.06	-0.50	0.02	
		0.07	-0.49	0.01	
		0.08	-0.48	0.01	
		0.09	-0.47	0.01	
		0.10	-0.46	0.01	
		0.11	-0.46	0	
		0.12	-0.45	0.01	
		0.13	-0.44	0.01	
		0.14	-0.43	0.01	
		0.15	-0.43	0	
Wall type 3	Insulation – Rock wool	0.05	-0.38	-	
		0.06	-0.36	0.02	
		0.07	-0.35	0.01	
		0.08	-0.34	0.01	
		0.09	-0.33	0.01	
		0.10	-0.32	0.01	
		0.11	-0.31	0.01	
		0.12	-0.30	0.01	
		0.13	-0.30	0	
		0.14	-0.29	0.01	
		0.15	-0.28	0.01	

Wall type 4	Insulation – Fiberglass	0.05	-0.38	-	
		0.06	-0.36	0.02	
		0.07	-0.35	0.01	
		0.08	-0.34	0.02	
		0.09	-0.33	0.01	
		0.10	-0.32	0.01	
		0.11	-0.31	0	
		0.12	-0.30	0.01	
		0.13	-0.30	0.01	
		0.14	-0.29	0	
		0.15	-0.28	0.01	
Wall type 5	Insulation - Polyurethane	0.05	-0.39	-	
		0.06	-0.37	0.02	
		0.07	-0.36	0.02	
		0.08	-0.34	0.01	
		0.09	-0.33	0.01	
		0.10	-0.32	0.01	
		0.11	-0.32	0	
		0.12	-0.31	0.01	
		0.13	-0.30	0.01	
		0.14	-0.30	0	
		0.15	-0.29	0.01	
Wall type 6	Insulation – Glass Wool	0.05	-0.40	-	
		0.06	-0.38	0.02	
		0.07	-0.37	0.01	
		0.08	-0.35	0.02	
		0.09	-0.34	0.01	
		0.10	-0.33	0.01	
		0.11	-0.32	0.01	
		0.12	-0.32	0	
		0.13	-0.31	0.01	
		0.14	-0.30	0.01	
		0.15	-0.30	0	
Wall type 7	Insulation – Polyurethane Foam	0.05	-0.37	-	
		0.06	-0.35	0.02	
		0.07	-0.33	0.02	
		0.08	-0.32	0.01	
		0.09	-0.31	0.01	
		0.10	-0.30	0.01	
		0.11	-0.30	0	
		0.12	-0.29	0.01	
		0.13	-0.28	0.01	
		0.14	-0.28	0	
		0.15	-0.27	0.01	

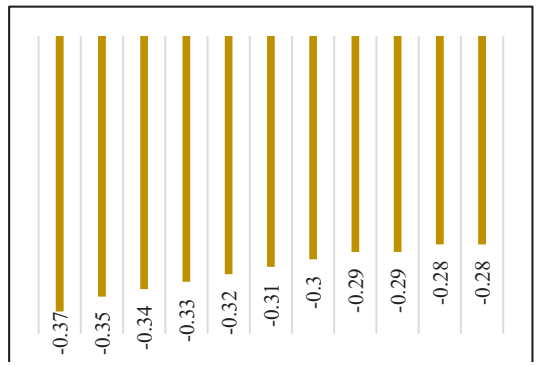
Wall type 8	Insulation – Extruded Polystyrene	0.05	-0.37	-	
		0.06	-0.35	0.02	
		0.07	-0.34	0.01	
		0.08	-0.33	0.01	
		0.09	-0.32	0.01	
		0.10	-0.31	0.01	
		0.11	-0.30	0.01	
		0.12	-0.29	0.01	
		0.13	-0.29	0	
		0.14	-0.28	0.01	
		0.15	-0.28	0	

Table 4: Wall types simulation results (source: authors)

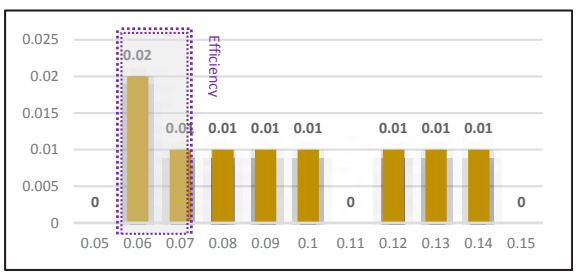


Diagram 3: PVC Heat Balance Change Ratio

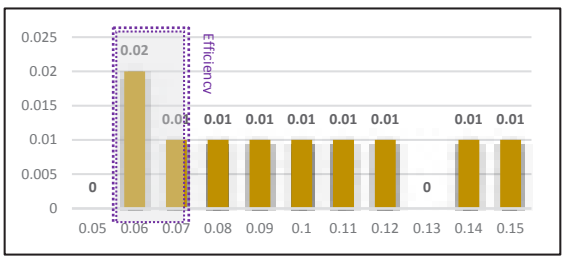


Diagram 4: Rock wool Heat Balance Change Ratio

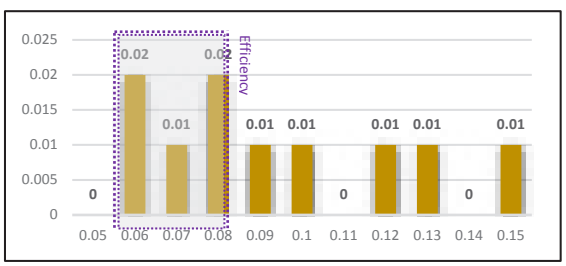


Diagram 5: Fiberglass Heat Balance Change Ratio

Overall, these findings provide the basis for a deeper discussion on comparative material performance, cost-effectiveness, and practical implications, which is addressed in the following section.

