

Determination of Optimum Energy-Economic Insulation Thickness for Building Walls in Climate Zones of Iran

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ABSTRACT

The major areas of energy consumption in buildings are heating, ventilation, and air conditioning. Applying thermal insulation in exterior building walls is one of the most effective and efficient methods to reduce energy consumption. It is highly recommended to optimize the walls insulation thickness in order to minimize total investment costs. In this study, numerical investigation is conducted in order to compute annual heating and cooling loads of a modelled building in Iran climate zones such as Tehran, Tabriz, and Bandar Abbas. Insulation materials including elastomeric, polyurethane, stone wool and glass wool with different thermal conductivities and costs are applied as one of the external wall layers. The main purpose of this paper is to obtain the optimum energy-economic insulation thickness based on total costs of insulation and energy over a lifetime of 20 years. The analysis of energy savings and payback periods are also evaluated in this research. Results indicate that optimum insulation thickness varies from 0.79 cm to 11.39 cm. It is evaluated that glass wool is the most optimal insulation in aspect of reducing total costs. Energy saving analysis demonstrates that polyurethane is the most efficient thermal insulation among other studied materials. Elastomeric, stone wool, and glass wool are placed in next positions, respectively.

Keywords: Building Energy, Optimum Insulation Thickness, Climate Zones, Energy Saving, Payback

1. INTRODUCTION

Global demand for energy is increasing rapidly due to the growth of population and industrial activities [1-3]. The enormous growth in urbanisation worldwide, particularly in developing countries, has negatively affected the local, regional and global environment. The major source of energy consumption in Iran as a developing country is fossil fuels. It should be noted that the large part of energy consumption in Iran is related to buildings sector [4-6]. Electricity and natural gas are the most common energy sources used in residential and commercial buildings. The energy requirement for space heating and cooling of a building is

approximately 60% of the total energy consumed in buildings, which accounts for the largest percentage of energy usage [7]. It is also noticeable that excessive consumption of fossil resources causes greenhouse effect, raising global temperature and environmental drawbacks [8, 9].

It is highly recommended to optimize building energy consumption in order to preserve fossil fuel resources and reduce global warming. There are various types of parameters which affect the amount of heating and cooling energy in buildings. Factors including insulation materials, climate types, windows orientation, sunshade, etc. play significant role in heating and cooling loads of buildings.

Thermal insulation of exterior walls is one of the most valuable tools in achieving energy conservation in buildings [10]. In order to reduce building energy consumption, investigation of walls insulation materials and appropriate thicknesses is crucial.

There are many investigations carried out by researchers to find out the most proper techniques in order to reduce building energy consumption. Simona et al. [11] conducted a comparative study of internal versus external thermal insulation systems to make residential buildings more energy efficient. Both external and internal thermal insulation significantly reduces the total energy requirement, but they bring different benefits in terms of wall protection and mold formation, and installation of the thermal insulation is more suitable in exterior. Cetiner and Shea [12] examined experimentally a natural fibre material in the form of wood waste to assess its suitability for use as a thermal insulation material, without the addition of any binder, within a timber frame wall construction. Results showed that the thermal conductivity values of wood waste with different densities, ranged from 0.048 to 0.055 W/m.K. These values are slightly higher than commonly used inorganic based insulation materials, although comparable to other natural insulation materials in the market, but have the economic advantage of being a low-cost by-product. Jain and Pathak [13] carried out thermal simulation for observing reduction in energy consumption of three residential buildings. Analysis was performed after using modern insulating techniques, namely ceramic tiles, high reflective coating, aluminium paint on roof, along with rock wool spread on opaque components of the building. The results indicate that the use of reflective solar coating in roof and walls of buildings reduces heat gain by as much as 25%. Ajib and Jaber [14] analysed best orientation of the building, windows size, thermal insulation thickness from energetic, economic and environmental point of view. The results illustrated that about 27.59% of annual energy consumption can be saved by these methods. Yu et al. [15] investigated envelope design on energy saving of air conditioner and the effects of energy saving strategies on electric consumption of different orientation rooms in hot summer and cold winter zone in China, which included exterior wall thermal insulation. The results indicate that envelope shading and exterior wall thermal insulation are the best strategies to decrease the electric consumption.

