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Research Article

Thermal transmittance analysis in Tehran residential units with an approach to building roof insulation simulation

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ABSTRACT

This study focuses on the impact of building thermal insulation on the energy consumption issue, which highlights the importance of reducing energy usage through efficient heat transfer management, especially in building roofs. The reviewed literature was categorized according to thermal transmittance, material properties, and simulation techniques. The identified gap is the lack of a numerical framework for insulation materials in building construction in Iran, which architects and building designers can use. The main method of investigation is a simulation-based approach using Design Builder software that follows the procedure from building modeling to the configuration of roof layers. Eight types of thermal insulation layers were simulated to evaluate their influence on improving the thermal balance of the roof. This research emphasizes a common roof detail used in Tehran residential buildings. This study evaluates the heat balance factor to identify the most suitable frameworks based on the insulation type. The findings of this study present a numerical framework that categorizes roof insulation materials and their thickness in terms of enhancing the thermal performance in Tehran's buildings, which is a considerable result of this study. Based on the results, architects and building designers in Tehran have the possibility to use the framework in their first design phase, which can choose the most efficient insulation based on their project calculations. This is counted as the novelty point of the current research. As a numeric point, high-rate insulations like polystyrene (HFC) and polyurethane demonstrate remarkable flexibility in enhancing thermal balance with coefficients ranging from 0.03 kW, to +0.06 kW which is considered based on the thickness increasing.

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INTRODUCTION

Excessive urbanization and human activities in cities have led to climate change and environmental damage. These effects include loss of biodiversity, ozone depletion, acid rain, global warming, the heat island (UHI) effect, and polluted air and water. [1] [2]. As a common opinion, it is accepted that reducing usage of energy is an essential factor

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for addressing climate change and fostering development. Buildings account for 40% of energy consumption, based on the conducted research, which has a significant effect on the environment and our energy resources [3,4].

An essential point to achieve optimal energy usage in one aspect and a comfortable indoor temperature in another aspect is designing the building facade in an efficient manner [5]. Retrofitting an energy-efficient building has some advantages, including a reduction in heating demand and an overall decrease in energy consumption, while providing the appropriate internal temperature condition [6]. In relation to the previously described topic, a system that improves the heat transmission of the building components would reduce the amount of thermal energy required in residential units.

This considerable point regarding building components states that one area that is neglected in Tehran's building design process is the examination of the various thermal insulation effects of building components. Although Tehran's construction industry uses a wide range of thermal insulation materials, many building designers do not consider this issue because Tehran's thermal insulation materials are not properly classified scientifically. This stems from a lack of adequate research on the material's role in Tehran's building typology.

Given the number of residential buildings in this city, this topic can therefore be regarded as a research gap because, in the long run, ignoring it will result in a loss of energy capital and large economic consequences for the city's residents. As a result, the development of a systematic framework for the class of thermal insulation materials found in building components is both useful and scientific. While there are many issues with examining the impacts of thermal insulation in building components within the Tehran building typology, it would also be beneficial to give Iranian architects, particularly those working in Tehran, a new framework for building design that, depending on their characteristics, can select the optimal thermal insulation for. This paper outlines the primary objectives of this study.

Literature Review

Building thermal transmittance

An investigation developed a material with minimal cloudiness and excellent light transmission to support the production of energy-efficient building supplies [7]. Another research conducted in 2020 employed artificial intelligence methodologies to forecast thermal transmittance values, thereby augmenting the automation of thermal transmittance characterization operations [8]. Another study emphasized the importance of transmittance in assessing the insulating properties of glazing materials, and its relevance to window technologies has been highlighted (Aguilar-Santana et al., 2020). In another investigation, the total U-value of a ventilated wall assembly was analyzed using an experimental method by considering the thermal resistance of the ventilated air space and the overall thermal transmittance of the wall assembly [9]. A study in 2021 investigated the impact of temperature on the heat transfer of window insulating glass units (IGUs), focusing on their influence on IGUs equipped with Low E coatings [10]. In 2021 the researcher suggested an inverse model-based technique that shows agreement with physics-based models for the characterization of envelope thermal transmittance and air presence using historical data [11]. Another study measured the impact of moisture transfer on the thermal performance of building nodes in high-temperature and high-humidity settings and showed that moisture transfer increased the thermal bridge influence and overall thermal transmittance [12]. In a study in 2022, researchers experimentally investigated techniques for measuring the thermal transmittance in building envelopes, and offered information on the hot box test, heat flow meter, and infrared thermography methods [13]. A researcher did a research that concentrated on measuring and tracking the thermal performance of Mediterranean homes over the winter, highlighting the significance of thermal transmittance in buildings envelopes for maintaining thermal comfort [14]. Another researcher presented an innovative data-gathering methodology that addressed issues with accuracy and cost by utilizing an Arduino transmittance-meter to overcome constraints in evaluating the thermal characteristics of building envelopes [15]. Based on the R-value definition, it indicates the capacity of the insulation material to resist heat flow. It is noteworthy that R-values can change depending on the direction in which heat flows through the product, and a higher R-value provides superior thermal performance [16]. The U-value is defined as the reciprocal of the R-value (1/R). The heat conduction is improved with a greater U-value [17].

Roof thermal transmittance

In another study entitled "Thermal Transmittance (U-value) Evaluation of Innovative Window Technologies, future cities and environment", researchers highlighted the importance of thermal transmittance in assessing the performance of glazing materials [18]. Kumar and colleagues highlighted the correlation between the transmittance value of the residential envelope, thermal transmittance of the roof, and visible light transmittance. This study specifically examines the energy efficiency of residential buildings in Kolkata [19]. Gunn and colleagues, in a research entitled "A multi-year comparative analysis of green and conventional roof thermal performance under temperate climate conditions," expressed a significant reduction in heat transfer when comparing the thermal efficiency of conventional roofs and green roofs in Ottawa, Canada (Gunn et al., 2021). In another study conducted in 2021, a model for radiative roof cooling was created to examine the net cooling capacity and equilibrium temperature of the building roofs. Research has revealed that the use of radiative roof cooling can substantially reduce temperatures [20]. In an investigation published in Case Studies in Thermal Engineering journal, researchers performed a hydrothermal investigation on a renovated double-skin flat roof and found that the thermal transmittance was greater during the heating season than under steady-state conditions [21]. In another study entitled "Comprehensive evaluation of thermal and energy performance of radiative roof cooling in buildings," researchers developed a novel building material made from bacterial cellulose that can radiate cooling. It also has the possibility of alternating between states of transparency and opacity. This material has the capacity to enhance building energy efficiency by protecting buildings against solar energy radiation and regulating thermal conditions (Chen et al., 2020). An inquiry into research highlights the importance of thermal transmittance in building component energy efficiency. It also demonstrates the various factors that affect the thermal properties and energy efficiency of a building.