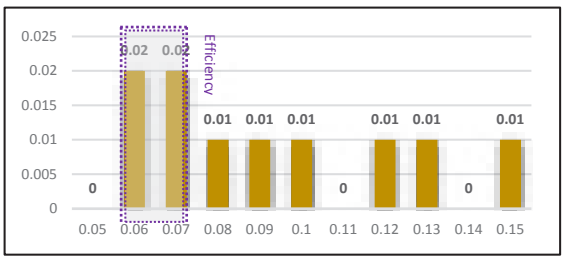


Diagram 6: Polyurethane Heat Balance Change Ratio

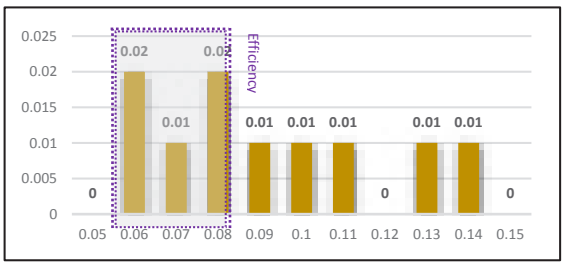


Diagram 7: Glass Wool Heat Balance Change Ratio

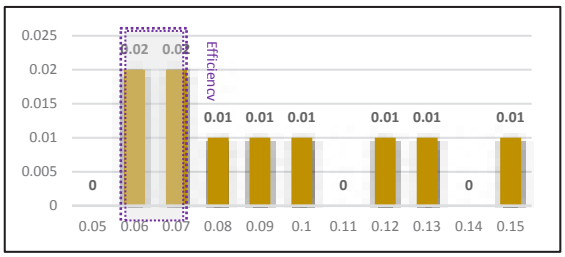


Diagram 8: Polyurethane Foam Heat Balance Change Ratio

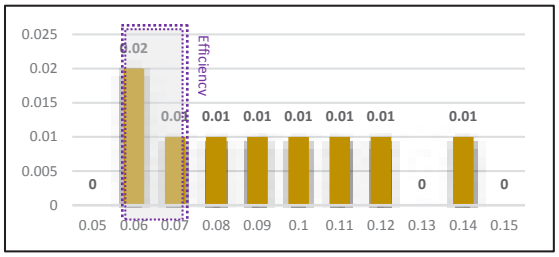


Diagram 9: Extruded Polystyrene Heat Balance Change Ratio

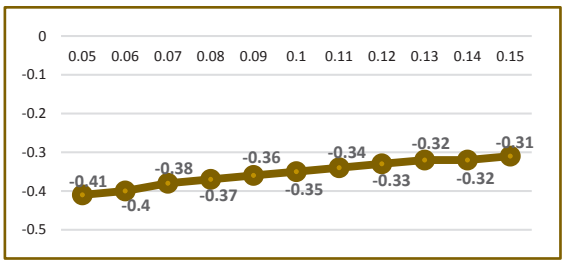


Diagram 10: Polystyrene Heat Balance

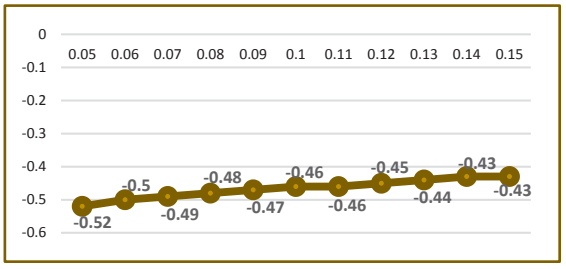


Diagram 11: PVC Heat Balance

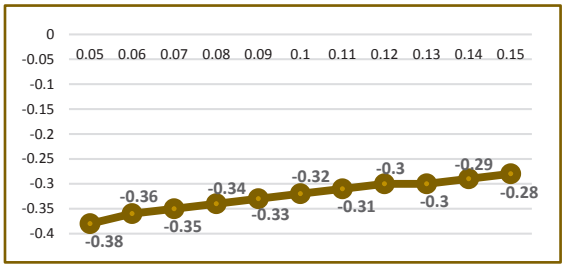


Diagram 12: Rock Wool Heat Balance

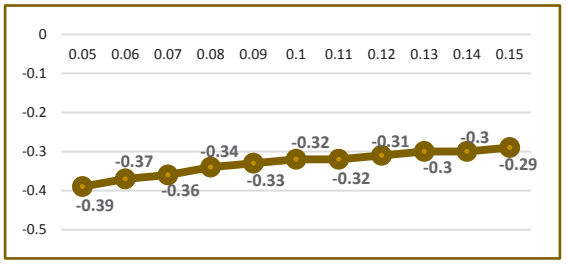


Diagram 13: Fiber Glass Heat Balance

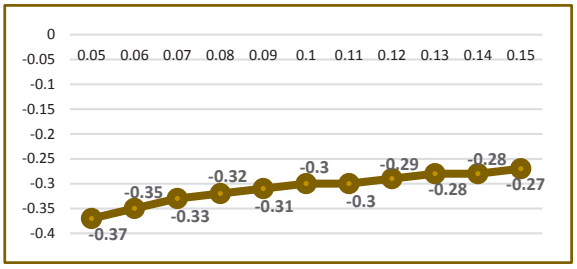


Diagram 14: Polyurethane Heat Balance

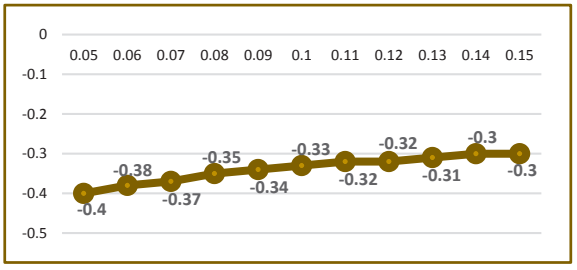


Diagram 15: Glass Wool Heat Balance

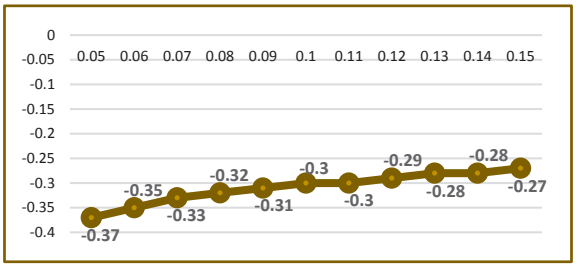


Diagram 16: Polyurethane Foam Heat Balance

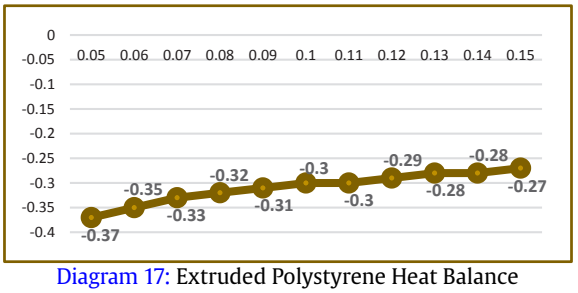


Diagram 17: Extruded Polystyrene Heat Balance

This study analyzed the thermal performance of eight insulation materials including polystyrene, PVC, rock wool, fiberglass, polyurethane, glass wool, polyurethane foam, and extruded polystyrene (XPS), in double-wall systems, which was based on residential buildings in Tehran. Each material was tested according to the thicknesses, which were between 5 cm and 15 cm, using DesignBuilder simulations to determine overall heat transfer in kilowatts (kW). The discussion highlights comparative efficiency, cost, and suitability for Tehran's climate.

Thermal Performance Analysis

Simulation results (Diagrams 10–17) confirm that increasing insulation thickness makes a significant reduction in heat transformation; however, efficiency gains plateau beyond 10–12 cm. Polyurethane and polyurethane foam showed the best thermal resistance, decreasing heat loss from −0.37 kW to −0.27 kW due to their dense closed-cell structure. XPS performed similarly, maintaining high efficiency at larger thicknesses. Polystyrene achieved notable improvement (−0.41 kW to −0.31 kW) with optimal performance around 10–12 cm, while PVC proved efficient at lower thicknesses but less cost-effective beyond 10 cm. Rock wool, fiberglass, and glass wool displayed consistent moderate