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The Effect of Employing a Thermal Insulation Layer in the Building Façade on Energy Consumption (A case study of a residential building in Tehran)

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ABSTRACT

Although currently, a large part of the existing buildings are considered inefficient in terms of energy, the ability to save energy consumption up to 80% has been proven in residential and commercial buildings. This study aims to calculate energy consumption during the operational phase caused by various scenarios of thermal insulation combinations in a building's exterior shell. The simulation was conducted using Design Builder software, with a five-story residential building in Tehran as the case study. Initially, the building was modeled in Design Builder, and keeping all other characteristics constant, ten scenarios were defined: nine using different types of thermal insulation and one without insulation. The software outputs for each scenario were analyzed. Results showed that the best thermal insulation layer is polyurethane foam, which saves 1070.15 kilowatt-hours of energy during one year of the building's operation. This article can help designers and construction engineers optimize the energy consumption of buildings by deciding the right materials.

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1. Introduction

According to the "Our World in Data" website, more than 73% of global greenhouse gas emissions stem from energy consumption, with 19% originating from the construction and building sector. This significant level of energy usage in buildings plays a crucial role in global warming. However, the silver lining is the considerable potential within this industry to reduce carbon emissions. The collaboration and optimal performance of engineers and architects in reducing energy consumption throughout the entire lifecycle of a building hold national and international importance in achieving sustainable and low-carbon buildings (www.ourworldindata.org).

In the coming decades, energy costs for heating, cooling, and lighting in homes and organizations, as well as driving industrial production processes, are expected to rise significantly. In the competitive global landscape of energy efficiency and production, countries that succeed in researching and implementing energy-saving solutions will

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come out ahead. One key approach to tackling this challenge is reducing energy consumption.

Today, one of the most impactful environmental concerns is the construction of buildings. Processes such as manufacturing building materials, transporting, and installing them use significant energy resources and emit large quantities of greenhouse gases. Additionally, during the operational phase of a building, these materials contribute to varying degrees of energy loss. The increasing global energy consumption raises concerns about future energy supply. Furthermore, reducing energy use leads to lower greenhouse gas emissions, such as carbon dioxide. According to the 2020 World Energy Outlook Report, approximately 55% of energy consumption occurs in buildings. Therefore, any measures to reduce this consumption can have substantial impacts.

The depletion of fossil fuel resources, global warming, industrialization, and population growth pose challenges for the energy sector [1]. Moreover, rising energy consumption contributed to 30% of annual greenhouse gas emissions worldwide in 2013 [2]. In Iran, with a population of around 85 million, energy consumption is comparable to that of a country with a billion inhabitants. The building sector accounts for the highest energy loss, making Iran one of the world's top energy consumers. Statistics reveal that energy consumption in the building sector alone is reported to be two to four times higher than global standards. Given these circumstances, if energy consumption patterns in the residential and commercial sectors are not modified, energy use in these areas is projected to surpass 1,400 million barrels of crude oil by 2031. This not only hinders the achievement of the 20-year vision goals, but also negatively impacts Iran's oil export position and puts pressure on the economy and environment. Continuing this trend could result in serious economic crises alongside environmental consequences [3].

2. Significance of the study

Global energy consumption, although showing temporary declines in certain years, has generally trended upwards and reached 172,119 trillion watt-hours in 2023. In Iran, energy consumption in 2023 was recorded at 3,531 trillion watt-hours. This trend is depicted in Figure 1. When this level of energy consumption is divided by the population, Iran's critical situation becomes clearer.

The average global energy consumption per person is 21,394 kilowatt-hours, whereas in Asia, this figure reduces to 19,239 kilowatt-hours. However, the average energy consumption per person in Iran is 39,599 kilowatt-hours, as illustrated in Figure 2.

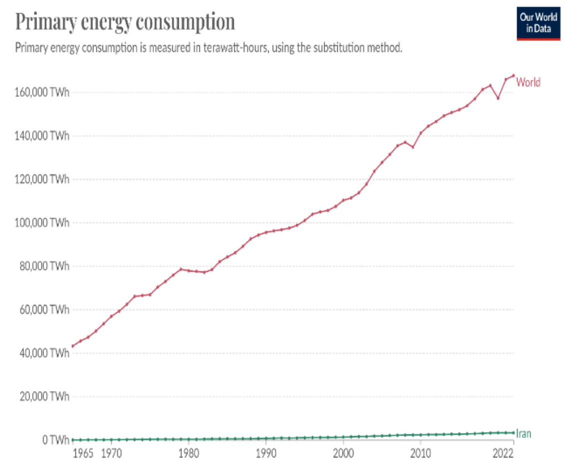


Fig. 1. the energy consumption trends in Iran and the world.

