International Journal of Architectural Engineering & Urban Planning, Volume 35, Number 2, 2025
DOI: 10.22068/ijaup.814

Research Paper

Investigating the Effect of the Thickness and Placement of Thermal Insulation on the Amount of Cooling and Heating Load of Residential Buildings in Qom City

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Received: April 2024, **Revised:** March 2025, **Accepted:** June 2025, **Publish Online:** June 2025

Abstract
The rise in energy consumption in recent years has not only heightened concerns about the depletion of fossil resources but has also led to severe and threatening environmental changes worldwide. Buildings play a significant role as major energy consumers, with residential buildings being particularly important due to their continuous use throughout the day and night. This study aims to investigate the impact of thermal insulation applied to the external walls of residential buildings on cooling and heating energy consumption. Additionally, it seeks to determine the differences between various placements of thermal insulation and identify their optimal thicknesses. Given that testing and comparing different scenarios on an accurate scale would require substantial time and resources, this research employs a simulation-based approach. Modeling and simulations were conducted using Rhino and EnergyPlus software. For this purpose, three common land plot sizes from the city of Qom were selected, and each was simulated in two configurations (north-facing and south-facing) and seven geographical orientations. The final outputs include (1) the percentage contribution of each external wall in reducing energy consumption, (2) the priority ranking of walls for insulation, (3) the effect of the last floor ceiling and pilot roof insulation, and (4) the recommended optimal thickness for thermal insulation. By analyzing the energy load reductions achieved, the study determines the most effective conditions and optimal thicknesses for thermal insulation in the external walls of buildings.

Keywords: *Thermal insulation, Energy consumption, Optimal thickness, Residential buildings, Qom, Energy Plus software.*

INTRODUCTION

International goals for reducing carbon dioxide emissions, which aim to address global climate change related to greenhouse gas emissions, place significant pressure on cities, as they account for up to 75% of global carbon dioxide emissions (Chalal et al., 2016). In Iran, the consumption of fossil fuels ranks first among other energy sources, leading to challenges such as the depletion of fossil fuel reserves, social and economic damage, environmental harm, and ecological imbalance. Therefore, the scientific and practical adoption of sustainable energy systems, clean energy, and renewable energy programs—particularly solar energy—requires more serious attention than ever before Energy consumption is distributed across four main sectors: industry, construction (residential/commercial), transportation, and agriculture. The building sector is the largest energy consumer after the industrial sector. Nearly half of the global annual energy supply is utilized in the construction, operation, and maintenance of buildings. Since most of this energy originates from fossil fuels, it significantly contributes to annual carbon emissions (Chenari et al., 2016; Dixit, 2017). While the building sector accounts for nearly one-third of final energy consumption, it represents approximately forty percent of total energy use (Talaei et al., 2021). Consequently, identifying strategies to reduce energy consumption in the building sector is a critical issue (Balaras et al., 2005). In general, the energy required for heating and cooling spaces

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constitutes the largest share of a building's energy consumption (Fallah & Medghalchi, 2020).

On a global scale, energy projections for the coming decades indicate that energy consumption will increase by 34% between 2014 and 2035, driven by demand from emerging economies (Hoseinzadeh et al., 2021). Additionally, electricity demand is rising due to population growth, development initiatives, and the need to maintain internal thermal comfort conditions. Moreover, increasing energy costs and the adverse environmental impacts of energy production facilities necessitate finding ways to significantly reduce energy consumption (Aragon et al., 2018). For several decades, many developed countries have prioritized improving the energy efficiency of buildings and reducing fossil fuel consumption. Research conducted by Oliva in Australia in 2017 highlights that incorporating energy efficiency in residential areas and distributed energy production is an essential step toward achieving sustainable energy systems (Oliva, 2017).

The Role of Architectural Design in the Energy Debate

At the building design stage, energy consumption can be reduced by considering factors such as building orientation, spatial planning based on alignment with solar cycles, selecting an appropriate building envelope suited to climatic and environmental conditions, optimizing the dimensions of openings to balance solar radiation and heat loss, and choosing suitable window types (e.g., single-pane or double-pane glass). Finally, integrating renewable energy solutions to replace non-renewable energy sources is crucial. Each of these factors plays a role in reducing a building’s energy consumption (Hashmi & Heydari, 2019). Given that the building envelope is responsible for the majority of energy loss, focusing on its optimization can significantly reduce energy consumption (Talaei et al., 2021).

The national building regulations, specifically Topic 19, provide recommendations for architectural design. Buildings should align with the local climate to maximize the use of favorable natural conditions while protecting against adverse climatic effects. The goal is to minimize energy consumption for heating and cooling and to meet part of the energy demand through natural methods, thereby ensuring indoor comfort. In addition to thermal insulation, other factors influencing the use of natural energy include building orientation, form, interior space layout, light-transmitting walls, shading devices, and the thermal inertia of walls (Iran's National Building Code, Topic 19, 2013).

The Role of the Building Envelope on Energy Consumption

The building envelope serves as the primary interface between the interior and exterior environments, playing a vital role in regulating climatic conditions and ensuring occupant comfort. As a result, it significantly influences cooling and heating loads. By designing and selecting appropriate materials, building envelopes can achieve optimal thermal comfort in indoor spaces without relying on mechanical systems, thereby reducing operational costs through substantial energy savings. This component of the building, as the primary receptor of light and solar energy, also affects heating, cooling, intentional and unintentional ventilation, noise control, and aesthetic aspects (Yellamraju, 2004).