reductions in heat loss, benefiting from their fibrous structure that traps air and limits conduction. Results demonstrate that developing thermal insulation thickness makes an improvement in energy performance, yet after a certain point, further addition yields limited benefits. The most effective wall setup consisted of two 10 cm cement blocks with the insulation layer centered between them, combined with an interior gypsum board and exterior brick finish. This configuration provides both thermal balance and structural stability suited to Tehran's climatic conditions.

Results Comparison

Previous investigations have established several benchmarks with the aim of evaluating the thermal performance of double-wall insulation systems. Research in Turkey confirmed that insulation thickness plays a significant role in making an improvement in energy efficiency within such systems (Ozbek et al., 2022). Studies conducted in Germany and South Korea further demonstrated that adaptive design measures can reduce the risk of overheating and cooling demands by up to 90% (Schünemann et al., 2022). In accordance with research by Malbila et al. (2021a), 76% of surveyed buildings used cement blocks; however, walls made with compressed earth blocks (CEB) achieved higher thermal resistance values of 357.37 m²·K/W and reduced heat flow by 85–90% compared with single-layer systems (Malbila et al., 2021a). COMSOL-based analyses also revealed that doubling wall surfaces can lower transmission coefficients by 22.9–32.5% while maintaining a stable indoor temperature of 27 °C (Ouedraogo et al., 2019). Furthermore, incorporating phase change materials (PCM) into double walls improved seasonal adaptability, which can increase delay time by 4.65 h and reduce attenuation by 80% (Gao et al., 2023). In a similar way, PCM wallboard simulations for Tehran residential buildings showed a 6.6% reduction in heating and 2.8% in cooling energy demand (Refahi et al., 2024). Collectively, these findings underline diverse strategies—from insulation thickness optimization to PCM integration—whereas the present study distinguishes itself by concentrating on the comparative performance of conventional insulation materials and their thickness variations within Tehran's double-wall configurations.