Also, many researchers made efforts in order to optimize the thicknesses of walls insulations [16-18]. Bojic et al. [19] performed an optimization in the thickness of thermal insulation layer by using Energy Plus software and Hooke–Jeeves direct search method for a small residential house in Serbia. Their results demonstrated that the optimal thickness of thermal insulation yields the minimum primary energy consumption. Nyers et al. [20] researched the optimum energy-economic thickness of polystyrene as thermal insulation layer

for external wall by applying investment-savings method. The minimum payback period of the investment was the optimization criterion. It was concluded that the optimum thickness of the polystyrene is 6.89 cm with payback period of 1.22 years. Aktemur and Atikol [21] conducted a life-cycle cost analysis to show the optimum insulation thickness and energy savings over a lifetime of 15 years. They applied six different fuels and insulation materials for four cities in Turkey. They concluded that the optimum insulation thickness varies between 2.8 cm and 45.1 cm, with energy savings between 16.4 $\text{₺}/\text{m}^2$ and 479 $\text{₺}/\text{m}^2$, and payback periods fluctuating between 0.078 and 0.860 years. Bolatturk [22] determined the optimum insulation thickness on external walls of buildings based on annual heating and cooling loads. The degree-hours method is used in his study. The results indicated that the use of insulation in building walls with respect to cooling degree-hours is more significant for energy savings compared to heating degree-hours in Turkey's warmest zone.

There are various types of studies performed by previous researchers in order to optimize insulation thickness. Most of the analysis carried out based on heating or cooling degree-days methods and other numerical methods were not considered widely. Also, different climate zones of Iran were not concentrated by investigators considerably.

In this study, numerical investigation is conducted in order to calculate annual heating and cooling loads of a modelled building in various climate zones in Iran. Also, various insulation materials with different thermal conductivities and costs are utilized as one of the wall layers of the building. The main aim of this paper is to optimize insulation thickness based on investment-savings method over lifetime of the building. The energy savings and payback periods will be also investigated.

2. METHODOLOGY

In order to optimize the economical thickness of insulations, annual heating and cooling loads of a sample modelled building are computed with the assistance of Design Builder software. The 3D model of the building with total area of 175 m^2 is illustrated in Fig. 1. The shaded windows have left and right hand wings which are 0.5 m. Also, a 0.5 m overhang is placed at the top of the glazing surface. In fact, various climate zones in country of Iran are considered and studied. For instance, Tehran, Tabriz, and Bandar Abbas cities with different weather conditions are examined.

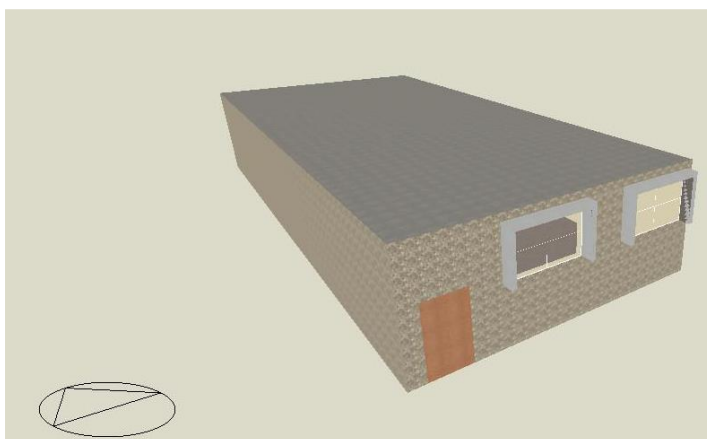


Fig. 1. 3D Model of the Building

Furthermore, insulation materials including elastomeric, polyurethane, stone wool and glass wool with different thermal conductivities and costs are used as one of the wall layers of the mentioned building. It should be noticed that the sunshade is considered for building windows. Heat transfer in buildings mainly occur through external walls, windows, roof, floors and air infiltration. In order to compensate heat loss, energy consumption increases. Energy consumption of buildings depends on parameters including weather condition, sunshade, insulation material and thickness which are discussed.

In this study, heating and cooling loads of the building are calculated. Then, the optimum insulation thickness of external walls is determined by applying investment-savings method. Increasing the insulation thickness reduces the energy consumption of buildings. However, it is highly noticeable that the thickness has an optimum value that minimizes the total investment cost, and determination of this optimum value is significant in aspect of economic analysis.