Energy loss through the building envelope is one of the main sources of energy waste in buildings because it acts as the boundary between the internal and external environments (Chen et al., 2011). Implementing insulation in walls is a key strategy for reducing energy consumption. Identifying suitable materials, designing efficient building envelopes, and considering their positioning and orientation are effective tools for minimizing annual heating and cooling loads, ultimately reducing energy demand (Kaynakli, 2012).

Innovation

As mentioned, the insulation of the building's walls and roof, along with the use of double-glazed windows, significantly impacts the energy consumed by the building for cooling and heating by influencing the building's behavior against sunlight and wind. Given that trial-and-error methods for selecting appropriate materials and evaluating their impact on occupant comfort through energy consumption measurement devices are time-consuming and require specialized tools and resources, this research provides a practical guide for determining the optimal layering in the construction of residential building walls in Qom city. It should be noted that this approach aligns with a consequence-based strategy, aimed at encouraging users to adopt reduced consumption patterns.

In this study, in addition to calculating the optimal insulation thickness, the impact of insulation on energy consumption across different building fronts (walls, the last floor ceiling, and the pilot roof) has been thoroughly investigated. The priority of insulation placement has also been carefully analyzed. Furthermore, to ensure the results are applicable and practical, various common land plot sizes in Qom city have been considered for simulation. These aspects distinguish this research from previous studies, which have typically focused on one or more factors affecting insulation in specific cities but have lacked the comprehensiveness and prioritization offered by this study. This research not only provides a detailed analysis but also proposes a suitable model considering the prioritization of insulation strategies.

Research Aims

The purpose of this research is to model and simulate buildings while modifying passive systems, such as wall materials and the effects of wall insulation, to assess per capita energy consumption for cooling and heating under different configurations of external walls. These configurations include thermal insulation applied to various building surfaces, such as the eastern, western, northern, southern walls, the roof, and pilot roof (ground floor ceiling).

The study evaluates the most effective surfaces for insulation and determines the optimal thickness of the thermal insulation layer. This ensures that the building can significantly reduce its operating costs with minimal initial investment. By integrating these parameters into the early stages of architectural design, this approach aligns with efficient planning practices and avoids additional costs.

The final output of the computer simulation includes the annual heating and cooling load required by the building, which determines the total electricity or gas consumption throughout the year. By comparing the cooling and heating loads, the study identifies the best surfaces and thicknesses for thermal insulation placement in the external walls, roof, and pilot roof of the building.

Using energy calculations, the impact of the mentioned parameters on energy consumption is evaluated. The numerical results obtained from the simulations allow for an accurate assessment of energy efficiency by considering the optimal thickness and location of thermal insulation. The findings of this research, supported by precise figures and data on annual per capita energy savings, aim to motivate builders and owners of residential projects to adopt optimal thermal insulation practices for roofs and external walls.

It is worth noting that three common land plot sizes were selected as the most frequently observed dimensions in Qom, and each was simulated in two building locations (courtyard at the beginning of the building and courtyard at the end of the building) and seven geographical rotations. This comprehensive approach ensures that all possible scenarios are considered, enhancing the practical applicability of the research outcomes.

Research Methods

The method used in this descriptive article is a case study, combining modeling and computer-based simulation to evaluate the impact of thermal insulation on energy consumption in residential buildings. In this research, Rhino software is utilized to create a three-dimensional model of the building, define thermal zones, openings, and other structural characteristics, and simulate the samples initially.

In the next step, the technical specifications of the building—such as wall materials, mechanical systems, and electrical facilities—are entered into the software through the Honeybee and Ladybug plugins, which are powered by the EnergyPlus analysis engine for detailed analysis. EnergyPlus is recognized as one of the most reliable independent energy simulation engines, widely used for modeling buildings and determining their energy consumption. To ensure accurate simulation results, parameters such as air infiltration, setback settings, and surrounding environmental conditions were carefully defined during the simulation process.

The results of the modeling are presented both numerically and graphically. For data analysis, Excel software and the Design Explorer website are employed (Rabie et al., 2021). Additionally, to validate the results, the software was tested against a basic model introduced by the International ASHRAE Standard. The validation process ensured that the simulation outputs align with established benchmarks, as detailed in Appendix 7-1.

Research Questions

Based on the materials discussed, this research aims to determine the best location and optimal thickness of thermal insulation for external walls and roofs of residential buildings in Qom, focusing on achieving optimal thermal performance. The following three research questions guide the study:

1. Is the effect of thermal insulation on different facades (north, south, west, and east walls, the roof of the top floor, and the pilot roof) the same? If not, which wall provides the most significant reduction in energy consumption?

2. To what extent does the placement of thermal insulation in external walls influence the thermal behavior of the building?

3. What is the optimal thickness of thermal insulation for the external walls of the building, considering energy savings and cost-effectiveness?

RESEARCH BACKGROUND

Insulation

As stated in the 19th topic of Iran's National Building Regulations, thermal insulation is a composite material or system that effectively reduces the transfer of heat from one space to another. In some cases, thermal insulation can also provide additional benefits, such as sound insulation, alongside reducing heat transfer. Thermal insulation in buildings is defined as having a thermal conductivity coefficient less than or equal to 0.65 m²·K/W and a thermal resistance equal to or greater than 0.5 m²·K/W (Iran's National Building Code, Topic 19, 2013). Various studies have focused on optimizing thermal insulation and analyzing heat transfer through external walls.

Insulation in Residential Buildings

Numerous studies have demonstrated the significant impact of insulation on energy consumption (Perez & Capeluto, 2009; Ucar & Balo, 2010). For instance, in Poland, energy consumption in the residential sector accounts for 30% of total energy consumption across all sectors. From an economic perspective, thermal insulation of buildings, along with the use of new materials and structural designs, has proven effective in reducing energy consumption (Adamczyk & Dylewski, 2017). Similarly, in Australia, energy efficiency regulations for buildings often focus exclusively on operational and thermal energy demands. Increasing the thickness of insulation and installing high-performance windows generally enhance a building's energy efficiency (Crawford et al., 2016).