Key Similarities and Differences:

Both this study and prior works (Ozbek et al., 2022) confirm insulation thickness as a major factor in thermal performance, showing that thicker layers generally enhance comfort but with diminishing returns. Similar behavior was observed for Polystyrene, Polyurethane, Rock Wool, and Fiberglass, while PVC reached optimal efficiency at lower thickness. Unlike broader studies that examined PCM systems or combined thermal and economic factors

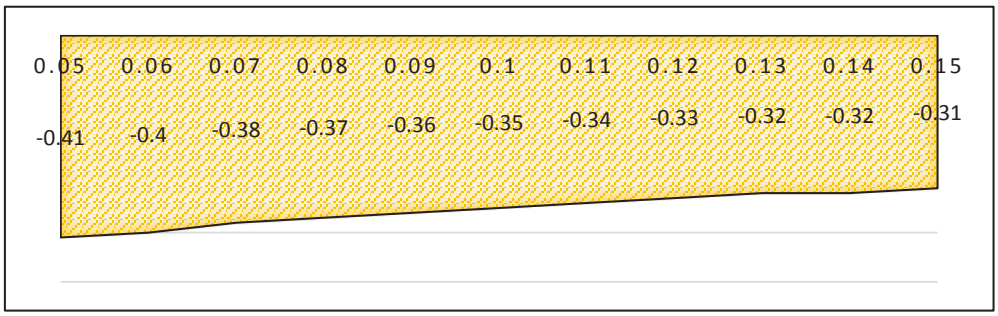
(Schünemann et al., 2022; Refahi et al., 2024), this research focuses solely on conventional materials and kilowatt-based thermal analysis, offering a narrower but more technical perspective.

Heat Balance Framework

The proposed framework, based on mathematical models and Matrix-Diagrams (1–8), identifies a threshold around 10–12 cm where insulation efficiency plateaus. Polyurethane materials maintain strong performance, while PVC and polystyrene decline beyond this point. The model offers a structured approach to compare materials and could expand to include cost and environmental criteria in future work.

Polystyrene

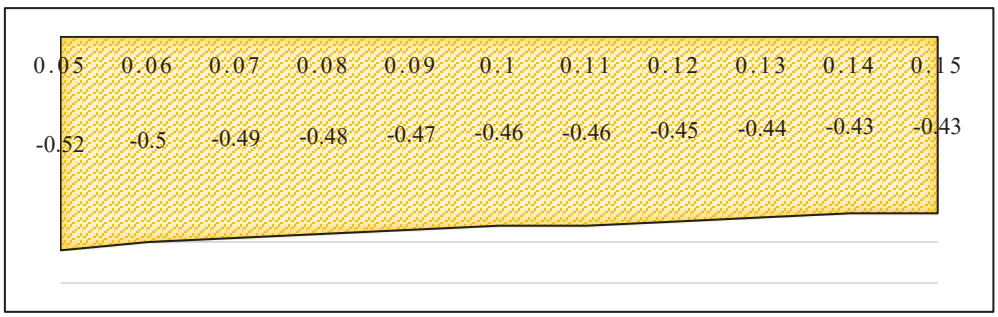
$$\begin{bmatrix} 0.05 & -0.41 \\ 0.06 & -0.40 \\ 0.07 & -0.38 \\ 0.08 & -0.37 \\ 0.09 & -0.36 \\ 0.10 & -0.35 \\ 0.11 & -0.34 \\ 0.12 & -0.33 \\ 0.13 & -0.32 \\ 0.14 & -0.32 \\ 0.15 & -0.31 \end{bmatrix}$$



Matrix-Diagram 1: Polystyrene thickness and heat balance

6.3.2. Polyvinyl chloride

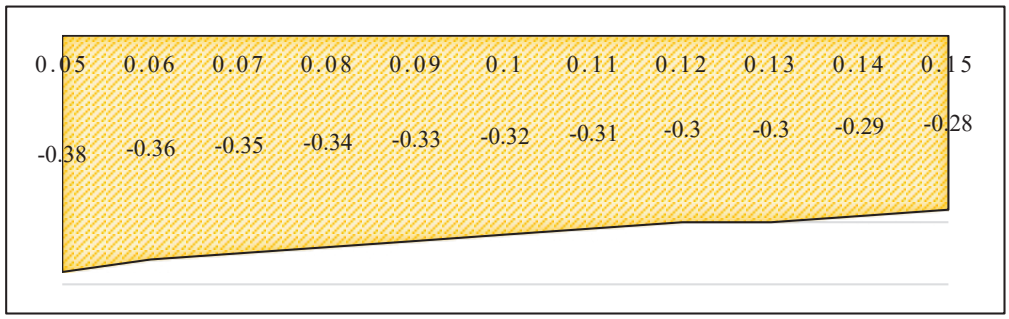
$$\begin{bmatrix} 0.05 & -0.52 \\ 0.06 & -0.50 \\ 0.07 & -0.49 \\ 0.08 & -0.48 \\ 0.09 & -0.47 \\ 0.10 & -0.46 \\ 0.11 & -0.46 \\ 0.12 & -0.45 \\ 0.13 & -0.44 \\ 0.14 & -0.43 \\ 0.15 & -0.43 \end{bmatrix}$$