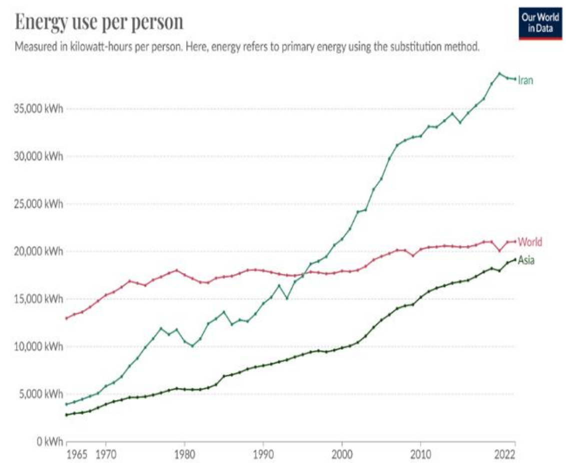


Fig. 2. the energy consumption per capita in Iran, Asia and the world.

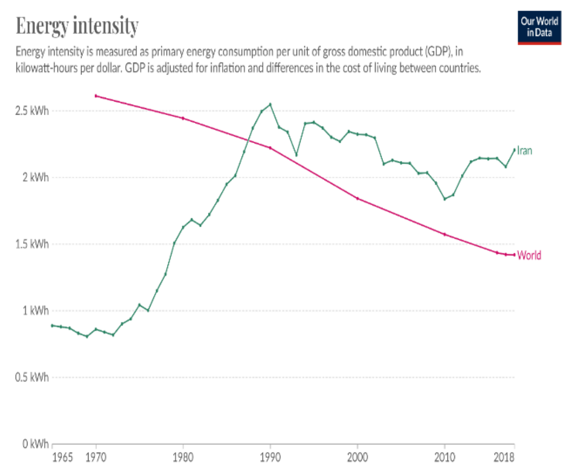


Fig. 3. the energy intensity in Iran and the world

Energy intensity is measured as primary energy consumption per unit of Gross Domestic Product (GDP) in kilowatt-hours per dollar. GDP is adjusted for inflation and differences in living costs between countries. In 2022, the global average energy intensity was 1.3 kilowatt-hours, while in Iran it was 2.21 kilowatt-hours. This is demonstrated in Figure 3.

3. Literature Review

In 2024, Soltani and Atashi conducted a study titled “The Impact of a Second Skin Facade on the Life Cycle Energy Consumption of Office Buildings: A Comparative Study.” They examined the use of a second facade as a mechanism to reduce energy consumption in an office building. Their research involved modeling, simulation, and analyzing an optimized second facade's impact on both operational energy consumption and the building's life cycle energy. They found that the second skin facade reduces both operational and life cycle energy consumption. However, life cycle energy temporarily increased in the building's initial years but decreased by 30% by the 30th year compared to the baseline scenario [4].

Feehan et al. (2021) explored the optimization of facades and fenestration in their study titled “Adopting an Integrated Building Energy Simulation and Life Cycle Assessment Framework for Optimizing Facades and Fenestration in Building Envelopes.” They used an integrated framework to select sustainable facade systems and windows for nearly zero-energy buildings. Results indicated that enhanced glazing reduced operational energy demand by 8.3%, though embodied energy increased by 10%, with a payback period of approximately 6–7 months. The optimal window-to-wall ratio for heating and cooling performance was 0.2, achieving an overall energy reduction of 2%. Insulated cavity walls exhibited the lowest embodied energy, while lightweight steel walls with brick facades had the highest [5].

Ousta Oghlu et al. (2021) conducted research titled “Investigation of Environmentally Friendly New Building Materials with Enhanced Energy Performance in Different Climatic Zones: Cost-Effective, Low-Energy, and Low-Carbon Emission.” They used various additives such as pumice, expanded vermiculite, fly ash, and sludge to produce fired clay bricks and lightweight foamed concrete. For instance, instead of commercially available insulation materials, they utilized lightweight concrete containing expanded vermiculite, and instead of conventional bricks, they employed a new type of fired clay brick. Finally, they calculated the annual energy savings and annual cost savings for different thicknesses of bricks and lightweight concrete and computed the greenhouse gas emissions from various fuels (coal, electricity, fuel oil, liquefied petroleum gas, and natural gas). The results indicated that using these new building materials resulted in energy savings of 11 kWh/m² in an insulated building and 31.2 kWh/m² in an uninsulated building. The annual energy savings rate reached 21.7%. The highest energy savings were observed in buildings using electricity for heating. The highest carbon emissions occurred with coal. Natural gas was the cleanest heating method. Electricity generated the highest carbon emissions after coal in the studied region. A reduction in carbon emissions for coal reached 18.7 kg/year. Using these new materials, the maximum reduction in carbon emissions reached 22% [6].