Building thermal transmittance simulation

Simulating the thermal transmittance of a building is important for evaluating its thermal and energy efficiency. Guattari and colleagues conducted a study on a roof-lawn system to ascertain the thermal characteristics of the roof for energy modeling (Guattari et al., 2020). Another study developed a methodology for measuring the impact of design elements on building performance, with a specific focus on the importance of window and roof thermal transmittance [22]. An investigation in 2020 discussed the growth of filamentous materials, and the filamentous materials analyzed in structures with low thermal transmittance, which shows a high probability of thermal bridge growth which could be impactful on building thermal performance [23]. Based on research in the Journal of Building Engineering, the researcher analyzed the effect of air infiltration rates on the thermal transmittance of the building envelope and proposed an infiltration factor to modify the formulas as a method to control heat energy usage (Mathur and Damle, 2021). In another study in 2021, the investigators examined a novel metric for evaluating the heat resistance of flat, nontransparent architectural elements during the summer season. During the investigation, two essential factors were considered: thermal insulation and solar reflectance (Akbari et al., 2021). In an article entitled "Numerical simulation of the effect of bamboo composite building envelope on summer overheating problem" a numerical simulation was conducted to assess the effect of bamboo composite building envelopes on summertime overheating quantities. The study emphasized the importance of ventilation and shade in mitigating the influence of this issue [24]. Serroni et al. developed an Internet of Things (IoT) thermography system to continuously monitor the thermal transmittance of walls in real time in order to identify and address any inefficiencies in the exterior of a building (Serroni et al., 2023).

Literature critical analysis

In accordance with recent research, focusing on thermal transmittance shows a relationship between building energy consumption and energy efficiency.

In one aspect, light transmittance materials, predictive models based on artificial intelligence, and precise measurement methods such as heat flow meters as a device and infrared method development, and the relationship between thermal transmittance and comfort, especially in Mediterranean houses in another aspect, are key areas of the reviewed literature.

Thermal simulation of insulation materials using Arduino and its analysis of further building envelope performance are also expressed as a considerable assessment of building energy transmittance.

Although several studies have been conducted in the field of thermal energy transformation in building components, there is a lack of research in the field of thermal insulation available in the Iranian market in the configuration of a certain roof typology in Tehran. In other words, although thermal insulation is used in the designed roofs of many buildings in Tehran, their thermal properties have not been accurately identified. This gap is significant because of the indeterminacy of the difference between each type of thermal insulation (from the point of view of thermal transfer coefficients) and their ratio with the thickness of this layer in the configuration of the roofs. Specifically, the gap affects the process of building design, which is being conducted by architects who carry out the calculation procedure in the climate of Tehran. Because of this issue, while choosing the right thermal insulation should be based on the properties of heat transfer and the appropriate thickness of its layer, this process is currently only based on the thermal insulation inventory in the Tehran building industry market. Therefore, the subsequent negative consequences of the loss of thermal energy in the building appear. Therefore, the aim of this study is to fill the aforementioned research gap by examining the existing types of thermal insulation as well as the roof typology that is generally designed in the city of Tehran, and this will be done by extracting the exact thermal characteristics of the roof thermal insulation layers in the urban climate of Tehran. Categorizing the thermal insulation of the Tehran building industry market based on thermal properties will shape a numerical framework that would help architects and building designers to choose the most efficient roof insulation for a specific project when designing the first phase of a building. The development of this framework is counted as the main novelty point of the current research to solve the mentioned issue and filling the research gap.

MATERIALS AND METHODS

According to the investigation title, a suitable research method that covers different aspects of building roof thermal transmittance is significant. To achieve this goal, the main approach is simulation-based, and it is employed using Design Builder software. This section demonstrates the research design based on the aforementioned case study and follows a step-by-step methodological process.

Research Procedure

The simulation was conducted in a controlled environment to accurately evaluate the thermal efficiency of building roofs under specific climatic conditions in Tehran. In addition, it enables a detailed analysis of roofs with different insulation layers. Design Builder version 6.10.006 and Energy Plus version 8.9 are widely acknowledged for their effective modeling tools and energy simulation capabilities. The study was conducted according to the following steps.

Step 1. building model creation: The initial phase involves creating detailed building models using the engineering drawing software Autodesk AutoCAD version 2020. Then, modeling was conducted using Design Builder. Figures 1-2 show a 2D model drawn using the AutoCAD software. After drawing the two-dimensional plan, it is important to attribute the zones. Based on this, Zones 1–5 are determined in Figure 2. In all determined zones of a residential unit, Zone 1 is the specific zone in which the simulation of the roofs will be performed. The chosen part of this case study was Zone 1.

Step 2. material properties assignment: According to the aforementioned case study, the simulation process was conducted on one specific type of building roof with various insulation layers. In this section, the properties of the selected roof material are assigned to the software element. Therefore, in accordance with the roof type in this study, there is one specific roof detail (Fig. 3 and 4) in which the insulation layer is changed. Therefore, in Design Builder, the new roof is designed based on its layers and thickness, as shown in Table 1.

Eight types of insulation layers were chosen in Design Builder, and they were customized in ten models based on ten thicknesses, and ten types of simulation were defined for each roof type.

It is noteworthy that the properties of the roof layers have been introduced. The layer thickness and specific thermal properties of the materials, such as the R-value and U-value, will be assigned based on standard values and manufacturer specifications. Table 1 lists the specific roofs, which are configured with various insulation layers, and there are eight roof configurations (Roof types 1-8) based on these eight types of insulation.

Figure 1. Building plan zoning.

Figure 2. Building plan 2d model zoning.

Table 1. Eight types of roof configuration layering properties

	Material	Thickness (m)	R-Value (m2-K/W) of roof type	U-Value (W/m2-K) of roof type
Roof type 1	Asphalt	0.02	1.73 – 4.73	0.578 – 0.211
	Concrete, cast-roofing slab	0.2		
	Insulation – Polystyrene – HFC	0.01 – 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 2	Asphalt	0.02	1.692 – 4.329	0.591 – 0.231
	Concrete, cast-roofing slab	0.2		
	Insulation – Polystyrene – CO2	0.01 – 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 3	Asphalt	0.02	1.519 – 2.020	0.658 – 0.495
	Concrete, cast-roofing slab	0.2		
	Insulation – Polyvinyl Chloride	0.01 – 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 4	Asphalt	0.02	1.675 – 4.166	0.597 – 0.240
	Concrete, cast-roofing slab	0.2		
	Insulation – Mineral Fiberglass	0.01 – 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 5	Asphalt	0.02	1.647 – 3.891	0.607 – 0.257
	Concrete, cast-roofing slab	0.2		
	Insulation – Fiberglass	0.01 – 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 6	Asphalt	0.02	1.610 – 3.521	0.621 – 0.284
	Concrete, cast-roofing slab	0.2		
	Insulation – Rock wool	0.01 – 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 7	Asphalt	0.02	1.453 – 1.953	0.688 – 0.512
	Concrete, cast-roofing slab	0.2		
	Insulation – Silicon	0.01 - 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		
Roof type 8	Asphalt	0.02	1.633 – 3.773	0. 612 – 0.265
	Concrete, cast-roofing slab	0.2		
	Insulation – Polyurethane	0.01 - 0.1		
	Plaster board	0.02		
	Bldg. paper felt	0.005		

Step 3. climate zone definition: Simulations will be conducted for Tehran climate zones, considering specific temperatures and humidity. Table 3 (environmental control) shows the details, which are defined in the Design Builder software. First, the heating and cooling temperatures were determined in accordance with the Tehran indoor comfortable temperature (4.1 and 4.2). Then, the importance of humidity was noted (4.3), and it was divided into two