Matrix-Diagram 2: Polystyrene thickness and heat balance

6.3.3. Rock Wool

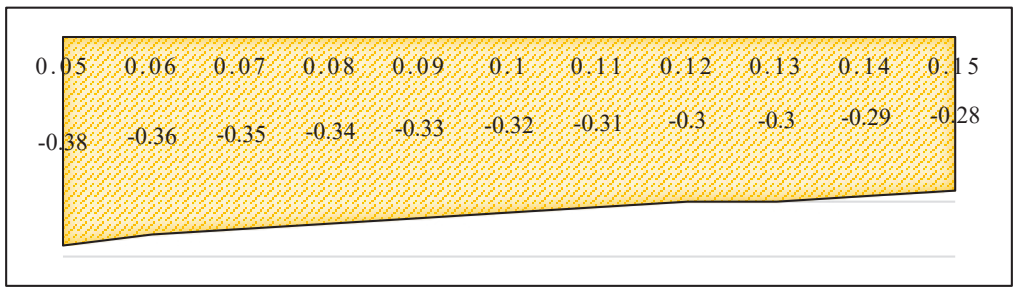
$$\begin{bmatrix} 0.05 & -0.38 \\ 0.06 & -0.36 \\ 0.07 & -0.35 \\ 0.08 & -0.34 \\ 0.09 & -0.33 \\ 0.10 & -0.32 \\ 0.11 & -0.31 \\ 0.12 & -0.30 \\ 0.13 & -0.30 \\ 0.14 & -0.29 \\ 0.15 & -0.28 \end{bmatrix}$$



Matrix-Diagram 3: Rock Wool thickness and heat balance

6.3.4. Fiberglass

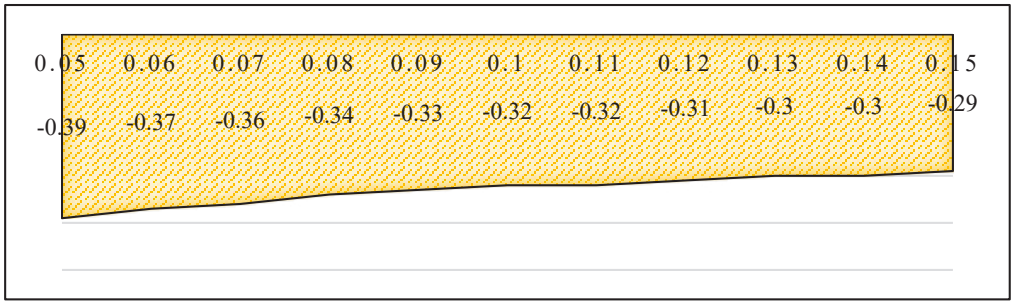
0.05	−0.38
0.06	−0.36
0.07	−0.35
0.08	−0.34
0.09	−0.33
0.10	−0.32
0.11	−0.31
0.12	−0.30
0.13	−0.30
0.14	−0.29
0.15	−0.28



Matrix-Diagram 4: Fiberglass thickness and heat balance

6.3.5. Polyurethane

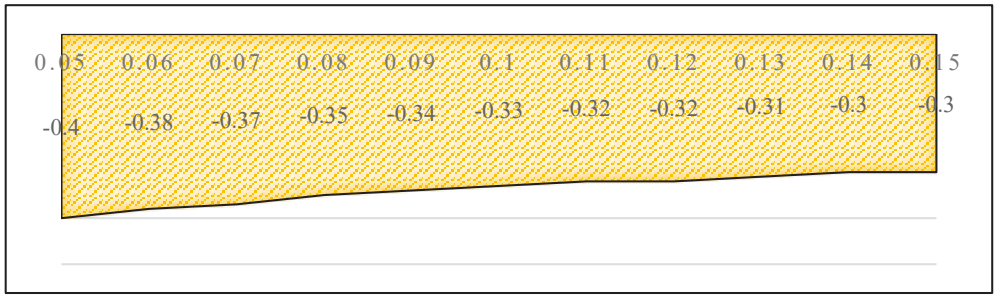
0.05	−0.39
0.06	−0.37
0.07	−0.36
0.08	−0.34
0.09	−0.33
0.10	−0.32
0.11	−0.32
0.12	−0.31
0.13	−0.30
0.14	−0.30
0.15	−0.29