2.1 The Structure of External Walls

Insulation material is utilized in one of the external wall layers. The thermal conductivity of insulation materials with various costs is illustrated in Table 1. The insulation thickness was investigated from 1 cm to 20 cm. The structure of building external walls is shown in Fig. 2. The thermal conductivity, thickness and thermal resistance of wall layers are specified in Table 2. The overall heat transfer coefficient of building external walls is given Eq. (1).

$$U = \frac{1}{R_{tot}A} = \frac{1}{\frac{1}{h_{outside}} + \frac{L_A}{k_A} + \frac{L_B}{k_B} + \frac{L_{ins}}{k_{ins}} + \frac{L_C}{k_C} + \frac{L_D}{k_D} + \frac{L_E}{k_E} + \frac{1}{h_{inside}}} \quad (1)$$

Table 1. Thermal Conductivity and Cost of Insulations

Insulation	Thermal conductivity (W/m.K)	Cost (Rials/m ³)
Glass Wool	0.04	6,860,000
Stone Wool	0.04	8,166,666
Elastomeric	0.035	21,600,000
Polyurethane	0.024	17,533,333

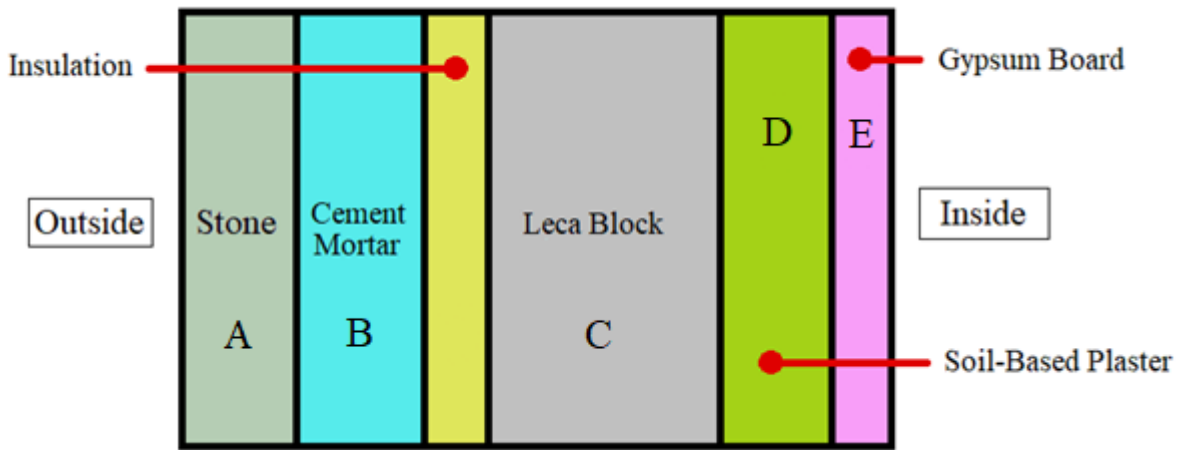


Fig. 2. Structure of External Wall Layers

Table 2. Properties of External Wall Layers

Layer	k (W/m.K)	Thickness (m)	R (m ² .K/W)
Stone	2.2	0.02	0.009
Cement Mortar	1.75	0.025	0.014
Leca Block	0.76	0.2	0.263
Soil-Based Plaster	0.5	0.02	0.04
Gypsum Board	0.5	0.01	0.02

2.2 Climate Zones

The specifications of studied climate zones are illustrated in Table 3. Three different cities in Iran with various weather conditions are examined in order to determine and compare loads, energy consumption and optimum insulation thickness.

Table 3. Specifications of Studied Climate Zones

City	Latitude (Degree)	Altitude (m)	Summer Dry Bulb Temp. (°C)	Summer Wet Bulb Temp. (°C)	Winter Dry Bulb Temp. (°C)
Tehran	35.68	1189	37.78	19.44	-4.44
Bandar Abbas	27.2	10	40.56	31.92	7.5
Tabriz	37.8	1366	33.89	18	-10.83