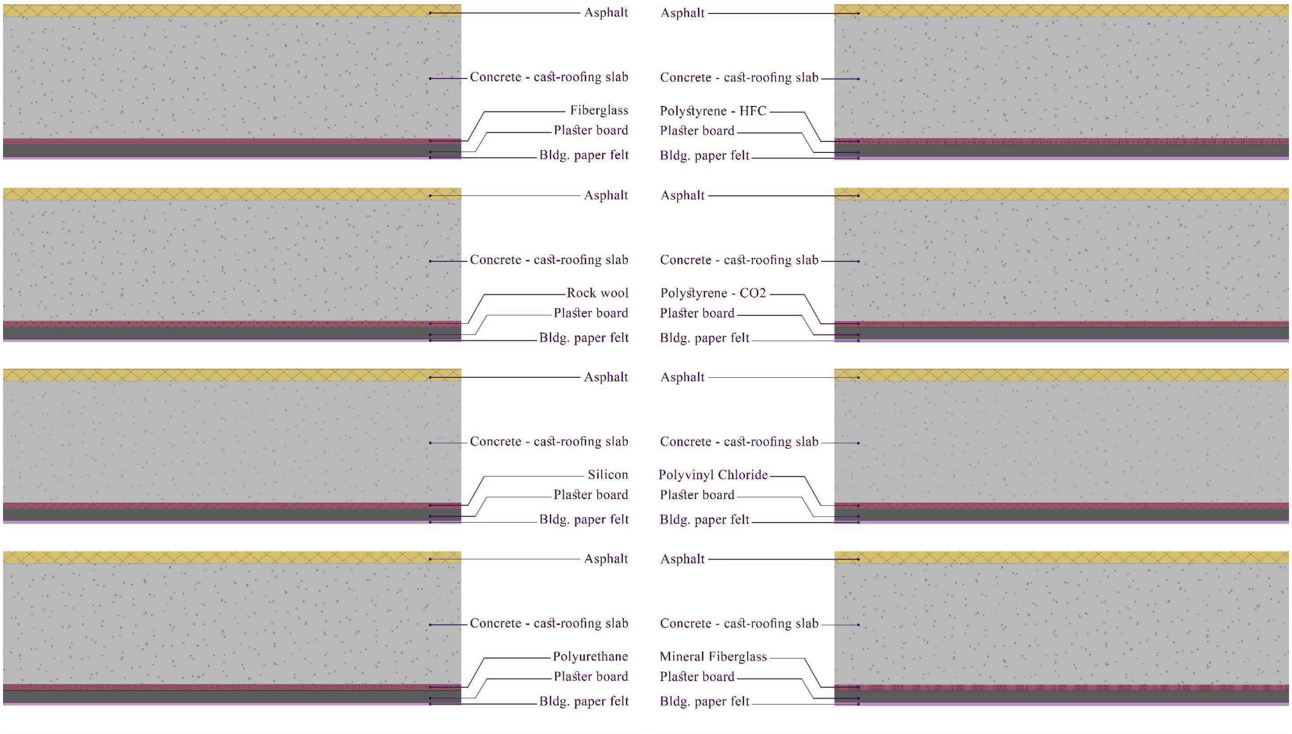


Figure 3. Roof configuration layering - part one

categories: RH humidification and RH dehumidification. The next three factors are ventilation, fresh air, and lighting. For ventilation, the temperature factor was set to 24 °C. which is defined as the basic temperature for the ventilation system to be activated or deactivated. The quantity of fresh air is determined based on the number of people in the area. Finally, the illumination of the lighting was defined as 150 lx.

Step 4. insulation layer configuration: Multiple simulations were performed for different insulation layer configurations. The major insulation differences include variations in the type, thickness, and placement of the insulation materials. As shown in Table 1, different types of insulation layers and their thicknesses are expressed, and these types were defined in the Design Builder software. Eight types of insulation with various thicknesses were defined as preliminary data. The thermal properties of each insulation layer were defined based on the standards and codes defined in Design Builder. It is noteworthy that the R-value and U-value quantities in Table 1 are presented for each roof type, which was achieved based on the simulation procedure.

Step 5. optimization process: Based on layer analysis, an optimization process is implemented to determine the most effective combination of insulation layers to achieve optimal thermal performance.

Research Analysis

In the analysis method of this research, after the determination of the simulation results related to eight types of roof configurations, the effect analysis of each type of thermal insulation used in the configurations is determined. In other words, according to the quantity of positive change that each of the thermal insulations has on the equilibrium coefficient of the roof, a classification will be made so that among the proposed configurations, the most efficient and the most appropriate thickness of the thermal insulation layer will be determined according to the Tehran climate condition.

The zoning of the plan is determined based on the functional classification of each indoor space within a residential unit, as shown in Figures 1 and 2 as a 2d model. Zone 1 is selected as experimental space for this investigation, which is designated for residential use. The chosen zone, functioning as a space, consists of components such as ceilings, floors, and walls, each made of materials with certain thermal qualities.

As a considerable point, there are several variables in the simulation procedure of this article, which include:

- **Independent variable**: As determined by applying changes in the insulation layer of the roof typology in Table 1, the type of thermal insulation layer is determined as an independent variable of this simulation because, based on the author's decision and available thermal insulation, it is changed in eight modes.

- **Dependent variable**: According to the changes that occur in the independent variable, the thermal properties of the roof typology would change. This property is presented in the Results section as a roof heat balance, which

Table 2. Construction template properties

1.Construction template	
Template	Medium weight, moderate insulation
External wall	**Variable**
Below grade walls	Brick/brick wall (insulated to 1995 regs)
Flat roof	Flat roof U-value = 0.25 W/m^{2}K
Pitched roof (occupied)	Clay tiles (25mm) on air gap (20mm)
1.1. Semi-exposed	
Semi-exposed ceiling	Roof space floor insulation 50mm
Semi-exposed floor	External floor-Energy code standard
1.2. Floors	
Ground floor	Ground floor slab
External floor	External floor
1.3. Sub-surfaces	
Walls	100mm concrete slab
Internal	100mm concrete slab
Roof	100mm concrete slab
1.4. Internal thermal mass	
Construction	100mm concrete slab
Exposed area (m^2)	0.00

is determined for each thermal insulation according to its thickness. therefore, the roof heat balance was considered as a dependent variable in the simulation process.

- **Control variable**: As described in the research design section, in this research, thermal properties (especially thermal balance) were investigated on a roof typology that is commonly used in many residential buildings in Tehran. In accordance with this, the roof typology used (as shown in Fig. 3,4) is fixed, and only its insulation layer is changed. Therefore, the roof typology in this research is a control variable studied because of changes in the independent and dependent variables.

As shown in Table 1, the selected roof typology layering was explained in eight categories (roof types 1 to 8) according to eight types of thermal insulation (fixed variable). In addition to the layering titles, the thickness of each layer was also expressed. In this regard, the number of 0.01-0.1 has been explained for the thermal insulation layer, and this indicates a change in the thickness of the thermal insulation layer during the simulation process. Therefore, various results are expected based on various types of thermal insulation with varying thicknesses.

Figures 3 show the layering of the roof (based on the Tehran common roof type. First, the difference in the eight designed roofs is in the thermal insulation layers, which are changed according to the types in Table 1, and the effect of their thickness changes was analyzed in the simulation. Another considerable point of the mentioned figure is the layering order, which is fixed.

Table 2 continue

1. Activity Template	
Template	Domestic Lounge
Sector	Residential space
Zone type	Standard
2. Floor Areas and Volumes	
Floor area (m^2)	25.63
Zone volume (m^3)	71.77
3. Occupancy	
Occupancy density (people/m^2)	0.0188
Schedule	Dwell_DomLounge_Occ
3.1.Metabolic	
Activity	Eating/drinking
Factor (Men=1.00, Women=0.85, Children=0.75)	0.90
3.2. Clothing	
Clothing schedule definition	3349
3.3. Comfort Radiant Temperature Weighting	
Calculation type	Zone average
4. Environmental Control	
4.1. Heating set point temperature	
Heating (°C)	21.00
Heating set back (°C)	12.00
4.2. Cooling set point temperature	
Cooling (°C)	25.00
Cooling set back (°C)	28.00
4.3. Humidity control	
RH Humidification set point (%)	10.00
RH Dehumidification set point (%)	90.00
4.4. Ventilation set point temperature	
Natural ventilation	
Indoor main temperature control	+
Min temperature definition	By value
Min temperature (°C)	24.00
Indoor max temperature control	-
4.5. Minimum fresh air	
Fresh air (l/s-person)	10.00
Mechanical ventilation per area (l/s-m^2)	0.00
4.6. Lighting	
Target Illuminance (lux)	150
Default display lighting density (W/m^2)	0.00

As categorized in Tables 2 and 3, the required properties of the simulation in Design Builder are expressed. These properties were defined based on the research case study.