In one study, it was noted that air conditioners in the residential sector account for a significant portion of energy consumption to maintain thermal comfort. To address this issue, thermal insulation is considered an efficient technology to improve energy efficiency while aligning with environmental characteristics to ensure thermal comfort. Proper installation of thermal insulation using energy-efficient materials can reduce heat loss and energy waste, leading to lower energy costs (Aditya et al., 2017).

Regarding the thickness of insulation, it is important to note that while the cost of insulation materials increases with thickness, the associated costs of cooling and heating are reduced. The appropriate insulation thickness is determined by considering factors such as the average temperature of the region, the thermal conductivity of the insulation material, and its cost (Bolattürk, 2006).

Bojic et al. investigated the effect of thermal insulation layers in external walls on the annual cooling load and maximum annual cooling demand in two typical residential apartments within a high-rise building in Hong Kong. They found that applying a 5 cm polystyrene insulation layer to either the interior or exterior reduced the peak cooling load by approximately 7% (Bojic et al., 2001).

Al-Khawaja studied the optimal thickness of various insulation materials used to reduce heat flow into buildings in hot climates (Al-Khawaja, 2004). Bojic et al. further demonstrated that incorporating thermal insulation in residential building envelopes leads to a reduction in the maximum annual cooling demand, with the largest reduction of approximately 10.5% observed when the insulation was placed on either the interior or exterior surfaces (Bojic et al., 2002).

Based on the reviewed literature, the importance of insulation in addressing the current energy crisis is evident. Many researchers have examined building insulation, often focusing on specific climates or cities to investigate insulation thickness or type. As noted earlier, this research provides a more detailed and comprehensive analysis of insulation to offer practical guidance for the city of Qom and similar climates. The subsequent sections will discuss the research methodology and the models studied and simulated.

MATERIALS AND METHODS

Modeling and Input Data

The First Stage of the Research: Climate Data and Building Specifications

In the first stage of the research, the weather data for Qom city were obtained based on available statistics. The file used to simulate the thermal performance of the building (energy consumption intensity) must be a climate file in the "epw" format (Talaei et al., 2021).

Table 1. Climatic Parameters of Qom City

Climatic Data	Unit	Daily Average
Dry Bulb Temperature	°C	16.23
Relative Humidity	%	53.62
Dew Point Temperature	°C	-8.67
Wind Speed	m/s	0.91
Direct Solar Radiation	W/m²	320
Sky Cover	%	8
Barometric Pressure	Pa	7823

To prepare the climate file, a reliable instrument called Manorum was utilized (Heyranipour, 2021). In this study, residential buildings with land dimensions of 25x6, 20x7.5, and 10x15 meters were selected in two configurations: southern construction (yard at the end of the building) and northern construction (yard at the beginning of the building). These configurations were chosen based on their prevalence in the detailed urban plan of Qom city.

The technical characteristics of the walls were defined according to the typical construction practices in Qom city. For peripheral walls without a facade, the layering from inside to outside is as follows: plaster, clay wall, and cement shell. For walls with a facade, the layers from inside to outside include: plaster, clay wall, sand, cement, stone mortar, and brick (with 40% brick facade and 20% stone facade).

The height of a building significantly influences its thermal performance (Aldawoud & Clark, 2008). As the height increases, the temperature difference between the top and bottom of the building also increases. Based on the current status of approved residential building plans in Qom city, as well as constructed buildings, the floor-to-floor height in residential buildings was set at 3.50 meters.

For different climates, varying levels of light transmission through windows should be considered. If the maximum outdoor temperature during the hottest month of the year is close to 40°C, it is recommended that 20% of the facade surface be transparent. Conversely, if the maximum outdoor temperature is close to 30°C, 80% of the window surface should be transparent. Additionally, if the maximum outdoor temperature is near 35°C, a 50% light transmission level is desirable (Ho & Rabitz, 1996).

The average temperature in Qom is approximately 38°C, so according to Ho (1996), the light transmission ratio should be slightly less than 50% (Ho & Rabitz, 1996). Similarly, Topic 19 of the National Building Regulations states that the light transmission ratio for high-rise buildings in hot and dry climates should not exceed 40%. Therefore, in this study, a 40% ratio of glazing surface to facade has been considered. The specifications of the basic research model related to walls and materials are presented in Tables 2 and 3.

Thermal simulation required defining the thermal properties of each material in the software. Table 4 lists the thermal characteristics of the materials used in the walls. The 3D structure was modeled in Rhino software for visualization, as shown in Figure 1.

Table 2. Characteristics of Traditional Local Walls

Specifications	Part	Row
10 cm two-layer clay wall with 5 cm polystyrene insulation	External Wall	1
The floor of the structure with insulation and concrete	Floor	2
Structural roof with moisture and thermal insulation	Ceiling	3

Table 3. Specifications of Building Wall Materials

Floor Layers	Roof Layers	External Wall Layers	From Inside to Outside
Ceramic	Plaster	Plaster	1
Mortar	Roof Structure	Clay Wall (10 cm)	2
Leveling Concrete	Leveling Concrete	Thermal Insulation	3
Thermal Insulation	Thermal Insulation	Clay Wall (10 cm)	4
Roof Structure	Moisture Insulation	Mortar	5
Plaster	Mortar	Brick and Stone Facade	6