Pedroso et al. (2020) conducted a study titled “Characteristics of a Multilayer External Wall Thermal Insulation System for Mediterranean Climates.” This research compares the performance of a multilayer thermal insulation system with a super-insulator under Mediterranean climatic conditions. A series of mechanical, physical, and microstructural tests were performed on the insulators. The results show improved mechanical performance and water resistance when protective layers are applied in a multilayer system. When compared to other multilayer products currently on the market, this new solution offers competitive results, demonstrating improved performance under real operating conditions [7].

Mahmoud et al. (2020) conducted a study titled “Comparative Energy Performance Simulation for Passive and Conventional Designs.” Their case study was an office building in Cairo, Egypt. They performed simulations using Design Builder software and weather data generated by the Meteonorm site. Their proposed passive design features included a courtyard, double-skin façade walls, overhangs, and a cross-ventilation system. Their results showed that the passive design resulted in an 11% reduction in annual energy consumption compared to the baseline conventional design [8].

Navayi et al. (1402) conducted a study titled “The Effect of Using Air Gaps in Walls on Reducing Energy Consumption in a Residential Building.” To investigate the impact of air gaps in walls on energy reduction, they analysed three different air gap thicknesses (1, 2.5, and 5 cm). The energy simulation results for these three walls compared to the baseline wall show that using an air gap reduced overall energy consumption and heating and cooling loads in different months of the year. Specifically, the monthly cooling load in the hottest month decreased by 10.3%, 12.8%, and 14%, respectively, while the monthly heating load in the coldest month decreased by 32.8%, 42.3%, and 48.2%, respectively. Annual heating energy consumption decreased by 25.7%, 30.9%, and 33.6%, respectively, and annual cooling energy consumption decreased by 8.3%, 10%, and 10.9%, respectively—a significant percentage considering the building's high annual cooling energy consumption [3].

Mirsaeidi and Mirrasheed (2020) in their research titled "Investigation of the Impact of Trombe Wall System on Thermal Comfort in a Moderate and Humid Climate (Case Study: Residential Building in Gonbad-e Kavus)" examined the effect of using a Trombe wall system on indoor air temperature in a residential building in Gonbad-e Kavus under both heating and cooling conditions using Design Builder software. The simulation results showed that the Trombe wall system can be beneficial for heating in the studied climate; however, it plays a less significant role in improving cooling conditions. Further studies are needed to investigate the role of this system in reducing energy consumption, considering economic and technical aspects [9].

Fathelian and Kargar (2020), in their research titled "Investigating the Impact of Various Energy Optimization Strategies on Building Energy Rating Using Design Builder Software (Case Study: Office Building),", examined the effect of different wall configurations in double-skin facades using Design Builder software. The results showed that changing the number of inner layers in the double-skin facade is more effective in reducing energy consumption, while changing the number of outer layers has no significant effect. Greater solar radiation on the south facade makes the use of a double-skin facade more effective on this side. The study also examined the effects of employing external horizontal shading and removing internal shading, replacing single-pane windows with low-emissivity double-pane windows, and installing a thermal insulation sheet on the exterior wall, resulting in energy consumption reductions of 2.15%, 4.18%, and 2.08% respectively, compared to the conventional case [10].

4. Theoretical foundations of the research

4.1. Governing equations

Heat transfer occurs through conduction, convection, air exchange, and radiation. Proper insulation is essential to reduce heat transfer. Adding insulation decreases the heat transfer value or increases thermal resistance. Proper placement of insulation also plays a crucial role.

4.2. Heat Insulation

A composite material or system that effectively reduces heat transfer from one environment to another. In some cases, in addition to reducing heat transfer, heat insulation can also have other abilities such as load bearing, soundproofing, etc. Under special weather conditions, it can also be considered heat insulation. Thermal insulation that can be used in the building refers to insulation that has a thermal conductivity coefficient less than or equal to 0.065 watts per meter degree Kelvin and a thermal resistance equal to or greater than 0.5 watts per meter degree Kelvin. The mentioned values are related to measurements in standard thermal conditions. Thermal insulation is done by a special material or materials or by a system with several functions. For example, a load-bearing wall can provide the role of thermal insulation at the same time. But in most cases, it is necessary to add a special layer to the wall as heat insulation.

The best practices for insulation include the following:

- Applying insulation to all exterior building components (roof, external walls, and floor).
- Installing firm and secure insulation layers on walls.
- Ensuring complete waterproofing of all cavities.

4.3. Equations Governing Building Envelopes

To assess thermal comfort in a space, we first need to calculate the indoor air temperature and surface temperatures. We write the energy balance equation for each surface. Let's denote the properties related to each surface with a subscript (i):

The radiative and convective heat transfer Shown in equation 1:

$$hiAi\,(Tair\; - \;Ti) + \;\varepsilon i\sigma Ai\,\{\sum_{k=1}^{n} Fi - k\,(Tk^{\,4}Ti^{\,4})\} = \;Qi \qquad (1)$$

The first term on the left represents heat transfer by convection between the inner wall surface and room air.