2.3 Calculation of Optimum Insulation Thickness

As it was mentioned, heating and cooling loads of the modelled building are calculated with the assistance of Design Builder software. Heat Transfer through external walls reduces by applying insulation in external walls. In order to optimize insulation thickness, investment-savings method is utilized. Annual heating and cooling energy costs of the building for unit surface are $C_{A,H}$ and $C_{A,C}$, respectively. Also, insulation cost can be calculated by Eq. (2). Where C_y is unit insulation cost and x is insulation thickness.

$$C_{ins} = C_y \times x \tag{2}$$

Finally, total heating, cooling, and both heating and cooling costs of an insulated building applying life cycle cost analysis (LCCA) are given in Eq. (3-5) [23, 24].

$$C_{t.H} = C_{A.H} \times PWF + C_y \times x \tag{3}$$

$$C_{t.C} = C_{A.C} \times PWF + C_y \times x \tag{4}$$

$$C_{t.H.C} = C_{A.H} \times PWF + C_{A.C} \times PWF + C_y \times x \tag{5}$$

PWF is present worth factor, where *i* and *g* are interest rate and inflation rate, respectively. Also, *r* is actual interest rate and *N* is the lifetime [21].

$$PWF = \frac{(1+r)^N - 1}{r \times (1+r)^N} \tag{6}$$

$$\text{if } i > g \Rightarrow r = \frac{i - g}{1 + g} \tag{7}$$

$$\text{if } g > i \Rightarrow r = \frac{g - i}{1 + i} \tag{8}$$

$$\text{if } i = g \Rightarrow PWF = \frac{N}{1 + i} \tag{9}$$

In this study, interest rate and inflation rate are assumed 42%. The minimum of total heating, cooling, and both heating and cooling costs, Eq. (3-5), will happen at optimized insulation thickness. Therefore, optimization of insulation thickness is carried out by minimizing the total heating and cooling cost which is calculated regarding LCCA.

2.4 Payback Period

Simple payback period is determined by counting the number of years it takes to recover the funds invested. $C_{O.ins}$ is optimized insulation cost and A_{year} is the difference between annual energy cost without insulation and annual energy cost considering insulation with optimized thickness.

$$PP = \frac{C_{O.ins.}}{A_{year}} \quad (10)$$

3. RESULTS AND DISCUSSION

The main objective of this study is to determine the optimum insulation thickness of external walls. The heating and cooling loads of the modelled building are investigated annually in Design Builder software. Then, optimization of insulation thickness is carried out due to the investment-savings method over lifetime of the building which is 20 years. The building is simulated in three cities in Iran with various weather conditions including Tehran, Tabriz, and Bandar Abbas. Also, insulation materials including elastomeric, polyurethane, stone wool and glass wool with various thicknesses from 0 to 20 cm are applied as the wall layer of external walls. It should be mentioned that sunshade is installed on building windows. The main source of heating and cooling energy is electricity with heating value of $3,6 \times 10^6 \text{ J/KWh}$. The cost of electricity in Tehran, Tabriz, and Bandar Abbas is 2793, 2793, and 2363 Rials per kWh, respectively. The results of insulations optimization thicknesses and Energy Savings over the building lifetime are discussed in this study.

3.1 Optimization of Insulations Thicknesses

It is highly considerable that insulations costs, climate zones, and energy costs affect directly on total costs over lifetime of the building. Applying insulation is one of the effective methods in order to reduce energy expenses, while initial expenses of insulation increases the total costs during the building lifetime. The thermal conductivity and cost of the insulation materials have great influence on energy consumption and total costs. Increasing insulation thickness reduces energy consumption and therefore, energy costs. However, the most significant factor is total costs of insulation and energy that must be considered. Selecting optimum insulation thickness is an efficient method to minimize overall costs of the buildings.

Insulation costs, heating or cooling energy costs and total costs versus insulations thickness are shown in Figs. (2-14). Impact of different insulation materials on energy and total costs are analyzed in various cities. As shown in Figs. (2-14), insulation investment cost increases linearly with respect to insulation thickness. As insulation thickness rises, the cost of heating or cooling energy decrease. The total cost, obtained by adding insulation and energy costs, first decreases upon increase of insulation thickness, and after a minimum value, it increases again. The minimum point of total cost curve illustrates the optimum insulation thickness.