Table 4. Thermal Characteristics of the Materials Used in the Walls

Thickness (cm)	Specific gravity (Kg)	Thermal transfer coefficient ($W/M^2 \cdot K$)	Interests	Row
2	2500 - 2700	2/8	Stone	1
5	1700 - 2000	1	Brick	2
2	1000 -1250	0/55	Mortar	3
10/5	1700 - 2000	0/52	Wall-mounted pottery	4
0/5	1000 - 1100	0/23	Moisture insulation	5
2	1800 - 2000	1/35	Mosaic	6
30	>2400	0/37	Roof structure	7
1	1400 - 1500	0/55	Ceramic	8
10	600 - 800	0/25	Leveling concrete	9
2	1000 -1300	0/57	Ceiling plaster	10
5	7 - 10	0/056	Polystyrene thermal insulation	11
7	7 - 10	0/055	Glass wool	12

Details of the Mechanical System

In this research, the HVAC system for thermal zones is of the Ideal Air Load System type, which essentially represents an Air Economizer system. This system is designed to provide optimal indoor thermal comfort with minimal energy consumption. The energy consumption analysis in this research is performed using the "Run Energy Simulation" component in the Honeybee environment.

Detailed Explanation of Simulation Parameters

Following the research, the necessary variables and default settings for simulating the building's thermal performance were defined for the Honeybee plugin. These parameters are selected based on Topic 19 of the National Building Regulations and are shown in Table 5. The details of the parameters are as follows:

Methodology for Determining Optimal Insulation Thickness

The optimal insulation thickness was determined through a systematic simulation process using EnergyPlus and Honeybee software. Four insulation thicknesses (2.5 cm, 5 cm, 7.5 cm, and 10 cm) were tested across six building fronts (south, east, north, west, roof, and pilot roof) for each building type (Section 7-4 of the Appendix). The simulations considered seven orientation scenarios ranging from -30° to +30° in 10-degree increments.

To evaluate the effectiveness of each insulation thickness, the following three criteria were used:

1) Energy Savings: The percentage reduction in energy consumption was calculated for each scenario.

2) Cost-Effectiveness: The balance between initial investment costs and long-term energy savings was considered.

3) Thermal Performance: The impact of insulation on maintaining indoor thermal comfort was assessed.

The results were analyzed using the Colibri component from the TT Toolbox plugin in Grasshopper, which allowed for the visualization and comparison of all possible scenarios. For example, in the case of the 6×25 (The courtyard at the front of the building), the east wall consistently showed the highest energy-saving potential, with an optimal insulation thickness of 7.5 to 10 cm, depending on the orientation and specific wall. Similarly, for the 10×15 (the courtyard at the end of the building), the east wall was identified as the most effective surface for insulation.

This approach aligns with standard optimization methods, such as Life Cycle Cost Analysis (LCC), which considers both initial costs and long-term benefits. Future studies could incorporate more advanced optimization algorithms, such as genetic algorithms or machine learning models, to further refine the selection process.

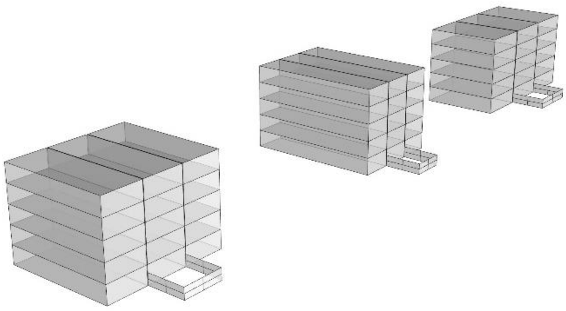

Fig 1. The 3D Model of Structures in Rhino Software

Table 5. Default Settings and Variables for Building Energy Simulation

Variables	Values
Cooling Setpoint Temperature	28°C
Heating Setpoint Temperature	20°C
Lighting Setpoint	300 Lux
Maximum Humidity	45%
Minimum Humidity	65%
Lighting Type	Dimmer
Equipment Load	2 Watts per square meter
Lighting Load	8 Watts per square meter (Compact Fluorescent Lamps)
Ventilation Rate	0.0025 cubic meters per second per square meter

Validation

The validation of this research was conducted using the "BESTest" (Building Energy Simulation Test) methodology, which is a standardized process for testing, diagnosing, and validating building performance simulation tools (ANSI/ASHRAE). According to the ASHRAE Standard 140, the performance of software used for thermal simulation of the building envelope and thermal loads was evaluated using the 600-sample test case, which is specifically designed for buildings with low thermal mass. In this test case, lightweight walls, floors, and ceilings were modeled to assess the accuracy of the simulation results.

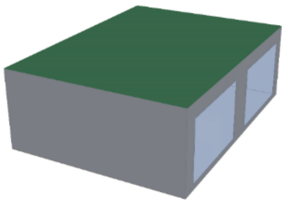

Fig 2. Sample Number 600

Honeybee software, integrated with EnergyPlus, supports the initial settings required for energy modeling. The workflow in this study involved importing the initial geometric form from Rhinoceros software into Honeybee via the Grasshopper plugin, where it was defined as an Energy Zone. Subsequently, the thermal characteristics of the Energy Zone, such as material properties and boundary conditions, were applied to the Honeybee zone. The results demonstrated that Honeybee software successfully passed the 600-sample test, with simulation outputs aligning closely with the validation criteria outlined in ASHRAE Standard 140.

In general, the results obtained from the simulations correspond well to the validation process of the ASHRAE Standard 140, ensuring the reliability of the findings. Additional information, images, and tables related to the validation analysis are provided in Appendix 7-1 for further reference.