The second term represents received heat transfer through radiation from other surfaces.

The equation for heat transfer from the surface is given by equation 2.

$$Qi\; = \;Qc(i)\; - \;Qr - in(i)\; - \;Qr - out(i) \qquad (2)$$

Qi represents the heat generated within the system (e.g., in a building).

$Qc(i)$ represents heat generated by internal sources (e.g., heating, cooling).

$Qr - in(i)$ represents heat transferred from the system to the external environment (e.g., through windows or other surfaces).

(Qr-out(i)) represents heat transferred from the system to other building components (e.g., walls or roof).

$Qr{-}in(i)$ includes two terms of direct sunlight ($Qr{-}direct(i)$) and scattered sunlight ($Qr{-}diffuse(i)$), where Aw is the area of the window and $As(i)$ is the area of the sun shining on surface i AST is the total area of the sun irradiated on the inner surface، $FW{-}I$ is the shape factor of the window to surface I. $Q"direct$ is the radiant heat entering from the window caused by direct sunlight per unit area and $Q"diffuse$ is the radiant heat entering from the window caused by scattered sunlight per unit area. The sum of $Q"direct$ and $Q"diffuse$ represents the total radiant energy of the sun per unit area of the window and is displayed as below.

The total solar radiation entering through the window is given by equation 3.

$$Q"s = Q"diffuse + Q"direct \quad (3)$$

In the equations of radiation from the window, the direct radiation is assumed to be negligible; therefore, only scattered radiation enters the room. $Qr\!-\!out(i)$ is also the heat radiation of the sun on the outer surface of the outer wall and is obtained according to the following relationship: In the calculations for the internal levels of the building, ، $Qr\!-\!out(i)$ is considered equal to zero.

The equation for calculating the external surfaces of the building is Shown in equation 4.

$$Qr - out(i) = Q"s.Ai \quad (4)$$

In addition to the internal surfaces, an equation must be written for the air as well.

The calculation equation for the internal levels of the building is Shown in equation 5.

$$minf\ .Cp,air(Tair - Tinf) = \sum_{i=1}^{N} hiAi\ (Ti - Tair) \quad (5)$$

where $minf$ and $Tinf$ are the mass flow rate and the temperature of the air entering the building, respectively.

Convection and transfer of heat are shown in equation 6.

$$Q = h * A * \Delta T \quad (6)$$

(Q) heat transfer rate (Watts)
(h) heat convection coefficient (watts per meter degrees Kelvin or Celsius)
(A) Cross-sectional area (square meters)
(ΔT) temperature change (Kelvin or Celsius)

The equation of conduction mechanisms is shown in equation 7.

$$Q = k * A * (\Delta T / d) \quad (7)$$

(Q) heat transfer rate (watts)
(k) coefficient of thermal conductivity (watts per meter per degree Kelvin)
(A) Cross-sectional area (square meters)
(ΔT) temperature change (Kelvin or Celsius)
(d) Thickness of the object (meters)

The next step, after calculating the air temperature and the temperature of the interior surfaces of the room, is to calculate the average thermal sensation of the room's occupants. For this purpose, the Finger model has been used. In the Finger model, there are seven important and effective parameters for thermal comfort, which are:

1. Metabolic rate
2. Amount of clothes
3. The amount of activity
4. Dry temperature
5. Average radiation temperature
6. Air flow speed
7. Relative humidity

The first three parameters are related to human factors, and the other four parameters are environmental factors. Finger has presented a relation that expresses the mentioned seven parameters in the form of one parameter.

Metabolic rate equation given by equation 8.

$$PMV = (0.303e^{-0.036M} + 0.028)(M - W) - 3.05 \times \{10\}^{\{-3\}[5733 - 6.99(M-W) - Pa]} - 0.42[(M - W) - 58.15] - 1.7 \times \{10\}^\wedge\{-5\} \times M(5867 - Pa) - 0.0014M(34 - Ta) - 3.96 \times \{10\}^\wedge\{-8\} \times Fci\,[((tci + \{273\}^\wedge 4) - \{Tmrt\}^\wedge 4] - fcihc\,(tci - ta) \quad (8)$$

Which is the average radiation temperature in the Finger relationship ، $Tmrt$ and Tci is calculated as shown in equation 9 and 10.

$$Tmrt^{\,4} = T1^4\,FP - 1 + T2^4\,FP - 2 + Tn^4\,FP - N \quad (9)$$

and

$$Tci = 35.5 - 0.028(M - W) - 0.155\ Ici\ \{3.96 \times 10^{-8}\ fci\,[((tci + 273^4) - Tmrt^4\,] + fcihc\,(Tci - Ta)\} \quad (10)$$

The terms $FP\!-\!1$ to $FP\!-\!N$ are the visibility coefficients of the human body with each side surface. These values can be calculated according to the situation of the people in the house and also their situation, whether they are sitting or standing. The value of PMV is between -3 and +3, and according to ASHRAE installation instructions, any integer between these two values somehow expresses the thermal feeling of the building occupants from the environmental conditions.