Effects of insulation thickness of glass wool, stone wool, and polyurethane on the total costs in Bandar Abbas city using cooling systems are shown in Figs. (3-5), respectively. It is impossible to determine optimum insulation thickness in Bandar Abbas in heating condition, since there is rarely required to use heating systems in this city. Therefore, the minimum point of total cost curve occurs when external walls are without insulation. It is also noticeable that applying elastomeric insulation is economically impractical in Bandar Abbas city, since the insulation expenses are much higher than cooling energy costs. The results of insulation

thickness optimization in Bandar Abbas city are specified in Table 4. The minimum optimized thickness is related to polyurethane. Nevertheless, by using glass wool, the minimum total insulation and energy costs is achieved. The payback periods of polyurethane, stone wool, and glass wool as insulations with optimized thicknesses are 8.55, 9.28, and 9.43 years, respectively.

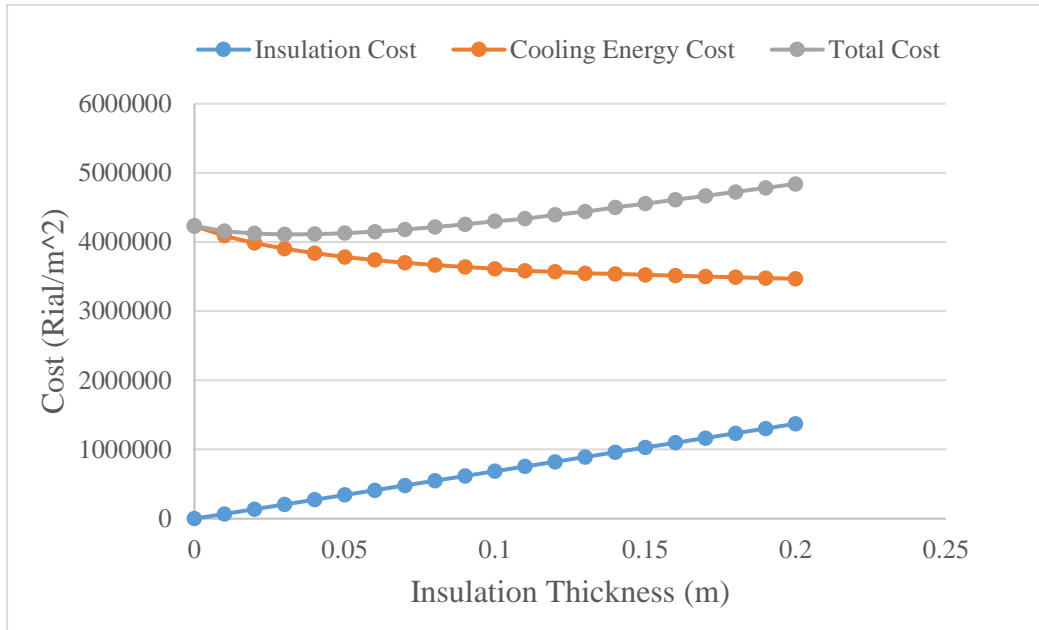


Fig. 3. Effect of Insulation Thickness of Glass Wool on the Total Cost in Bandar Abbas city in Cooling Condition