RESULTS

The First Stage

The First Stage: Simulation of Thermal Insulation Effects

In the first stage, the simulation focused on evaluating the effect of thermal insulation on different walls of the building, including the north, south, west, and east walls, and comparing their cost-effectiveness. At this stage, the modeling of common residential buildings in Qom city was conducted parametrically using Honeybee software, while the surrounding neighborhoods were modeled in Grasshopper software. For this purpose, the dimensions of the land plot were defined as a parameter in Grasshopper, and seven orientation modes ranging from -30° to +30°, with increments of 10 degrees (Figure 3), were modeled as parameters.

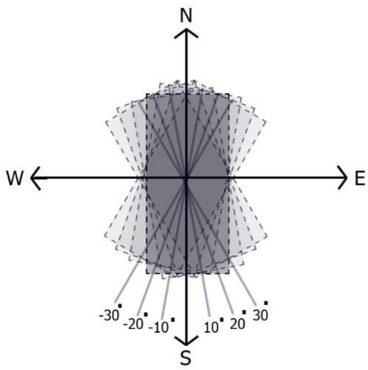

Fig 3. Seven Orientations of the Land Plot in the Simulation

Additionally, the walls on each side of the building were modeled separately, and an insulation parameter was applied to each wall to assess the reduction in energy consumption. The results of this modeling provided insights into the effectiveness of thermal insulation across different orientations and wall placements.

According to Table 6, the most effective fronts in terms of thermal insulation for northern building configurations are the eastern and western fronts. In the case of 20×7.5 m and 25×6 m (The courtyard at the end of the building) configurations, the most effective fronts for thermal insulation are the northern and southern fronts. Additionally, for 10×15 m (The courtyard at the end of the building) configurations, thermal insulation has the greatest impact on the eastern and western fronts (Appendices 7-3).

Table 6. Summary of the Results of the First Stage

Row	Layout Type	Plot Dimensions (m)	Angle of rotation relative to north-south direction (°)	Critical Façade for Insulation
1	North-Builder	15 × 10	30	Eastern/Western (varies)
			20	Eastern/Western (varies)
			10	Eastern
			0	Eastern/Western (varies)
			-10	Eastern/Western (varies)
			-20	Eastern/Western (varies)
			-30	Eastern/Western (varies)
2		20 × 7.5	30	Eastern/Western (varies)
			20	Eastern/Western (varies)
			10	Eastern/Western/Northern (varies)
			0	Eastern/Western (varies)
			-10	Eastern/Western (varies)
			-20	Eastern/Western (varies)
			-30	Eastern/Western (varies)
3		25 × 6	30	Northern /Southern (varies)
			20	Eastern/Western (varies)
			10	Eastern/Western (varies)
			0	Eastern/Western (varies)
			-10	Eastern/Western (varies)
			-20	Eastern/Western (varies)
			-30	Eastern/Western (varies)
4	South-Builder	15 × 10	30	Eastern/Western/Northern (varies)
			20	Eastern/Western (varies)
			10	Eastern
			0	Eastern
			-10	Eastern/Western (varies)
			-20	Eastern/Western (varies)
			-30	Eastern
5		20 × 7.5	30	Eastern/Western (varies)
			20	Northern /Southern (varies)
			10	Northern /Southern (varies)
			0	Northern /Southern (varies)
			-10	Northern /Southern (varies)
			-20	Northern /Southern (varies)
			-30	Northern /Southern (varies)
6		25 × 6	30	Northern
			20	Southern
			10	Northern /Southern (varies)
			0	Northern
			-10	Northern /Southern (varies)
			-20	Northern /Southern (varies)
			-30	Northern /Southern (varies)

The Second Stage

In this part of the research, the same methodology described in the first stage of the simulation was applied to investigate the effect of thermal insulation thickness. In the previous section, 28 simulations were analyzed for each building type. However, in this stage, 168 cases were analyzed to evaluate the thickness and placement of thermal insulation across different parts of each building type. This increase in cases accounts for testing four insulation thicknesses (2.5, 5, 7.5, and 10 cm) across six building fronts (south, east, north, and west walls, as well as the roof and pilot roof), while considering seven orientation scenarios (-30°, -20°, -10°, 0°, +10°, +20°, +30°). A comprehensive review of all possible configurations for each building type is provided in the appendix (Section 7-4).

The analysis was conducted for six different building sizes, simulating insulation thickness variations across various walls. In Appendix, Section 7-3, for each building type, all possible configurations for each orientation were first specified using "Colibri" software. By filtering the results to identify the most optimal outcomes in terms of energy consumption intensity, the most effective building front for insulation and the recommended insulation thickness were determined. The findings for some sections of the buildings are summarized in Tables 7 to 12.

The First Type

The first building type has dimensions of 25 x 6 meters and features a yard located at the end of the building. This configuration represents one of the common residential building layouts in Qom city. The placement of the yard at the end of the building influences the thermal performance and energy consumption patterns, particularly due to its impact on solar exposure and ventilation dynamics.

According to Table 7, for the southern 25×6 building configuration, the orientation changed from +30 degrees east to -30 degrees west, and the most effective fronts were expressed in order of priority. As can be seen, in all the orientations studied, the eastern wall is the most effective in terms of energy savings, with the western wall being the second priority. Additionally, the optimal insulation thickness varies between 7.5 and 10 centimeters.