5. Research Methodology

Given the nature of the data, this research falls into the quantitative category. Since it measures the energy loss variables by varying the types of building envelope materials and thermal insulations used, it employs a correlational approach.

Considering that the goal of this study is to improve behaviors, methods, materials, and insulation used in construction, leading to the development of practical knowledge in the construction industry, it qualifies as applied research.

5.1. Software Used

For this research, Design Builder software version 6.1.0.006 was utilized.

Design Builder Software

Design Builder software facilitates building modeling from various aspects, including building physics (construction materials), architectural design, heating and cooling systems, lighting systems, and more. Apart from modeling heating and cooling loads, it dynamically simulates various energy usages in buildings, such as heating, cooling, lighting, appliances, and domestic hot water. Additionally, it can model day lighting and even CFD (Computational Fluid Dynamics). Other capabilities include natural and mechanical ventilation modeling, thermal comfort assessment in indoor spaces, and energy gains/losses from different building components. The results of these simulations can be extracted for the entire year, specific months, daily, and even hourly. Furthermore, the results can be obtained for the entire building, different floors, and individual spaces. A special feature of this software is the ability to present modeling results in the form of diagrams or tables, which can be useful for subsequent analyses.

5.2. Case Study Sample

The case study in this research involves a five-story residential building located in Tehran. The first floor serves as a parking area, while the other four floors are residential units. Each floor contains one apartment unit with an approximate area of 100 square meters. Each apartment includes two bedrooms, an open kitchen, a living room, a bathroom, a toilet, and a balcony. The floor plan zoning is depicted in Figure 4, with the building oriented to the south, where the living room and kitchen are on the north side and the bedrooms are on the south side. The land area is 250 square meters, with an occupancy area of 150 square meters. Exterior views of the building are shown in Figures 5A, 5B.

Building Components:

Roof (Top Layer) Defined with 5 layers:

1. First layer: Bituminous waterproofing (a protective polymer layer based on bitumen and synthetic fibers) with a thickness of 3 mm.
2. Second layer: Cement plaster with a thickness of 2 cm.
3. Third layer: Concrete foam with a thickness of 20 cm.
4. Fourth layer: Reinforced concrete with a thickness of 20 cm.
5. Fifth layer: Gypsum and clay with a thickness of 2 cm.

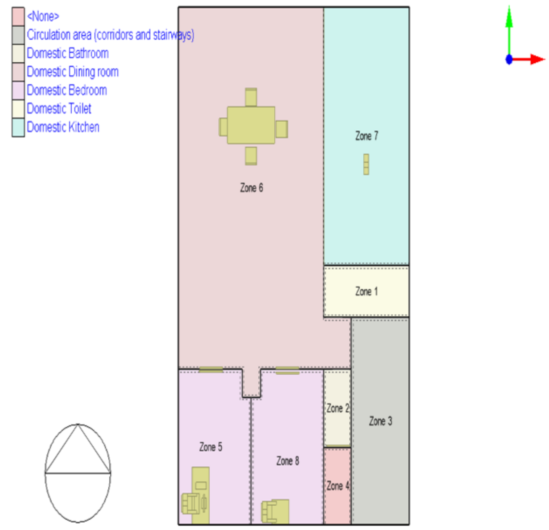


Fig. 4. Building Plan and Zoning

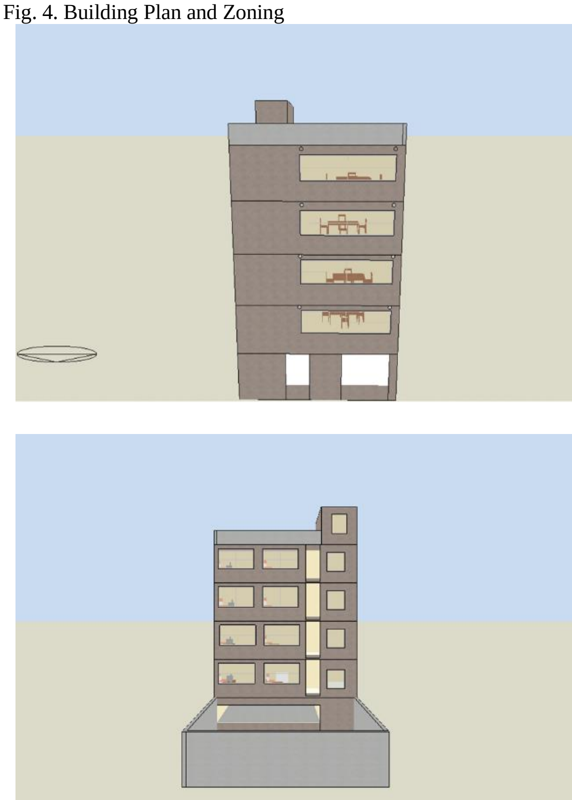


Fig. 5.a) Northern Facade of the Building. b) Southern Facade of the Building

Interior Walls (3 layers):

1. First layer: Gypsum and clay with a thickness of 2 cm.

2. Second layer: Lightweight aerated concrete blocks with a thickness of 10 cm.
3. Third layer: Gypsum and clay with a thickness of 2 cm.