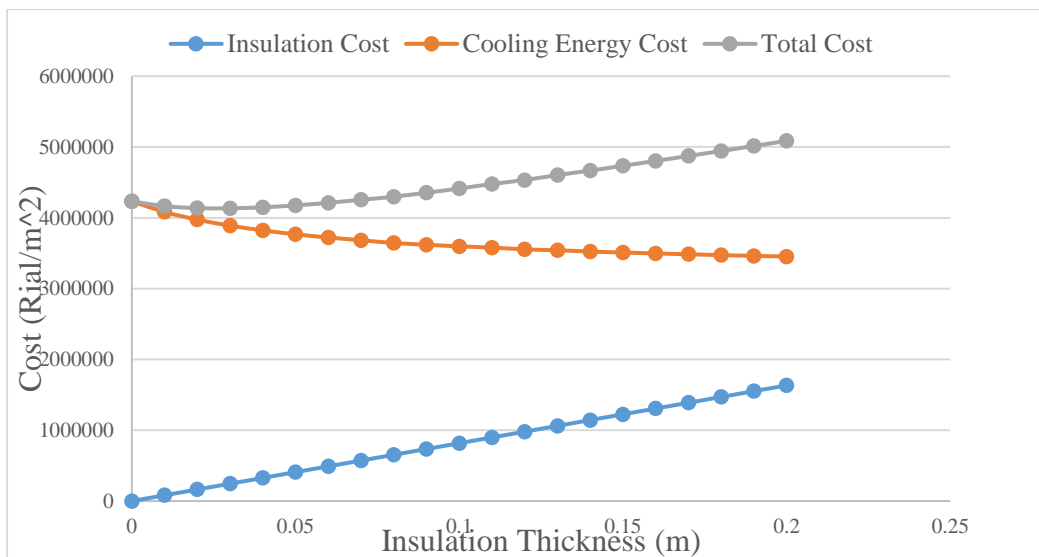


Fig. 4. Effect of Insulation Thickness of Stone Wool on the Total Cost in Bandar Abbas city in Cooling Condition

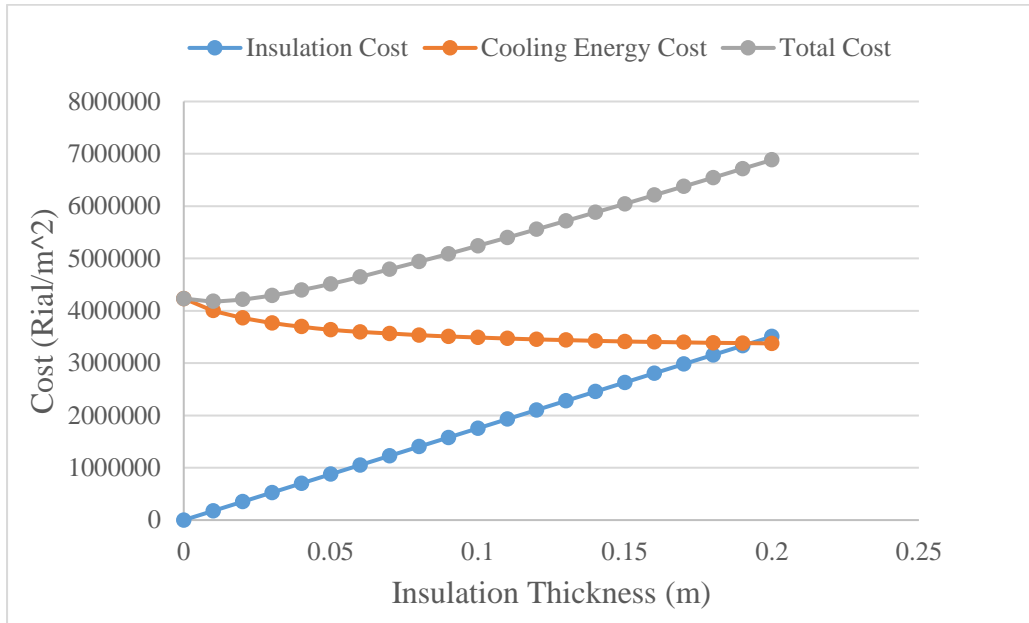


Fig. 5. Effect of Insulation Thickness of Polyurethane on the Total Cost in Bandar Abbas city in Cooling Condition

Table 4. Optimum Insulations Thicknesses in Bandar Abbas City in Cooling Condition

Insulation Material	Optimum Thickness (cm)
Glass Wool	4.4
Stone Wool	2.79
Polyurethane	0.79

Influence of insulation thickness of glass wool, stone wool, polyurethane, and elastomeric on the total costs in Tabriz city in heating condition are illustrated in Figs. (6-9), respectively. Investigation of optimum insulation thickness in Tabriz is carried out in only heating condition, because heating load is demanded in most of the months. Optimization of insulations thicknesses is performed and shown in Table 5. The least overall costs is related to glass wool. Stone wool, polyurethane, and elastomeric are placed in next positions, respectively. The payback periods of elastomeric, polyurethane, stone wool, and glass wool as insulations with optimized thicknesses are 8.85, 7.35, 6.11, and 5.66 years, respectively.