Matrix-Diagram 5: Polyurethane thickness and heat balance

6.3.6. Glass Wool

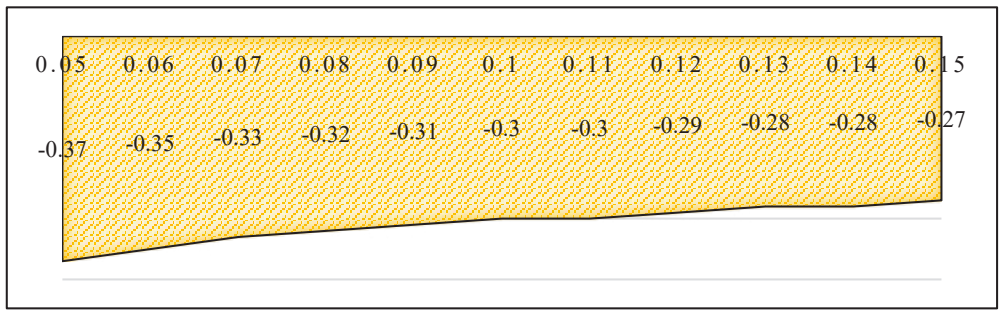
0.05	−0.40
0.06	−0.38
0.07	−0.37
0.08	−0.35
0.09	−0.34
0.10	−0.33
0.11	−0.32
0.12	−0.32
0.13	−0.31
0.14	−0.30
0.15	−0.30



Matrix-Diagram 6: Glass Wool thickness and heat balance

6.3.7. Polyurethane Foam

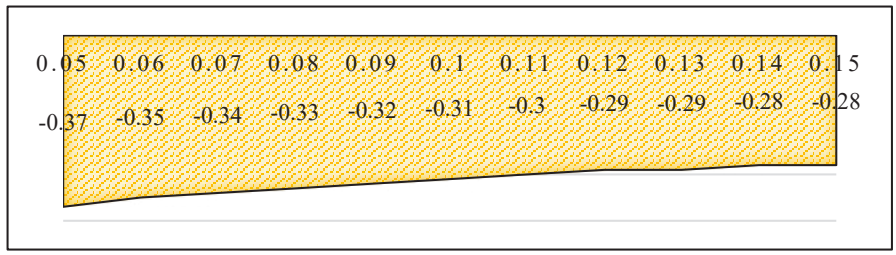
0.05	−0.37
0.06	−0.35
0.07	−0.33
0.08	−0.32
0.09	−0.31
0.10	−0.30
0.11	−0.30
0.12	−0.29
0.13	−0.28
0.14	−0.28
0.15	−0.27



Matrix-Diagram 7: Polyurethane Foam thickness and heat balance

6.3.8. Extrude Polystyrene

0.05	−0.37
0.06	−0.35
0.07	−0.34
0.08	−0.33
0.09	−0.32
0.10	−0.31
0.11	−0.30
0.12	−0.29
0.13	−0.29
0.14	−0.28
0.15	−0.28



Matrix-Diagram 8: Extrude Polystyrene thickness and heat balance

This research evaluated the thermal performance of eight insulation materials—polystyrene, PVC, rock wool, fiberglass, polyurethane, glass wool, polyurethane foam, and extruded polystyrene—applied in double-wall systems for Tehran's housing context, using DesignBuilder with the EnergyPlus engine. Insulation thicknesses of 5, 10, and 15 cm were tested. Results revealed that thermal efficiency generally increased with greater thickness, though at varying rates. Polyurethane and polyurethane foam achieved the highest performance at larger thicknesses, while fiberglass and rock wool showed stable but moderate efficiency across all layers.

The study addressed a regional gap by providing quantitative data on double-wall insulation systems in Tehran's climate. Previous research offered limited analysis of insulation performance under local environmental conditions. This work established a simulation-based quantitative framework for assessing thermal balance, providing architects and engineers with practical insights into energy-efficient wall design for residential buildings in Tehran.

The novelty of this study lies in its data-driven quantification of thermal performance, contrasting earlier qualitative or general approaches. By integrating mathematical modeling and simulation outcomes, it introduces a precise analytical method that supports design optimization. The developed heat balance framework (Section 5.2) serves as a reference for future regional studies.

However, the analysis was limited to eight materials and excluded factors such as acoustic, fire, or moisture performance. Future research should expand the scope to include hybrid or advanced materials, diverse building components, and environmental and economic evaluations. Integrating life-cycle assessment and emerging technologies like PCM or nanomaterials could further enhance energy efficiency and adaptive performance under different climates.

REFERENCES

ABDUL NASIR, M. H. & HASSAN, A. S. (2020). Thermal performance of double brick wall construction on the building envelope of high-rise hotel in Malaysia. Journal of Building Engineering, 31, 101389. https://www.sciencedirect.com/science/article/abs/pii/S2352710219319114

AKETOUANE, Z., BAH, A., MALHA, M. & ANSARI, O. (2016). Effect of emissivity on the thermal behavior of a double wall facade with a closed cavity. 2016 International Renewable and Sustainable Energy Conference (IRSEC), 828-833. https://ieeexplore.ieee.org/document/7984077/

AL FAKHOURY, J., SASSINE, E., CHERIF, Y., DGHEIM, J., ANTCZAK, E. & CHARTIER, T. (2024). Thermal performance of double walls with polystyrene beads insufflation. Journal of Thermal Science and Engineering Applications. https://www.researchgate.net/publication/377716963_Thermal_performance_of_double_walls_with_polystyrene_beads_insufflation