Floor (Parking Level, 4 layers):

1. First layer: Granite stone with a thickness of 3 cm.
2. Second layer: Cement plaster with a thickness of 2 cm.
3. Third layer: Hand-compacted soil with a thickness of 20 cm.
4. Fourth layer: Reinforced concrete with a thickness of 1 meter.

Intermediate Floors and Ceilings (5 layers):

1. First layer: Ceramic tiles with a thickness of 1 cm.
2. Second layer: Cement plaster with a thickness of 2 cm.
3. Third layer: Concrete foam with a thickness of 10 cm.
4. Fourth layer: Reinforced concrete with a thickness of 20 cm.
5. Fifth layer: Gypsum and clay with a thickness of 2 cm.

Exterior Walls (Four Layers):

1. A 2 cm cement plaster layer.
2. A 15 cm AAC block.
3. The variable insulation layer (depending on the scenario).
4. A 2 cm gypsum finishing layer.

Windows (30% of wall area):

1. Double-glazed windows (2 layers of 3 mm clear glass with a 6 mm air gap).
2. UPVC frames without external shading, but with internal roller blinds made of aluminum.

Natural Ventilation:

1. Each unit has two non-mechanical ventilation openings with roller blinds, circular, and a diameter of 10 centimeters.

Lighting:

1. All lighting is LED, and external façade lights have sensors, operating for 12 hours.

Heating and Domestic Hot Water:

1. Gas-based heating and domestic hot water system (one unit per zone).
2. Cooling system: Water-cooled air conditioning with electricity consumption.

Unit Zoning:

Each unit is divided into the following zones:

1. Living room
2. Open kitchen
3. Two bedrooms
4. One toilet
5. One bathroom
6. One balcony connected to one of the bedrooms.

Occupancy:

Each unit accommodates 4 people.

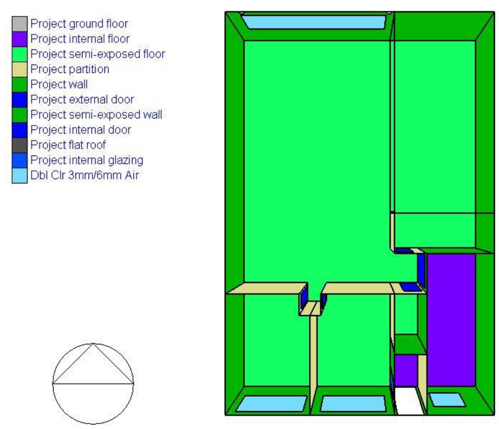
Weather Data:

Weather data for the region was provided to the software via a file.

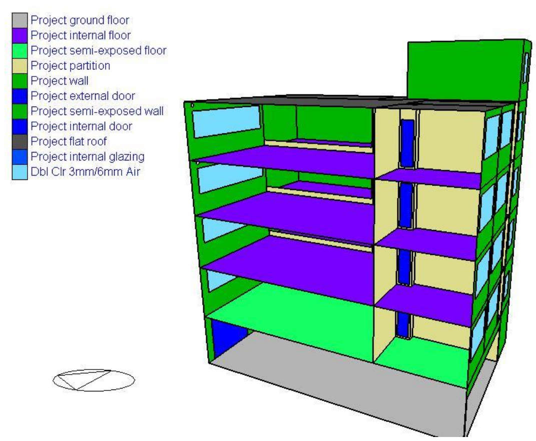
The geographical location of this building is at 68.35° latitude and 32.51° longitude. The building's elevation above sea level is 1191 meters. The prevailing wind direction is from west to east, with an average speed of 11.9 meters per second. Weather simulation data from Tehran's Mehrabad Airport has been used for the analysis.

The heating system in each unit consists of wall-mounted gas heaters and radiators. Each unit has five radiators installed. The hot water supply for each unit also comes from the same system, while the cooling system relies on electricity.

Regarding the structural elements, they are categorized based on their controlled or uncontrolled exposure and various types, as shown in Figure 6.a and 6.b.



a)



b)

Fig. 6.a) Building surfaces and openings. b) Building surfaces and openings

6. Research Steps

1. Data Collection:

Gather architectural, structural, electrical, and mechanical plans for the studied building.

2. Weather Data Preparation:

Compile relevant weather information.

3. Building Use Definition:

Specify the intended use of the building.