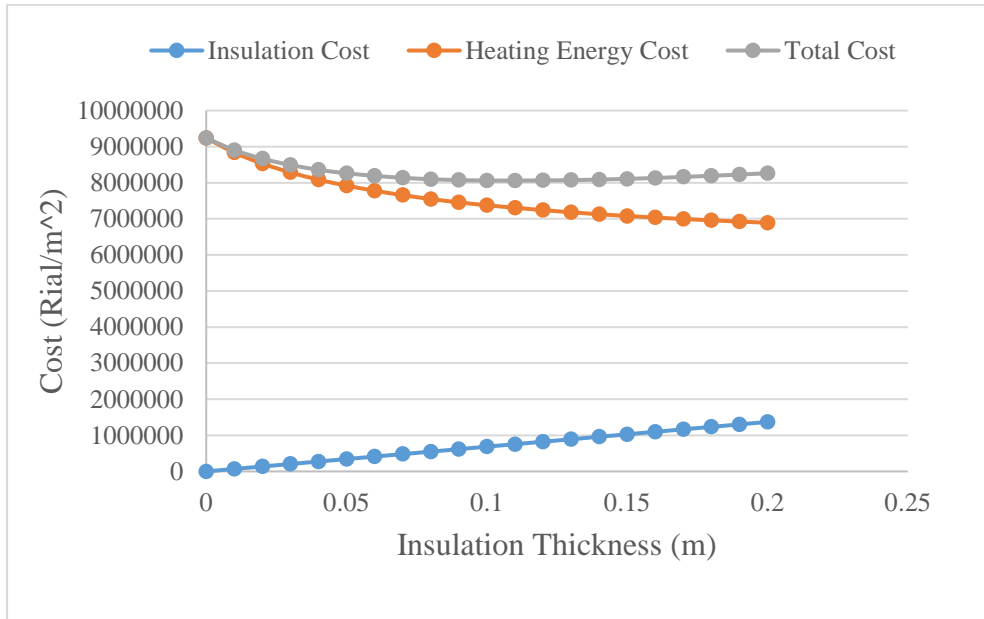


Fig. 6. Effect of Insulation Thickness of Glass Wool on the Total Cost in Tabriz city in Heating Condition

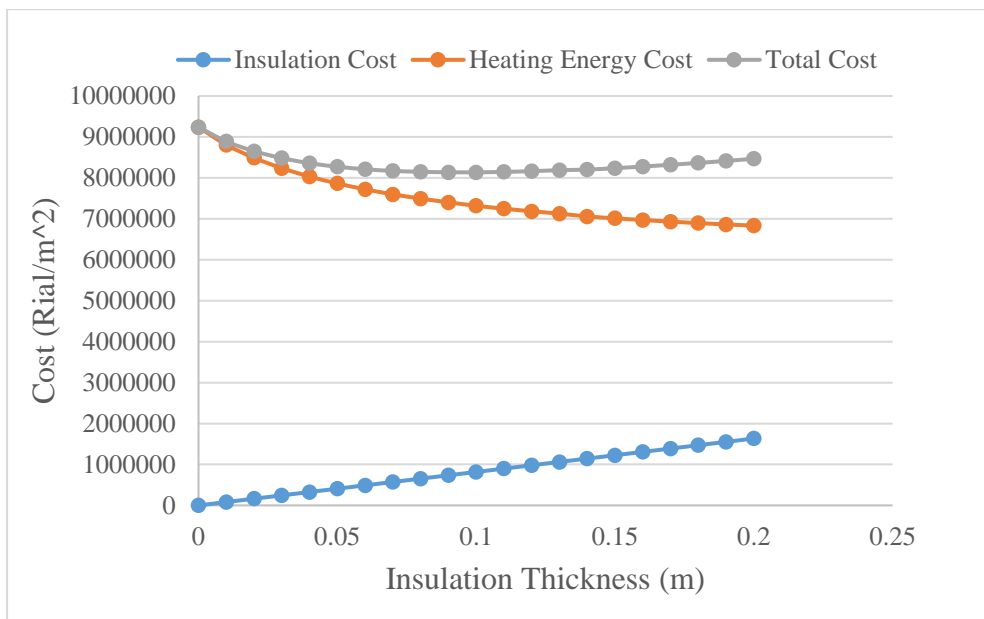


Fig. 7. Effect of Insulation Thickness of Stone Wool on the Total Cost in Tabriz city in Heating Condition