Awad, A., Abougamos, H. R. (2020). 'Climate Changes in Africa, Does Urbanization Matter? A semi-Parametric Panel Data Analysis', International Journal of Urban Management and Energy Sustainability, 1(3), pp. 1-7. doi: 10.22034/ijumes.2017.18.12.018 . https://www.ijumes.com/article_30107.html

BUCKLIN, O., MÜLLER, T., AMTSBERG, F., LEISTNER, P. & MENGES, A. (2023). Analysis of thermal Transmittance, air Permeability, and hygrothermal behavior of a solid timber building envelope. Energy and Buildings, 299, 113629. https://www.sciencedirect.com/science/article/abs/pii/S0378778823008599

Boroumand, M. (2023). 'Evaluation of smart materials application in optimizing energy consumption in office buildings (Case Study: cold and mountainous regions of Iran, Tabriz)', International Journal of Urban Management and Energy Sustainability, 4(2), pp. 153-167. doi: 10.22034/jumes.2023.710666. https://www.ijumes.com/article_710666.html

DLIMI, M., AGOUNOUN, R., KADIRI, I., SAADANI, R. & RAHMOUNE, M. (2023). Thermal performance assessment of double hollow brick walls filled with hemp concrete insulation material through computational fluid dynamics analysis and dynamic thermal simulations. e-Prime - Advances in Electrical Engineering, Electronics and Energy, 3, 100124. https://www.sciencedirect.com/science/article/pii/S2772671123000190

FARAHANI, M. H., NAMAZZADEH, M. & FARAHANI, A. H. 2022. Assessing renewable-energy potential and feasibility in Tehran's buildings. Clean Energy. https://academic.oup.com/ce/article/6/6/944/6966479

GAO, Y., LIU, Z., GAO, Y., MAO, W., ZUO, Y. & LI, G. 2023. Employing the double-PCM (Phase-Change Material) layer to improve the seasonal adaption of building walls: A comparative studies. Journal of Energy Storage. https://www.sciencedirect.com/science/article/abs/pii/S2352152X23008010

Hajali Zadeh, G. (2022). 'Investigation of energy consumption of traditional houses in approach to sustainable architecture (Case Study: Ardebil, Sanandaj, Hamedan and Tabriz cities of Iran)', International Journal of Urban Management and Energy Sustainability, 4(1), pp. 130-146. doi: 10.22034/jumes.2023.1996326.1124. https://www.ijumes.com/article_704180.html

JABER ABDULHAMEED, J. & TAWFEEQ WASMI MOHAMMED, T. 2023. REDUCING HEAT IN A COMPOSITE WALL BY USING NANOMATERIALS: A REVIEW. Journal of Engineering and Sustainable Development. https://www.researchgate.net/publication/381167012_REDUCING_HEAT_IN_A_COMPOSITE_WALL_BY_USING_NANOMATERIALS_A_REVIEW#:~:text=Compared%20to%20conventional%20insulation%2C%20insulation,due%20to%20their%20thin%20layers.

JAMAL, B., BOUKENDIL, M., ABDELBAKI, A. & ZRIKEM, Z. 2020. Numerical simulation of coupled heat transfer through double solid walls separated by an air layer. International Journal of Thermal Sciences, 156, 106461. https://www.sciencedirect.com/science/article/abs/pii/S1290072918306884

KAREEM ABDULLAH, H. & HASHIM FARAJ, S. 2022. Experimental study for the effect of air gap in building walls on heat gain reduction. Materials Today: Proceedings, 61, 1043-1051.

KNAPCZYK-KORCZAK, J., SZEWCZYK, P. K., BERNIAK, K., MARZEC, M. M., FRĄC, M., PICHÓR, W. & STACHEWICZ, U. Flexible and Thermally Insulating Porous Materials Utilizing Hollow Double-Shell Polymer Fibers. Advanced Science, n/a, 2404154. https://www.sciencedirect.com/science/article/abs/pii/S2214785321068140

KNAPCZYK-KORCZAK, J., SZEWCZYK, P. K., BERNIAK, K., MARZEC, M., FRĄC, M., PICHÓR, W. & STACHEWICZ, U. 2024. Flexible and Thermally Insulating Porous Materials Utilizing Hollow Double-Shell Polymer Fibers. Advanced science, e2404154. https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/advs.202404154

KOEBEL, M. M., WERNERY, J. & MALFAIT, W. J. 2017. Energy in buildings—Policy, materials and solutions. MRS Energy & Sustainability, 4, 1-24. https://link.springer.com/article/10.1557/mre.2017.14

MALBILA, E., ZOMA, F., TOGUYENI, D., COMPAORE, C.-V. & BATHIEBO, D. 2021a. Developing Double Walls System to Improve Building Energy Performances in Dry Tropical Climates. IRA-International Journal of Applied Sciences (ISSN 2455-4499), 16, 39. https://www.researchgate.net/publication/353778605_Developing_Double_Walls_System_to_Improve_Building_Energy_Performances_in_Dry_Tropical_Climates

MARQUES, B., TADEU, A., ALMEIDA, J., ANTÓNIO, J. & DE BRITO, J. 2020. Characterisation of sustainable building walls made from rice straw bales. Journal of Building Engineering, 28, 101041. https://www.sciencedirect.com/science/article/abs/pii/S2352710219313221