Table 7. Summarizing the Results of the Second Stage of Simulation for 6x25 Plots, the Yard at the End of the Building (First Type)

The results of the land 6*25 (South yard at the end of the building)								Row
Optimal thickness of roof insulation (cm)	Roof insulation effectiveness percentage (KWh/m^2)	Optimal thickness of pilot roof insulation (cm)	The percentage of insulation effect of the pilot roof (KWh/m^2)	Optimal wall insulation thickness (cm)	Energy saving percentage	The most effective fronts in order of priority	Orientation towards the South	1
10	8/8	10	8/6	10	11/2	East 1	30	2
				10	9/9	West 2		3
				10	8/8	Roof 3		4
				10	8/6	Floor 4		5
10	8	10	7/9	10	11/7	East 1	20	6
				10	10/5	West 2		7
				10	8	Roof 3		8
				10	7/9	Floor 4		9
10	7/9	10	7/9	10	12/6	East 1	10	10
				10	10/1	West 2		11
				10	7/9	Roof 3		12
				10	7/9	Floor 4		13
10	7/9	10	7/9	7/5	12/8	East 1	0	14
				10	10/5	West 2		15
				10	7/9	Roof 3		16
				10	7/9	Floor 4		17
10	7/4	10	7/2	10	11/7	East 1	-10	18
				10	10/4	West 2		19
				10	7/4	Roof 3		20
				10	7/2	Floor 4		21
10	7/4	10	7/6	10	12/1	East 1	-20	22
				10	10/4	West 2		23
				10	7/9	North 3		24
				10	7/6	Floor 4		25
10	8/1	10	8/6	10	11/3	East 1	-30	26
				10	10/7	West 2		27
				10	8/6	North 3		28
				10	8/6	Floor 4		29

The Second Type

According to Table 8, for the northern 25×6 building configuration, the orientation changed from +30° east to -30° west, and the most effective fronts were prioritized. As can be seen, in most of the orientations studied, the eastern wall is the most effective in terms of energy savings. However, in two specific orientations, at +10°, the western wall, and at -30°, the floor of the pilot takes the first priority. Additionally, the optimal insulation thickness varies between 7.5 and 10 centimeters.

The Third Type

According to Table 9, for the southern 10×15 building configuration, the orientation changed from +30° east to -30° west, and the most effective fronts were expressed in order of priority. As can be seen, in most of the orientations studied, the northern and southern walls are the most effective in terms of energy savings. Additionally, the optimal insulation thickness varies between 7.5 and 10 centimeters.

Table 8. Summarizing the Results of the Second Stage of Simulation for 6x25 Plots, the Yard in Front of the Building (Second Type)

The results of the land 6x25 (North yard at the beginning of the building)									Row
Optimal thickness of roof insulation (cm)	Roof insulation effectiveness percentage (KWh/m^2)	Optimal thickness of pilot roof insulation (cm)	The percentage of insulation effect of the pilot roof (KWh/m^2)	Optimal wall insulation thickness (cm)	Energy saving percentage	The most effective fronts in order of priority		Orientation towards the South	1
10	13/9	10	13/7	10	15/2	East	1	30	2
				10	14/7	North	2		3
				10	14/3	South	3		4
				10	13/9	Roof	4		5
10	14	10	14/1	10	18/2	East	1	20	6
				7/5	15/3	West	2		7
				10	14	Roof	3		8
				10	12/8	North	4		9
10	14/2	10	14/1	10	15/8	West	1	10	10
				10	14/2	Roof	2		11
				10	14/2	East	3		12
				10	14	North	4		13
10	14/3	10	14/2	7/5	16	East	1	0	14
				10	15/7	West	2		15
				10	14/3	Roof	3		16
				10	12/9	North	4		17
10	13	10	12/8	7/5	14/4	East	1	-10	18
				10	13/7	West	2		19
				10	13	Roof	3		20
				10	11	North	4		21
10	12/9	10	12/9	10	17/8	East	1	-20	22
				10	14/7	West	2		23
				10	14/7	South	3		24
				10	12/9	Roof	4		25
10	13/3	10	14/8	10	14/8	Floor	1	-30	26
				10	13/7	South	2		27
				10	13/6	West	3		28
				10	13/4	North	4		29

Table 9. Summarizing the Results of the Second Stage of Simulation for 10x15 Plots, the Yard at the End of the Building (Third Type)

The results of the land 15*10 (South yard at the end of the building)									Row
Optimal thickness of roof insulation (cm)	Roof insulation effectiveness percentage (KWh/m^2)	Optimal thickness of pilot roof insulation (cm)	The percentage of insulation effect of the pilot roof (KWh/m^2)	Optimal wall insulation thickness (cm)	Energy saving percentage	The most effective fronts in order of priority		Orientation towards the South	1
10	9/5	10	9	10	18/7	South	1	30	2
				10	10/5	North	2		3
				10	9/5	Roof	3		4
				10	9	West	4		5
10	8/6	10	7/9	10	14/7	South	1	20	6
				10	10	North	2		7
				10	8/6	Roof	3		8
				10	7/9	Floor	4		9
10	8/8	10	7/3	10	10/4	South	1	10	10
				10	9/9	North	2		11
				10	8/8	Roof	3		12
				10	7/3	Floor	4		13
10	10/6	10	9/1	7/5	10/8	North	1	0	14
				10	10/6	Roof	2		15
				10	9/1	Floor	3		16
				10	8/7	East	4		17
10	24/5	10	23/2	10	25/5	North	1	-10	18
				10	24/5	Roof	2		19
				10	23/2	Floor	3		20
				10	22/9	East	4		21
10	18	10	17/5	10	19	North	1	-20	22
				10	18	Roof	2		23
				10	17/5	Floor	3		24
				10	17	East	4		25
10	11/3	10	11/8	10	12/9	North	1	-30	26
				10	11/8	Floor	2		27
				10	11/4	East	3		28
				10	11/3	Roof	4		29

The Fourth Type

According to the obtained results (Table 10), for the northern 10×15 building configuration, the orientation was varied from +30° east to -30° west, and the most effective fronts were prioritized. As can be seen, in most of the orientations studied, the eastern wall is the most effective in terms of energy savings. However, in two specific orientations, similar to the second type (+10°, the western wall, and at -30°, the floor), take the first priority. Additionally, the optimal insulation thickness varies between 7.5 and 10 centimeters.