They are divided into two main parts. The first is about the construction properties (Table 2), and the next is about the activity in a specific space (Table 3).

The first part (construction) is divided into a construction template and four subsets (semi-exposed, floors, subsurface, and internal thermal mass). Another part (activity), is divided into four subsets (activity, floor area and volume, occupancy, and environmental control.

RESULTS AND DISCUSSION

In this study, the quantity of roof thermal transfer in a residential unit in Tehran City was being analyzed based on the specifications mentioned in the case study. Considering the variety of thermal insulation materials, a roof typology widely used in Tehran was selected, and eight types of thermal insulation were selected in the layering section, which was the basis of the simulations. In this section, the simulation results are categorized based on the Design Builder reports, and are explained in detail in the tables and Figures.

In this section, the results of the simulations for eight types of thermal insulation are presented. Table 1 lists the types of simulated roofs based on various insulation types. The categories are expressed, and the key factors include insulation type, thickness, heat balance, and heat balance change ratio. The last part of Table 1 presents the thickness-to-thermal balance ratio.

In the first part of Table 4, roof types 1-8, which express the mentioned roof typology with various insulation layers, and the type of thermal insulation is named in the second column. The main variables in this research are the type of thermal insulation in roof layering (second column) and the thickness of the insulation layer as expressed in the third column, which is defined from 1cm to 10cm for each type of thermal insulation.

Roof Heat Balance Classification

According to the classification presented in Table 4, under equal thermal conditions and with the same insulation thickness (one centimeter), the **lowest heat balance** was related to the roof type in which polyvinyl chloride and silicon were used as thermal insulation. This value is equal to -0.43 kW for both of them. In similar circumstances, the **highest heat balance** is related to the roof that uses polystyrene-HFC and polyurethane as thermal insulation, and this value is equal to -0.37 kW for both of them. The most repeated numerical amount in this case is equal to -0.38 kW, which is intended as average value. Regarding the changes in thermal balance changes, each of the eight roofs changed based on the type of thermally used insulation and the thickness of the insulation layer. In accordance with the thickness and heat balance diagrams in Table 4, these changes were different based on the various insulation materials in the eight types of roof comparison. This was also observed in each roof thermal balance. These diversities require a new variable that can be used to measure changes in thermal balance. Therefore, the heat-balance change ratio was defined.

Roof Heat Balance

Based on the requirements mentioned in section 3.1, the rate of heat balance changes was measured for each roof type, and this measurement was categorized as the heat balance change ratio. These quantities are based on the changes that occur in insulation types and thicknesses. In other words, this factor expresses the rate of thermal balance change in each of the roofs in kilowatts. According to this criterion, the rate of change in three types of thermal insulation, including polystyrene (HFC), rock wool, and polyurethane, is equal to 0.23 kW, which is the highest rate of changeability in the samples examined in this study. Therefore, these three types of thermal insulation provide greater flexibility for use with multiple thicknesses. In another aspect, two thermal insulations, including silicon and polyvinyl chloride, have values of 0.10 and 0.11 kilowatts as change rates, which are known as lowest change values in the investigated insulations.

therefore, based on the simulation results presented in Table 1, each roof type is analyzed in this section.

- **Roof type 1 - Insulation – Polystyrene – HFC**

  It is obvious that the change in growth percentage starts from 6 and continues at 4 percent, but it will reduce to 2 and 1 percent. Based on this change rate, most insulation improvements occur at thickness of 2,3, and 4 cm.

- **Roof type 2 - Insulation - Polystyrene – CO2**

  It is obvious that the change in growth percentage starts from 5 and continues at 4 and 3 percent, but it will reduce to 1 percent. Based on this change rate, most insulation improvements occur at thickness of 2,3, and 4 cm.

- **Roof type 3 - Insulation – Polyvinyl Chloride**

  It is obvious, the change in growth percentage starts from 2 and continues at 1 percent. Although this is weak insulation in comparison with the others, the main growth point occurs when the thickness is 2 cm.

- **Roof type 4 - Insulation – Mineral Fiberglass**

  It is obvious that the change in growth percentage starts from 4 and continues at 3 percent, but it will reduce to 2 percent. Based on this change rate, most insulation improvement occur at thickness of 2,3, and 4 cm.

- **Roof type 5 - Insulation - Fiberglass**

  It is obvious that the change in growth percentage starts from 5 and continues at 4 percent, but it will reduce to 1 percent. Based on this change rate, most insulation improvements occur at thickness of 2,3, and 4 cm.

- **Roof type 6 - Insulation – Rock wool**

  It is obvious that the change in growth percentage starts from 6 and continues at 4 percent, but it will reduce to 1 percent. Based on this change rate, most insulation improvements occur at thickness of 2,3, and 4 cm.

- **Roof type 7 - Insulation - Silicon**

It is obvious, the change in growth percentage starts from 1 percent and continues in a similar manner. Although this is weak insulation in comparison with the others, the main growth point occurs when the thickness is 2 cm.

- **Roof type 8 - Insulation – Polyurethane**

It is obvious that the change in growth percentage starts from 6 and continues at 4 percent, but it will reduce to 1 percent. Based on this change rate, most insulation improvements occur at thickness of 2,3, and 4 cm.

Roof Heat Balance Changes Ratio

The last section of Table 4 shows diagrams that were shaped in accordance with the heat balance change ratio. The main considerable point of these diagrams is the relation between the quantity of the heat balance change ratio and the slope of the diagrams. The slope percentage