4. Building Model Creation:

Develop a model of the building.

Define zones within each unit.

5. Zone Definition:

Assign specific uses to each zone.

6. Material Definitions and Structural Elements:

Define building materials and structural components.

7. Opening Definitions:

Specify openings (doors, windows, etc.).

8. Lighting Definitions:

Define lighting systems and their intensity.

9. Heating and Cooling System Definition:

Describe the heating and cooling systems used in the units.

10. Model Simulation:

Simulate the building model.

11. Output Compilation:

Collect simulation results in a table.

7. Validation

Fathalian and Kargar Sharifabad (2019) in research titled Investigating the effect of different energy optimization strategies in building energy classification using design builder software and Zomorodian and Tehsil Doost (2019) in research titled Validation of energy simulation software in buildings: with an experimental and comparative approach. Validation of two energy simulation software programs, Eco Tech and Design Builder. Witt et al. (2001), Heninger et al. (2003), and Gatti (2003) have each investigated the validity of Energy Plus software in separate research. In all the above research, the validity and correctness of the results of these software programs have been confirmed. Also, by studying the results of the following tests, which are based on different standards, you can be sure of the accuracy of the results and outputs of the Design Builder and Energy Plus software.

- EnergyPlus Testing with ANSI/ASHRAE Standard 140-2001

- EnergyPlus Testing with HVAC BESTEST Part 1 - Tests E100 to E200

- DesignBuilder v6 Compliance With ANSI/ASHRAE/ACCA Standard 183-2007

- ANSI/ASHRAE Standard 140-2017 Building Thermal Envelope and Fabric Load Tests DesignBuilder v6.1 with EnergyPlus v8.9 27 Jan 2021

- ANSI/ASHRAE Standard 140-2017 Space-Cooling Equipment Performance Analytical Verification Tests AE101 to AE445 DesignBuilder v6.1 with EnergyPlus v8.9 27 Jan 2021

- ANSI/ASHRAE Standard 140-2017

- Space-Cooling Equipment Performance Analytical Verification Tests CE100 to CE200 DesignBuilder v6.1 with EnergyPlus v8.9 27 Jan 2021

- ANSI/ASHRAE Standard 140-2017 Space-Heating Equipment Performance Tests

- HE100 to HE230 DesignBuilder v6.1 with EnergyPlus v8.9 27 Jan 2021

8. Findings

This research investigates the impact of using insulation layers in external building walls and compares energy consumption in different scenarios. To better understand this, we will analyze the energy consumption of a building over a one-year operational period, using examples of software output. For instance, Table 1 shows energy consumption broken down by consumption sector, and Table 2 shows energy consumption broken down by energy type.

Table 1.
Energy Consumption Categorized by Usage

Fuel Breakdown (Run period: 1 Year)	
Room Electricity	9543.45 (kWh)
Lighting	10364.7 (kWh)
Heating	4346.79 (kWh)
Cooling (Electricity)	14196.07 (kWh)
DHW (Gas)	17658.32 (kWh)
Exterior lighting	384.85 (kWh)

Table 2.
Energy Consumption Categorized by Type of Energy

Fuel Totals (Run period: 1 Year)	
Electricity	34489.06 (kWh)
Gas	22005.12 (kWh)

The building materials used for the construction of 15-centimeter-thick external walls are autoclaved aerated concrete (AAC) blocks. The layering of the external wall is shown in Figure 4.

A total of 10 different scenarios are defined using 9 distinct insulation layers. These scenarios are identified using coding. In all scenarios, the interior wall finish is defined as a 2 cm plaster layer, marked with the letter G. The insulation layers placed on the internal side before plastering include cork (C), coconut pith (CP), fiberglass

Table. 3.
Energy Consumption by Scenario

Scenario	Heat Loss	Electricity Consumption (kWh)	Gas Consumption (kWh)	Total Energy Consumption (kWh)
G-0-AAC-C	-7700.10	34489.06	22005.12	56494.18
G-CP-AAC-C	-7312.93	34359.80	21575.89	55935.69
G-C-AAC-C	-7131.40	34297.39	21394.72	55692.11
G-GW-AAC-C	-7133.28	34293.54	21397.01	55690.55
G-PW-AAC-C	-7530.16	34440.87	21814.43	56255.30
G-PS-AAC-C	-7134.02	34301.79	21398.13	55699.92
G-PU-AAC-C	-6914.18	34241.50	21182.53	55424.03
G-R-AAC-C	-7248.67	34336.88	21510.66	55847.54
G-SW-AAC-C	-7134.04	34304.33	21398.91	55703.24
G-W-AAC-C	-7106.36	34292.33	21369.88	55662.21