Table 10. Summarizing the Results of the Second Stage of Simulation for 10 * 15 Plots, the Yard in Front of the Building (Fourth Type)

The results of the land 15*10 (North yard at the beginning of the building)								Row
Optimal thickness of roof insulation (cm)	Roof insulation effectiveness percentage (KWh/m^2)	Optimal thickness of pilot roof insulation (cm)	The percentage of insulation effect of the pilot roof (KWh/m^2)	Optimal wall insulation thickness (cm)	Energy saving percentage	The most effective fronts in order of priority	Orientation towards the South	1
10	14/2	10	14/1	10	12/8	East 1	30	2
				10	14/5	North 2		3
				10	12/4	South 3		4
				10	13/2	Roof 4		5
10	14/4	10	14/5	10	15/9	East 1	20	6
				7/5	11/4	West 2		7
				10	13/4	Roof 3		8
				10	9/1	North 4		9
10	14/3	10	14/2	10	15/3	West 1	10	10
				10	14/2	Roof 2		11
				10	14/1	East 3		12
				10	11/6	North 4		13
10	14/8	10	14/6	7/5	13/3	East 1	0	14
				10	13	West 2		15
				10	12/4	Roof 3		16
				10	9/7	North 4		17
10	13/1	10	13	7/5	13/7	East 1	-10	18
				10	13/5	West 2		19
				10	12/3	Roof 3		20
				10	9	North 4		21
10	13/4	10	13/3	10	14/5	East 1	-20	22
				10	14/5	West 2		23
				10	14/3	South 3		24
				10	12/9	Roof 4		25
10	13/4	10	14/9	10	14/4	Floor 1	-30	26
				10	12/2	South 2		27
				10	9/3	West 3		28
				10	10/5	North 4		29

The Fifth Type

According to the obtained results (Table 11), for the southern 20×7.5 building configuration, the orientation changed from +30° east to -30° west, and the most effective fronts were expressed in order of priority. As can be seen, in all the orientations studied, the eastern wall is the most effective in terms of energy savings. Additionally, the optimal insulation thickness for this building type varied between 5 cm and 10 cm, indicating a broader range of acceptable insulation depths compared to other building types.

Table 11. Summarizing the Results of the Second Stage of Simulation for 7.5 x 20 Plots, the Yard at the End of the Building (Fifth Type)

The results of the land 7.5*20 (South yard at the end of the building)								Row
Optimal thickness of roof insulation (cm)	Roof insulation effectiveness percentage (KWh/m^2)	Optimal thickness of pilot roof insulation (cm)	The percentage of insulation effect of the pilot roof (KWh/m^2)	Optimal wall insulation thickness (cm)	Energy saving percentage	The most effective fronts in order of priority	Orientation towards the South	1
10	44	10	44	7/5	44/4	East 1	30	2
				7/5	44/4	West 2		3
				5	44	Roof 3		4
				5	44	Floor 4		5
10	11/3	10	10/6	10	50/7	East 1	20	6
				10	50/5	West 2		7
				10	12/6	North 3		8
				10	11/8	South 4		9
10	11/1	10	11/1	10	16/1	East 1	10	10
				10	16/1	West 2		11
				10	12/5	North 3		12
				10	11/6	South 4		13
10	11/1	10	11/2	7/5	16/3	East 1	0	14
				10	16/3	West 2		15
				10	12/5	North 3		16
				10	11/6	South 4		17
10	11	10	11/1	10	16/1	East 1	-10	18
				10	16/2	West 2		19
				10	12/3	North 3		20
				10	11/6	South 4		21
10	11/2	10	11/1	7/5	51/3	East 1	-20	22
				7/5	51/1	West 2		23
				10	12/5	North 3		24
				10	11/6	South 4		25
10	44/4	10	44/4	7/5	45/2	East 1	-30	26
				7/5	45/1	West 2		27
				7/5	44/5	South 3		28
				5	44/4	Roof 4		29

The Sixth Type

According to the obtained results (Table 12), for the northern 20×7.5 building configuration, the orientation changed from +30° east to -30° west, and the most effective fronts were expressed in order of priority. As can be seen, in all the orientations studied, the eastern wall is the most effective in terms of energy savings. Additionally, the optimal insulation thickness for this building type also ranged from 5 cm to 10 cm, consistent with the findings for the fifth type.

Table 12. Summarizing the Results of the Second Stage of Simulation for 7.5 x 20 Plots, the Yard in Front of the Building (Sixth Type)

The results of the land 7.5*20 (North yard at the beginning of the building)								Row
Optimal thickness of roof insulation (cm)	Roof insulation effectiveness percentage (KWh/m^2)	Optimal thickness of pilot roof insulation (cm)	The percentage of insulation effect of the pilot roof (KWh/m^2)	Optimal wall insulation thickness (cm)	Energy saving percentage	The most effective fronts in order of priority	Orientation towards the South	1
10	16/1	10	15/9	10	42/9	East 1	30	2
				10	44/2	West 2		3
				10	42/7	Roof 3		4
				10	43/5	Floor 4		5
10	16/5	10	16/7	10	49/3	East 1	20	6
				7/5	48/2	West 2		7
				10	12	North 3		8
				10	8	South 4		9
10	18/5	10	18/4	10	15/7	East 1	10	10
				10	16/1	West 2		11
				10	12/4	North 3		12
				10	9/1	South 4		13
10	19	10	18/9	7/5	13/6	East 1	0	14
				10	13/6	West 2		15
				10	10/6	North 3		16
				10	8/3	South 4		17
10	16/4	10	16/3	7/5	15/6	East 1	-10	18
				10	16	West 2		19
				10	11/7	North 3		20
				10	9/5	South 4		21
10	13/4	10	13/2	10	49/3	East 1	-20	22
				10	50/9	West 2		23
				10	12	North 3		24
				10	11/6	South 4		25
10	13/2	10	14/7	10	45	East 1	-30	26
				10	43/6	West 2		27
				10	41/8	South 3		28
				10	42/6	Roof 4		29