Table 4. Roof simulation result categories

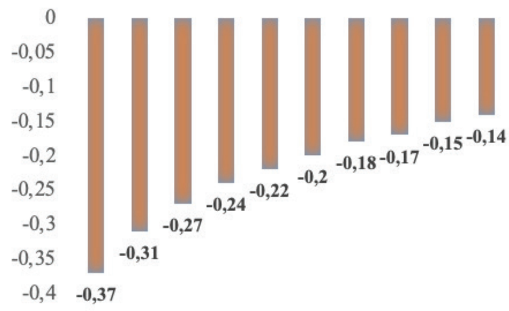
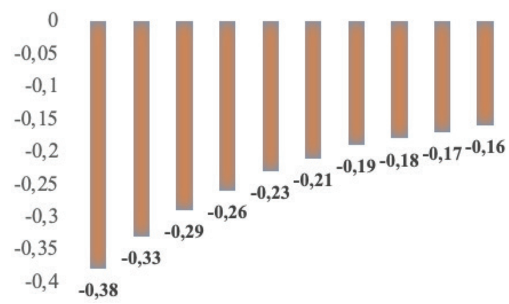
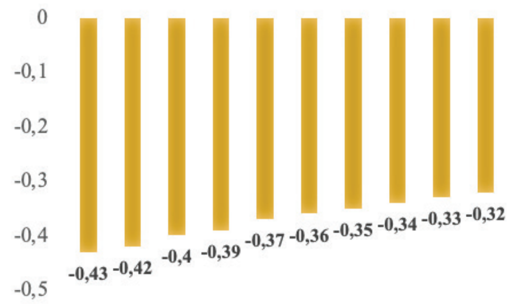
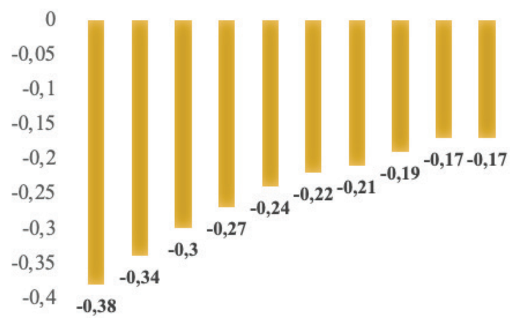
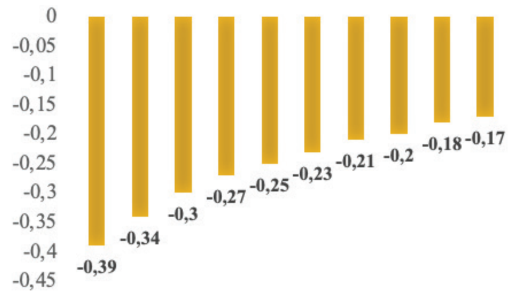
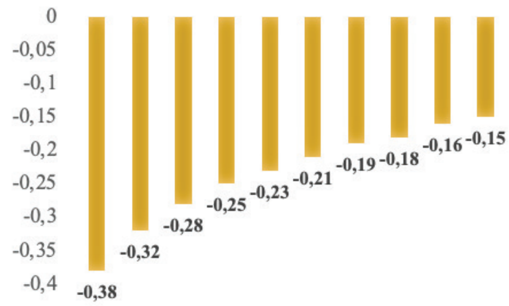
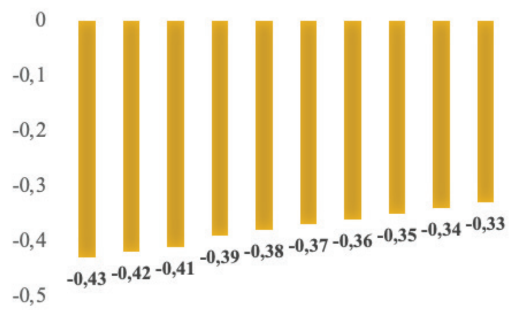
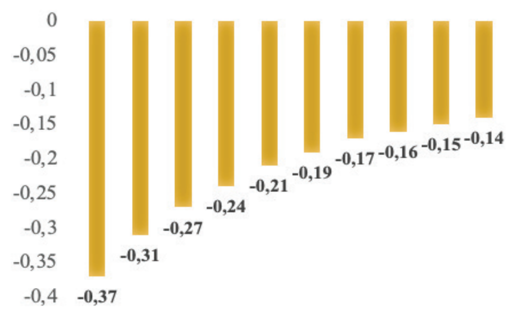
	Insulation	Thickness (m)	Roof Heat balance (KW)	Heat balance change ratio (KW)	Thickness and Heat balance diagram
Roof type 1	Insulation – Polystyrene - HFC	0.01	-0.37	-	
		0.02	-0.31	+0.06	
		0.03	-0.27	+0.04	
		0.04	-0.24	+0.03	
		0.05	-0.22	+0.02	
		0.06	-0.20	+0.02	
		0.07	-0.18	+0.02	
		0.08	-0.17	+0.01	
		0.09	-0.15	+0.02	
		0.10	-0.14	+0.01	
Roof type 2	Insulation - Polystyrene – CO2	0.01	-0.38	-	
		0.02	-0.33	+0.05	
		0.03	-0.29	+0.04	
		0.04	-0.26	+0.03	
		0.05	-0.23	+0.03	
		0.06	-0.21	+0.02	
		0.07	-0.19	+0.02	
		0.08	-0.18	+0.01	
		0.09	-0.17	+0.01	
		0.10	-0.16	+0.01	
Roof type 3	Insulation – Polyvinyl Chloride	0.01	-0.43	-	
		0.02	-0.42	+0.01	
		0.03	-0.40	+0.02	
		0.04	-0.39	+0.01	
		0.05	-0.37	+0.02	
		0.06	-0.36	+0.01	
		0.07	-0.35	+0.01	
		0.08	-0.34	+0.01	
		0.09	-0.33	+0.01	
		0.10	-0.32	+0.01	
Roof type 4	Insulation – Mineral Fiberglass	0.01	-0.38	-	
		0.02	-0.34	+0.04	
		0.03	-0.30	+0.04	
		0.04	-0.27	+0.03	
		0.05	-0.24	+0.03	
		0.06	-0.22	+0.02	
		0.07	-0.21	+0.01	
		0.08	-0.19	+0.02	
		0.09	-0.17	+0.02	
		0.10	-0.17	+0.02	

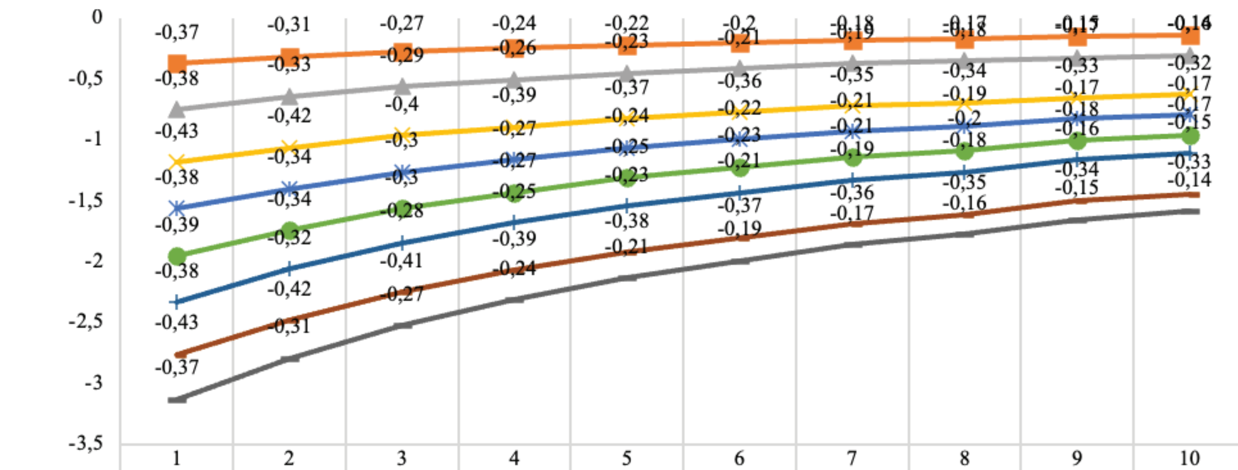
Table 4. Roof simulation result categories (continued)