NASTRI, M. 2023. Double Skin Façade Mechanical Systems as Ad-vanced Building Technologies. Proceedings of the International Conference on Advanced Technologies. https://proceedings.icats-conf.org/conf/index.php/ICAT/article/view/19

OUEDRAOGO, E., COULIBALY, O., BOUREIMA, K., IMBGA, K. & OUEDRAOGO, A. 2019. OPTIMIZATION OF THE AIR GAP THICKNESS FOR THE INSULATION OF DOUBLE-WALLED WALLS OF A BUILDING. https://www.researchgate.net/publication/328743687_Optimization_of_the_air_gap_thickness_for_the_insulation_of_double-walled_walls_of_a_building

OZBEK, K., GELIS, K. & OZYURT, O. 2022. Optimization of external wall insulation thickness in buildings using response surface methodology. International Journal of Energy and Environmental Engineering, 13, 1367-1381. https://link.springer.com/article/10.1007/s40095-022-00490-9

PAIVA, A. R., VARUM, H., CALDEIRA, F., SÁ, A. B., NASCIMENTO, D. & TEIXEIRA, N. Textile subwaste as a thermal insulation building material. 2011. https://www.researchgate.net/publication/263071552_Textile_Subwaste_as_a_Thermal_Insulation_Building_Material

PENIĆ, M., VATIN, N. I. & MURGUL, V. 2014. Double Skin Facades in Energy Efficient Design. Applied Mechanics and Materials, 680, 534 - 538. https://www.researchgate.net/publication/286722772_Double_Skin_Facades_in_Energy_Efficient_Design#:~:text=Double%20skin%20facades%20(DSF)%20aim,compared%20to%20conventional%20facade%20systems.

REFAHI, A., ROSTAMI, A. & AMANI, M. 2024. Implementation of a double layer of PCM integrated into the building exterior walls for reducing annual energy consumption: Effect of PCM wallboards position. Journal of Energy Storage, 82, 110556. https://www.sciencedirect.com/science/article/abs/pii/S2352152X24001403

SADHUKHAN, D., PERI, S., SUGUNARAJ, N., BISWAS, A., SELVARAJ, D. F., KOINER, K., ROSENER, A., DUNLEVY, M., GOVEAS, N., FLYNN, D. & RANGANATHAN, P. 2020. Estimating surface temperature from thermal imagery of buildings for accurate thermal transmittance (U-value): A machine learning perspective. Journal of Building Engineering, 32, 101637. https://www.sciencedirect.com/science/article/abs/pii/S2352710219327263

SANTOS, P., LEMES, G. & MATEUS, D. 2020. Analytical Methods to Estimate the Thermal Transmittance of LSF Walls: Calculation Procedures Review and Accuracy Comparison. Energies, 13, 840. https://www.mdpi.com/1996-1073/13/4/840

SCHÜNEMANN, C., SON, S. & ORTLEPP, R. 2022. Heat resilience of apartment buildings in Korea and Germany: comparison of building design and climate. International Journal of Energy and Environmental Engineering, 13, 889-909. https://

link.springer.com/article/10.1007/s40095-022-00476-7

UENO, K., LSTIBUREK, J. W. & ENG, P. Field Monitoring of Cold Climate Double Stud Walls with Cellulose and Low-Density Foam Insulation. 2015. https://www.researchgate.net/publication/318699444_Field_Monitoring_for_Cold-Climate_Double_Stud_Walls_with_Cellulose_and_Low_Density_Foam_Insulation?_tp=eyJjb250ZXh0Ijp7InBhZ2UiOiJzY2llbnRpZmljQ29udHJpYnV0aW9ucyIsInByZXZpb3VzUGFnZSI6bnVsbH19

VUČENOVIĆ, S. M., ŠETRAJČIĆ, N., VOJNOVIĆ, N., ŠETRAJČIĆ, J. P. & DUPLJANIN, S. A. 2022. THE HEAT BALANCE FOR EXTERNAL COMPOSITE WALLS. САВРЕМЕНА ТЕОРИЈА И ПРАКСА У ГРАДИТЕЉСТВУ. https://www.researchgate.net/publication/376655782_THE_HEAT_BALANCE_FOR_EXTERNAL_COMPOSITE_WALLS

YANG, H., ZHANG, G., DOU, B., YAN, X., LIU, Z. & QI, W. 2021. Investigations of double layer phase change walls with expanded graphite on the temperature and energy consumption. Energy Reports, 7, 9023-9034. https://www.sciencedirect.com/science/article/pii/S235248472101372X

YU, Y., TIAN, P., MAN, M., CHEN, Z., JIANG, L. & WEI, B. 2021. Experimental and numerical studies on the fire-resistance behaviors of critical walls and columns in modular steel buildings. Journal of Building Engineering, 44, 102964. https://www.sciencedirect.com/science/article/abs/pii/S2352710221008226

COPYRIGHTS
©2023 The author(s). This is an open access article distributed under the terms of the Creative Commons Attribution (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, as long as the original authors and source are cited. No permission is required from the authors or the publishers.