DISCUSSION

The findings of this research underscore the critical role of thermal insulation in reducing energy consumption in residential buildings, particularly in Qom's climate. These results are consistent with previous studies that have emphasized the importance of insulation in lowering cooling and heating loads (Perez & Capeluto, 2009; Ucar & Balo, 2010). For instance, the eastern wall consistently emerged as the most effective surface for insulation across various orientations, a finding that aligns with prior research highlighting the significance of solar exposure in building design (Bojic et al., 2002). This outcome can be attributed to the eastern wall's direct exposure to morning sunlight, which increases heat gain during cooler parts of the day and reduces the need for artificial heating.

Additionally, the northern and southern walls were found to be highly effective in certain configurations, particularly for south-facing buildings. This variation underscores the importance of considering building orientation when designing insulation strategies. For example, in south-facing buildings, the eastern wall showed the highest energy-saving potential, while in some cases, the northern and southern walls also demonstrated significant impacts. These findings highlight the need for tailored insulation strategies based on specific building characteristics and orientations.

While the results provide valuable insights, several limitations of this study should be acknowledged. First, the research relies on simulation tools such as EnergyPlus and Honeybee, which, despite their robustness, may not fully capture real-world complexities such as occupant behavior, microclimatic variations, or non-ideal HVAC system performance. Second, the analysis assumes ideal operational conditions, which may differ from actual building usage patterns. Future research could address these gaps by conducting empirical studies on real buildings over extended periods, incorporating real-time data on energy consumption and occupant behavior.

From a practical perspective, the findings suggest that prioritizing insulation on the eastern wall, followed by the western wall, can significantly reduce energy consumption in Qom's residential buildings. This has important implications for policymakers, as it highlights the potential for targeted insulation strategies to achieve substantial energy savings. Furthermore, the optimal insulation thickness identified in this study—ranging from 7.5 cm to 10 cm—provides clear guidance for designers and builders, ensuring a balance between initial investment costs and long-term energy savings.

To further enhance the sustainability of residential buildings in Qom, future studies could explore the economic feasibility of implementing these recommendations, particularly given the high initial costs associated with thermal insulation. Additionally, integrating renewable energy solutions, such as rooftop solar panels, could complement insulation strategies and contribute to a more sustainable built environment. For instance, combining optimal insulation thickness with solar energy systems could maximize energy efficiency and reduce reliance on fossil fuels.

In conclusion, this study not only contributes to the growing body of knowledge on energy-efficient building design but also provides actionable insights for practitioners and policymakers. By emphasizing the importance of building orientation, optimal insulation thickness, and targeted placement, the findings offer a practical framework for reducing energy consumption in residential buildings in Qom and similar climates.

CONCLUSION

In this research, the effect of thermal insulation in common residential buildings in Qom city was studied. The study was divided into two main parts:

First Part: Investigated the effect of insulation on different building fronts (e.g., north, south, east, and west walls) to identify the most effective areas for insulation placement.

Second Part: Examined the optimal insulation thickness for different walls of the building to determine the most energy-efficient configurations.

The findings of this research specify the most critical building fronts for insulation to reduce energy consumption and provide recommendations for the optimal insulation thickness for each building type. The results are summarized as follows:

First Type: For the building with dimensions of 25 × 6 meters (yard at the end of the building), thermal insulation on the northern wall was found to be the most effective in reducing energy loss.

Second Type: Similarly, for the building with dimensions of 25 × 6 meters (yard at the beginning of the building), the east wall again emerged as the most effective area for insulation.

Third and Fourth Types: For the building with dimensions of 15 × 10 meters, thermal insulation on the east and west walls had the greatest impact on reducing energy loss.

Fifth Type: For the building with dimensions of 20 × 7.5 meters (yard at the end of the building), the northern and southern wall was identified as the most impactful area for insulation.

Sixth Type: Similarly, for the building with dimensions of 20 × 7.5 meters (yard at the beginning of the building), the east wall again demonstrated the highest effectiveness in reducing energy loss.

This research aimed to provide a quantitative definition of the optimal use of thermal insulation in roofs and walls, aligning with outcome-based strategies. The potential cost savings resulting from reduced energy consumption can serve as a strong motivator for adopting these findings in practice. By integrating the results of this study into the implementation frameworks of Topic 19 of the National Building Regulations, the city of Qom could become a model for practical compliance with energy efficiency standards.

It is worth noting that while conducting these tests on real-world buildings would provide empirical validation, such an approach would require multiple operational projects and substantial financial investment. Given the availability of advanced simulation tools like EnergyPlus, conducting this research in a laboratory setting using simulations proved to be a cost-effective and efficient alternative. However, future studies could explore real-world applications by applying these hypotheses to actual residential buildings and monitoring their performance over a year to validate the simulation results.

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HOW TO CITE THIS ARTICLE

Ghanbaran, A. H., Daloe Heydari, M. (2025). Investigating the Effect of the Thickness and Placement of Thermal Insulation on the Amount of Cooling and Heating Load of Residential Buildings in Qom City. *Int. J. Architect. Eng. Urban Plan,* 35(1): 1-17, https://dx.doi.org/ijaup.814.

URL: http://ijaup.iust.ac.ir