	Insulation	Thickness (m)	Roof Heat balance (KW)	Heat balance change ratio (KW)	Thickness and Heat balance diagram
Roof type 5	Insulation - Fiberglass	0.01	-0.39	-	
		0.02	-0.34	+0.05	
		0.03	-0.30	+0.04	
		0.04	-0.27	+0.03	
		0.05	-0.25	+0.02	
		0.06	-0.23	+0.02	
		0.07	-0.21	+0.02	
		0.08	-0.20	+0.01	
		0.09	-0.18	+0.02	
		0.10	-0.17	+0.01	
Roof type 6	Insulation – Rock wool	0.01	-0.38	-	
		0.02	-0.32	+0.06	
		0.03	-0.28	+0.04	
		0.04	-0.25	+0.03	
		0.05	-0.23	+0.02	
		0.06	-0.21	+0.02	
		0.07	-0.19	+0.02	
		0.08	-0.18	+0.01	
		0.09	-0.16	+0.02	
		0.10	-0.15	+0.01	
Roof type 7	Insulation - Silicon	0.01	-0.43	-	
		0.02	-0.42	+0.01	
		0.03	-0.41	+0.01	
		0.04	-0.39	+0.02	
		0.05	-0.38	+0.01	
		0.06	-0.37	+0.01	
		0.07	-0.36	+0.01	
		0.08	-0.35	+0.01	
		0.09	-0.34	+0.01	
		0.10	-0.33	+0.01	
Roof type 8	Insulation – Polyurethane	0.01	-0.37	-	
		0.02	-0.31	+0.06	
		0.03	-0.27	+0.04	
		0.04	-0.24	+0.03	
		0.05	-0.21	+0.03	
		0.06	-0.19	+0.02	
		0.07	-0.17	+0.02	
		0.08	-0.16	+0.01	
		0.09	-0.15	+0.01	
		0.10	-0.14	+0.01	

indicates the flexibility level of the insulation material. This means that the greater the changes in the slope of the diagrams, the more effective the material will be for different thicknesses. Based on the Heat balance change ratio domains, the average slopes of the diagrams related to polystyrene (HFC), rock wool, and polyurethane are equal to five, which is greater than that of the others. Therefore, they were considered the most efficient insulation roof material in this study. In the next group, polystyrene (CO2), mineral fiberglass, and fiberglass are considered as the mid-coefficient roof insulation materials in which the slopes are expressed as equal to 4 in the diagrams.

Polyvinyl chloride and silicon are the low-efficiency roof insulation materials. The Heat balance change ratio is equal11, which is attributed to the low flexibility of these materials at various thicknesses.

Figure 4 is drawn based on the criteria, which include the thickness of the thermal insulation layer and the



	1	2	3	4	5	6	7	8	9	10
Seri9	-0,37	-0,31	-0,27	-0,24	-0,21	-0,19	-0,17	-0,16	-0,15	-0,14
Seri8	-0,43	-0,42	-0,41	-0,39	-0,38	-0,37	-0,36	-0,35	-0,34	-0,33
Seri7	-0,38	-0,32	-0,28	-0,25	-0,23	-0,21	-0,19	-0,18	-0,16	-0,15
Seri6	-0,39	-0,34	-0,3	-0,27	-0,25	-0,23	-0,21	-0,2	-0,18	-0,17
Seri5	-0,38	-0,34	-0,3	-0,27	-0,24	-0,22	-0,21	-0,19	-0,17	-0,17
Seri4	-0,43	-0,42	-0,4	-0,39	-0,37	-0,36	-0,35	-0,34	-0,33	-0,32
Seri3	-0,38	-0,33	-0,29	-0,26	-0,23	-0,21	-0,19	-0,18	-0,17	-0,16
Seri2	-0,37	-0,31	-0,27	-0,24	-0,22	-0,2	-0,18	-0,17	-0,15	-0,14

Figure 4. Roof simulation result categories.

quantity of thermal balance mentioned in Table 1. The horizontal axis of this diagram represents the thickness of the thermal insulation layer, which changed from 1 to 10 cm, and the vertical axis represents the quantity of the thermal balance proportional to the thickness of each thermal insulation layer. This drawing is based on eight types of thermal insulation.

Adaptation of Results

In this part of the research, a comparison study was conducted to determine the differences between the current research conclusions and other similar investigations. Based on research entitled "Weathering of Roofing Insulation Materials under Multi-Field Coupling Conditions," which was performed based on the numerical simulation software (COMSOL), this research analyzed the increasing structural deformation due to uneven heating, so the roof insulation system developed by up to 5% [25]. Although the current investigation goal was a framework related to indoor air and insulation effects, the aforementioned research followed a framework that determined the structural changes related to the insulation layers. In another investigation conducted in 2020, the investigator performed a simulation with paraffin as a phase change material, and the results showed a temperature decrease from 50°C on the exterior to 20°C on the interior [26]. As another aspect of insulation, the analysis of this material in the approach of current research, especially in Tehran, could develop the result framework.

In the next research, which was conducted by T. Carter, cool roofs were the main point of investigation, and the researcher conducted research based on the numerical simulation, and the simulation of roof type was affected by the heating island as a crucial factor in thermal transmittance [27]. As a considerable result that can influence the current research, physical thermal happening can lead to the insulation layer in both aspects of the low value and high value. In another study published in the Results in Engineering journal, researchers conducted a thermal comfort simulation in the UAE, and their related findings were categorized into various elements. As an achievement based on a U-value of 0.14 W/m2K, a 2.3% decrease with better roof insulation was expressed [28]. Although there are similarities between the methodology of this research and the current investigation, conducting simulations in different climates is considered an important point. In the research entitled "Numerical simulation of heat transfer in a roof assembly with reflective insulation and radiant barrier," researchers investigated the thermal performance of reflective insulation in a gable roof using computational fluid dynamics (CFD) simulation. Based on these achievements, increasing the reflective air space thickness from 25 to 100 mm had the greatest impact on the thermal performance of the roof. Despite the different methodology of this research in comparison with the current investigation, the achieved result can be used to develop the results of the current research in layer optimization.

Roof heat balance factor

The concept of heat balance, which involves equilibrium between incoming and outgoing heat to maintain a stable temperature, has been explored in various contexts [29]. This meaning in buildings expresses the difference between the heat entering the space and the heat leaving the space; in this study, the thermal transmittance of the building roof was determined.

According to the simulation results, roofs are the intended output, which expresses the heat balance of the zone that has been analyzed (zone 1 of the case study). The roof heat balance quantity may be expressed by the following three concepts:

- If the roof heat balance is ≥ 0, it means that the heat gains exceed the heat losses. This means that a building receives more heat from various sources (such as solar gain and internal heat generation) than it is lost through factors such as conduction, convection, and radiation.
- If the roof heat balance is zero, there is no heat loss or heat gain in that space, and the roof layer insulation can save indoor thermal energy.
- If the roof heat balance is ≤ 0, a negative heat balance implies that the heat loss is greater than the heat gain. A building losses more heat than it is gaining, which could result in increased energy consumption for heating to maintain a comfortable indoor temperature.

According to Table 1, the categorized results of the simulation indicate that the heat balance in the specified roof of the space introduced in the case study is expressed as a negative value despite the use of various thermal insulations. This indicates that the amount of heat transferred from the indoor to the outdoor is greater than the quantity of heat transferred from the outdoor to the indoor. Therefore, the design details and thermal insulation are not in the best developed situation, but since this issue is happening in building construction in Tehran City, it is important to discuss a better classification of this roof typology based on various thermal insulations.

In accordance with the evidence presented in Figure 4, it is important to discuss each thermal insulation layer used separately. Therefore, a diagram of the thickness - thermal balance ratio for the introduced roof (in various thermal insulation layers) was drawn, which is evident in Figures 5 - 12.

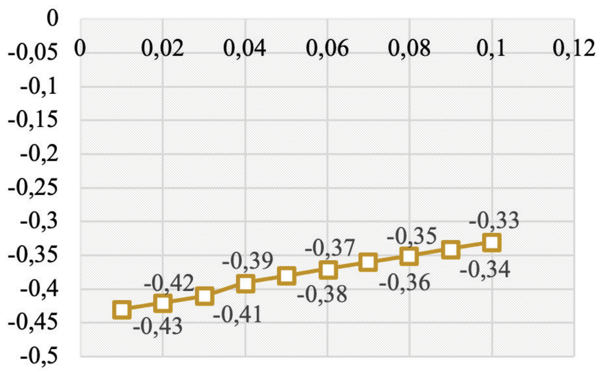


Figure 5. Polystyrene – HFC (Thickness – Heat balance).