Table. 4.
Sorted by Electricity Consumption

Scenario	Heat Loss	Electricity Consumption (kWh)	Gas Consumption (kWh)	Total Energy Consumption (kWh)
G-PU-AAC-C	-6914.18	34241.5	21182.53	55424.03
G-W-AAC-C	-7106.36	34292.33	21369.88	55662.21
G-GW-AAC-C	-7133.28	34293.54	21397.01	55690.55
G-C-AAC-C	-7131.4	34297.39	21394.72	55692.11
G-PS-AAC-C	-7134.02	34301.79	21398.13	55699.92
G-SW-AAC-C	-7134.04	34304.33	21398.91	55703.24
G-R-AAC-C	-7248.67	34336.88	21510.66	55847.54
G-CP-AAC-C	-7312.93	34359.8	21575.89	55935.69
G-PW-AAC-C	-7530.16	34440.87	21814.43	56255.3
G-0-AAC-C	-7700.1	34489.06	22005.12	56494.18

Table. 5
Sorted by Gas Consumption

Scenario	Heat Loss	Electricity Consumption (kWh)	Gas Consumption (kWh)	Total Energy Consumption (kWh)
G-PU-AAC-C	-6914.18	34241.5	21182.53	55424.03
G-W-AAC-C	-7106.36	34292.33	21369.88	55662.21
G-C-AAC-C	-7131.4	34297.39	21394.72	55692.11
G-GW-AAC-C	-7133.28	34293.54	21397.01	55690.55
G-PS-AAC-C	-7134.02	34301.79	21398.13	55699.92
G-SW-AAC-C	-7134.04	34304.33	21398.91	55703.24
G-R-AAC-C	-7248.67	34336.88	21510.66	55847.54
G-CP-AAC-C	-7312.93	34359.8	21575.89	55935.69
G-PW-AAC-C	-7530.16	34440.87	21814.43	56255.3
G-0-AAC-C	-7700.1	34489.06	22005.12	56494.18

wool (GW), plywood (PW), polystyrene (PS), polyurethane foam (PU), rock wool (SW), rice husk (R), and wool (W), as well as a non-insulated option (0). All insulation layers have a uniform thickness of 1 cm. The external finish of the building is defined as ca cement layer with a thickness of 2 cm, marked as (C). To facilitate comparison, the energy outputs of all 10 scenarios are collected in table 3.

Note: In all scenarios, wall systems, openings, structural and non-structural elements, and other variables remain consistent, with the only difference being the insulation layer. For calculation ease, the Design Builder software expresses gas consumption in kilowatt-hours. To determine the cost of gas consumption and convert it to cubic meters, kilowatt-hours are divided by 10.4 (the calorific value of each cubic meter of gas).

In table 3, the first column lists the coded scenarios. The second column shows heat loss from the external envelope, the third column indicates total electricity consumption for the building, the fourth column presents annual gas consumption during the operational phase, and the fifth column displays total energy consumption. Sorting this table by the metrics mentioned results in tables 4, 5, and 6.

Table. 6
Sorted by Total Energy Consumption

Scenario	Heat Loss	Electricity Consumption (kWh)	Gas Consumption (kWh)	Total Energy Consumption (kWh)
G-PU-AAC-C	-6914.18	34241.5	21182.53	55424.03
G-W-AAC-C	-7106.36	34292.33	21369.88	55662.21
G-GW-AAC-C	-7133.28	34293.54	21397.01	55690.55
G-C-AAC-C	-7131.4	34297.39	21394.72	55692.11
G-PS-AAC-C	-7134.02	34301.79	21398.13	55699.92
G-SW-AAC-C	-7134.04	34304.33	21398.91	55703.24
G-R-AAC-C	-7248.67	34336.88	21510.66	55847.54
G-CP-AAC-C	-7312.93	34359.8	21575.89	55935.69
G-PW-AAC-C	-7530.16	34440.87	21814.43	56255.3
G-0-AAC-C	-7700.1	34489.06	22005.12	56494.18

9. Conclusion

The findings indicate that the best thermal insulation layer for reducing energy consumption is polyurethane foam. By comparing Tables 4 and 5, it is evident that the rankings of scenarios G-GW-AAC-C and G-C-AAC-C differ in terms of electricity and gas consumption. Specifically, using glass wool insulation results in greater electricity savings, whereas cork insulation leads to higher gas savings.

Analyzing Tables 4, 5, and 6 makes it clear that scenario G-0-AAC-C, which represents the case without using any thermal insulation layer, ranks last.

- Not using a thermal insulation layer results in the loss of 247.56 kilowatt-hours of electricity in one year.
- Not using a thermal insulation layer results in the loss of 79 cubic meters of gas in one year.
- Not using a thermal insulation layer results in the loss of 1070.15 kilowatt-hours of total energy in one year.

The data emphasize the critical role that thermal insulation plays in reducing energy consumption and highlight the considerable energy-saving potential of polyurethane foam in particular. This insight underscores the importance of selecting the appropriate insulation layer to optimize energy efficiency in buildings.

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