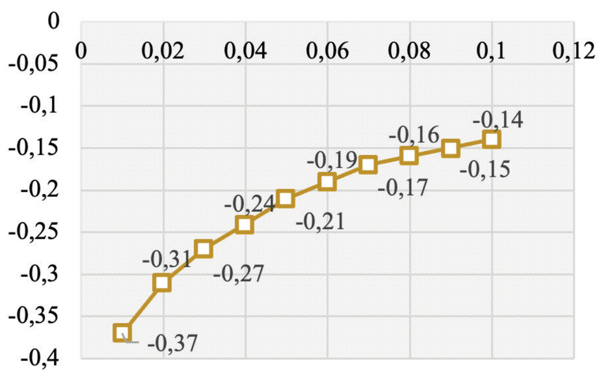


Figure 6. Polystyrene – CO_2 (Thickness – Heat balance).

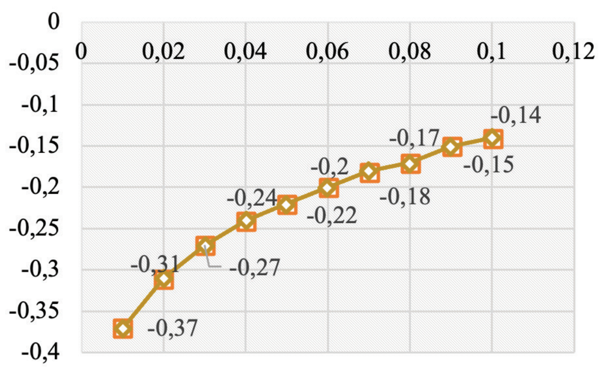


Figure 7. Polyvinyl Chloride (Thickness – Heat balance).

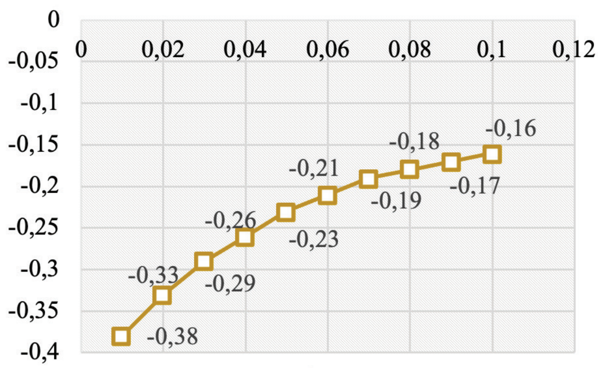


Figure 8. Mineral Fiberglass (Thickness – Heat balance).

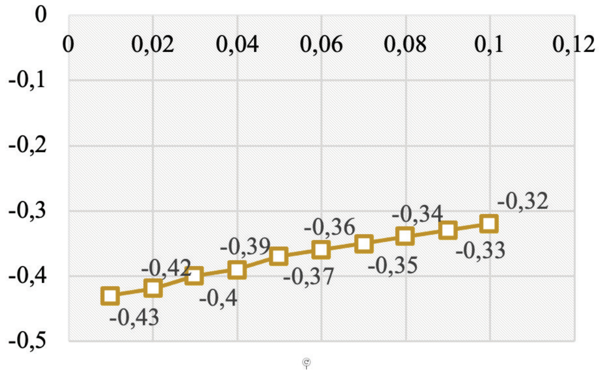


Figure 9. Fiberglass (Thickness – Heat balance).

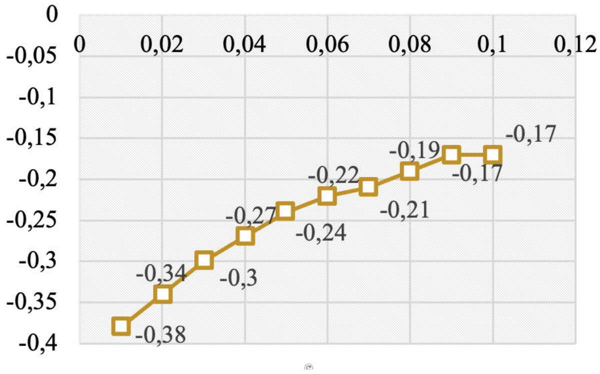


Figure 10. Rock wool (Thickness – Heat balance).

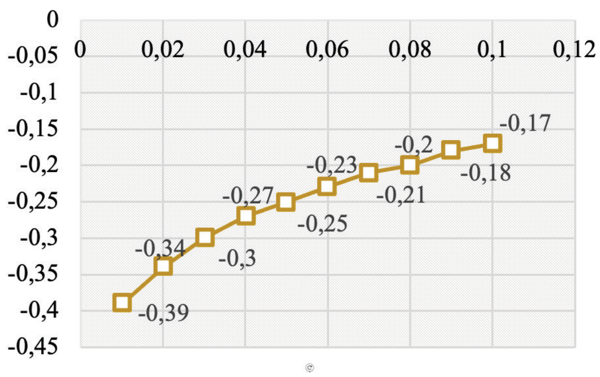


Figure 11. Silicon (Thickness – Heat balance).

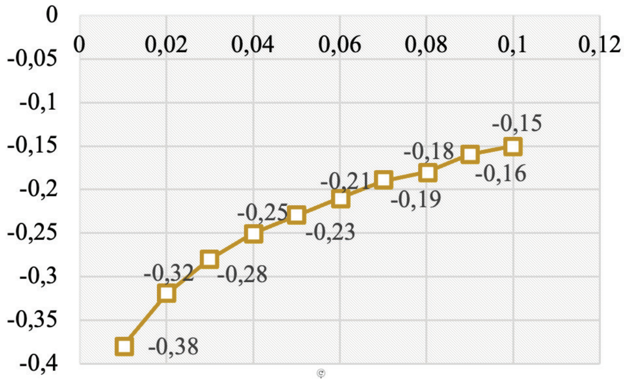


Figure 12. Polyurethane (Thickness – Heat balance).

Table 5. Polystyrene – HFC, Rock wool and Polyurethane heat balance change ratio

	Polystyrene - HFC	Polystyrene – CO_2	Rock wool	Polyurethane
0.01	-	-	-	-
0.02	+0.06	+0.05	+0.06	+0.06
0.03	+0.04	+0.04	0.04	+0.04
0.04	+0.03	+0.03	+0.03	+0.03
0.05	+0.02	+0.03	+0.02	+0.03
0.06	+0.02	+0.02	+0.02	+0.02
0.07	+0.02	+0.02	+0.02	+0.02
0.08	+0.01	+0.01	+0.01	+0.01
0.09	+0.02	+0.01	+0.02	+0.01
0.1	+0.01	+0.01	+0.01	+0.01

High-rate insulation analysis: polystyrene (HFC), polystyrene (CO2), rock wool, and polyurethane

According to the possibility of high rates of changes in thermal balance and thickness in these four types of thermal insulation, these insulations have the possibility of being more flexible than others. As shown in Figs. 3, 4, 8, and 10, the display element in the diagrams moved from a linear state to a curved state, which shows the flexibility of these four thermal insulations according to the simulation results.

As presented in Table 5, the three most flexible thermal insulations in the roof details were categorized into three colors. The first green color indicates the most efficient thermal residence, based on the thickness of the insulation layer. In other words, increasing the thickness of the thermal insulation layer up to a certain amount causes a significant increase in the efficiency of the thermal insulation layer, and these values are 0.03 KW to +0.06 KW for the thermal insulation layer in thickness between 0.01m and 0.04m (for polystyrene (CO2), it is until 0.05m). Another part of Table 5, which is displayed in yellow and red colors, has played a role in improving the thermal balance coefficient, but due to the small increase in the improvement of the thermal balance coefficient (between +0.01 KW and +0.02 KW) in thicknesses between 0.05m and 0.1m for the thermal insulation layer, it will not be suitable from an efficient point of view.

Low-rate insulation analysis: polyvinyl chloride and silicon

In another aspect of the heat balance change ratio, owing to the possibility of a low rate of change in the thermal balance thickness in the thermal insulation, silicon and polyvinyl chloride are categorized as having a low rate. This was based on the simulation results in Table 4. As is evident in Figures 7 and 11, the diagram element displays a linear path.

As presented in Table 6, two types of thermal insulation with no flexibility in terms of the change in thermal rate coefficient thickness are provided. Results were classified into two groups: yellow and red. In part of the results that are in the yellow color group, the growth rate of the thermal balance coefficient in the layer thickness range of 0.01m to 0.05m is between +0.01 kw and +0.02 kw, and this value is very little in comparison with the three thermal insulations discussed in Section 4.2. On the other hand, in those results, which are grouped in the red color, the growth rate of the thermal balance coefficient in the layer thickness range of 0.06m to 0.1m is equal to +0.01 kw, which is less than the previous case. Based on the point mentioned in Table 6, the use of these two types of thermal insulation (polyvinyl chloride and silicon) with a layer thickness of up to 0.05 meters has a low efficiency justification. Also, according to the presented values, the use of the mentioned insulations in thicknesses of 0.06m to 0.1m will not be justified in terms of efficiency.

Table 6. Polyvinyl Chloride and Silicon heat balance change ratio

		Polyvinyl Chloride		Silicon
0.01		-		-
0.02	yellow	+0.01	yellow	+0.01
0.03	yellow	+0.02	yellow	+0.01
0.04	yellow	+0.01	yellow	+0.02
0.05	yellow	+0.02	red	+0.01
0.06	red	+0.01	red	+0.01
0.07	red	+0.01	red	+0.01
0.08	red	+0.01	red	+0.01
0.09	red	+0.01	red	+0.01
0.1	red	+0.01	red	+0.01

Table 7. Mineral Fiberglass and Fiberglass heat balance change ratio

		Mineral Fiberglass		Fiberglass
0.01		-		-
0.02	green	+0.04	green	+0.05
0.03	green	+0.04	green	+0.04
0.04	green	+0.03	green	+0.03
0.05	green	+0.03	red	+0.02
0.06	red	+0.02	red	+0.02
0.07	red	+0.01	red	+0.02
0.08	red	+0.02	red	+0.01
0.09	red	+0.02	red	+0.02
0.1	red	+0.02	red	+0.01

Mid-Rate Insulation Analysis: polystyrene (CO2), mineral fiberglass, and fiberglass

In the next category of simulated thermal insulations, there is a group of insulations (polystyrene (CO2), mineral fiberglass, and fiberglass) that are categorized in the average position in terms of heat balance-thickness change ratio efficiency.

According to Table 7, there are two types of thermal insulation categorized by the mid-rate of thermal balance change rate thickness. The results are classified into two groups: green and red. In part of the results that are in the green color group, the growth rate of the thermal balance coefficient in the layer thickness range of 0.01m to 0.04m (for fiberglass at 0.05m) is between +0.03 KW and +0.05 KW. Therefore, in this category, these insulations are leveled efficiently. On the other hand, part of the results in this table, which are categorized in the red group, show that the growth rate of the thermal balance coefficient in the layer thickness range of 0.06m to 0.1m (for fiberglass in the range of 0.05m to 0.1m) is between +0.01 KW and +0.02 KW and is not recognized as an efficient quantity.

Practical Implication for Construction and Design

The results show that the proper selection of the type and thickness of thermal insulation can cause a significant difference in the thermal balance of the building, thereby affecting interior comfort and energy consumption. For example, polystyrene-HFC and polyurethane insulation applied to roofs under the same conditions provided the best value for thermal balance, showing that they are outstanding in their performance against heat transfer reduction. This would make them especially suitable for projects that target higher energy efficiency standards.

Guidance for Material Selection

This study also underlined the requirement for the selection of insulation materials based on the ratio of the heat balance change. In this regard, polystyrene, rock wool, and polyurethane, which have higher rates of changeability, can be effectively used at different thicknesses to provide design flexibility to meet specified goals of thermal performance. Materials such as silicon and polyvinyl chloride which have lower rates of change, could very well suit use cases when less variability in insulation thickness is required.

CONCLUSION

This study focuses on roof insulation and offers quantitative insights into its thermal behavior in Tehran's urban context, providing valuable guidance for optimizing the thermal performance of buildings. Through simulation-based analyses using Design Builder software, the research revealed significant findings regarding the effectiveness of various roof insulation types and thicknesses in improving thermal transmittance. Quantitative analysis revealed distinct trends in the thermal performance of roof insulation materials, and based on this assessment, the quantitative framework was established as a novel tool that would help architects and building designers in Tehran to choose the most efficient roof insulation in their first design phase based on their project calculations.

Research Key Achievements

- Quantitative analysis reveals distinct trends in the thermal performance of roof insulation materials. High-rate insulations such as polystyrene (HFC) and polyurethane demonstrate remarkable flexibility in enhancing the thermal balance across different thicknesses. Increasing their thickness within roof structures leads to substantial improvements in thermal balance, with coefficients ranging from 0.03 kW to +0.06 kW.
- Conversely, low-rate insulations such as polyvinyl chloride and silicon exhibit limited efficiency gains, particularly beyond a specific thickness threshold. While contributing to some thermal balance enhancement, their effectiveness diminishes considerably beyond thicknesses of 0.05 meters, with coefficients ranging from +0.01 kW to +0.02 kW.
- Mid-rate insulation materials such as polystyrene (CO_2), mineral fiberglass, and fiberglass display moderate flexibility in improving thermal balance. Within thickness ranges of 0.01 meters to 0.04 meters (0.05 meters for fiberglass), notable efficiency gains are observed, with coefficients ranging from +0.03 kW to +0.05 kW. However, beyond thicknesses of 0.06 meters to 0.1 meters (0.05 meters to 0.1 meters for fiberglass), efficiency gains diminish, emphasizing the importance of optimizing insulation thickness within specific ranges.

Research Limitations and Future Potentials

Based on the current research and the investigation process, there are some potential limitations that affect the results. In this part, two considerable limitations are expressed. First of all, although the approach of simulation-based research is valuable, it needs to continue with an experimental process to complete both theoretical and practical parts of research. Secondly, the accessibility to the other insulation materials is a local market limitation, and because of that, the research function is limited to the local market.

In accordance with the current results of this research, there are some considerable points that can be used as future investigation topics. First of all, comparative analysis with the other climatic region is a valuable investigation, especially in the local form of Iran.

This can help in understanding how roof insulation performance varies across diverse environmental contexts in Iran. Secondly, considering the other types of buildings based on the function could be expressed as useful research in the same city of Tehran. It could be commercial, industrial, educational, etc. The third research destination could be the effect of thermal transmittance on the comfortability of indoor areas, which can have a direct influence on people's health.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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