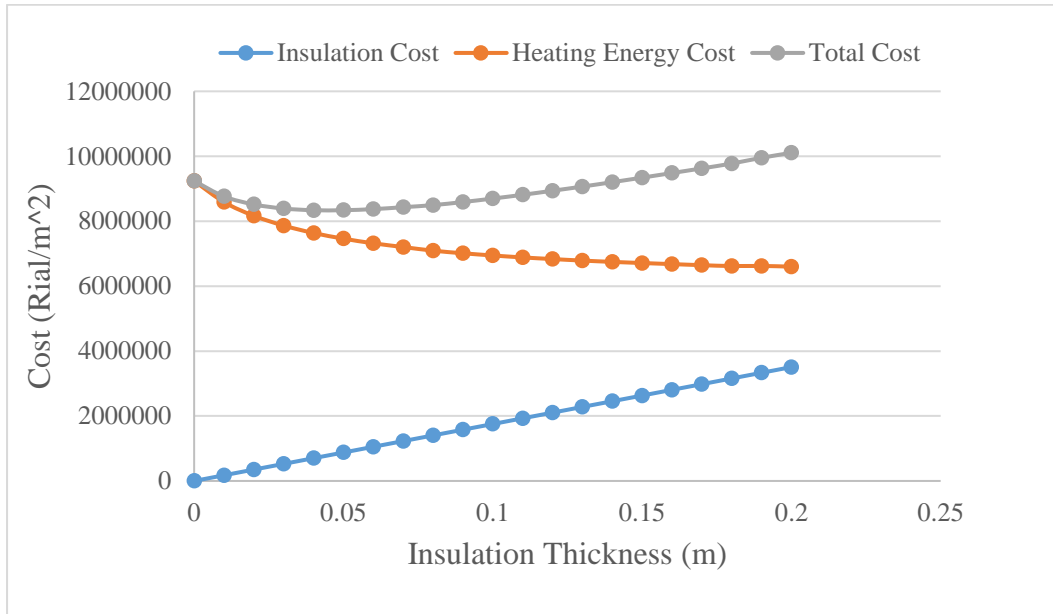


Fig. 8. Effect of Insulation Thickness of Polyurethane on the Total Cost in Tabriz city in Heating Condition

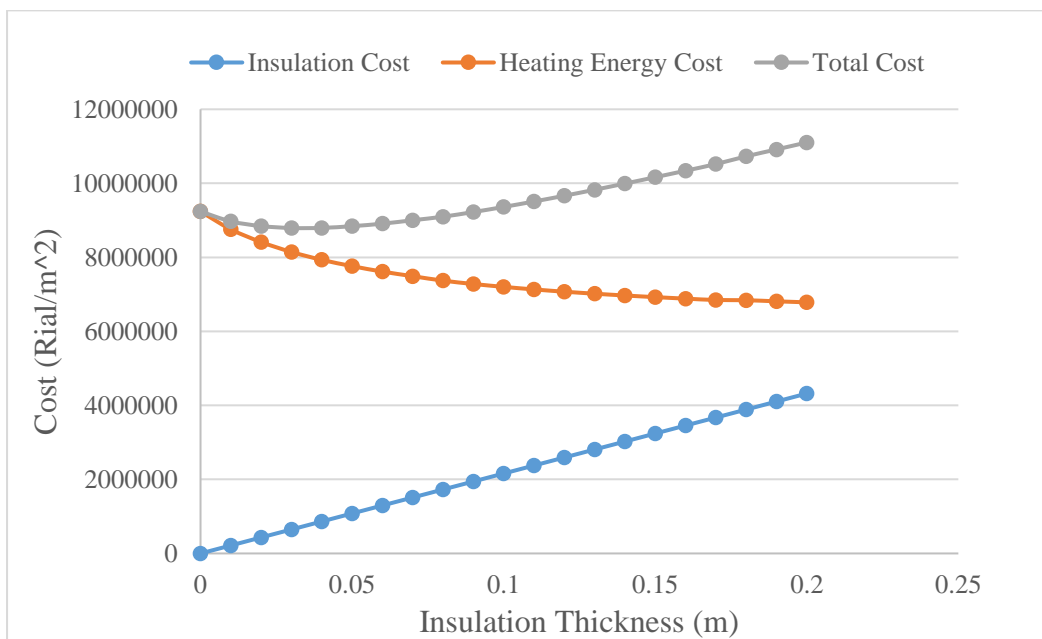


Fig. 9. Effect of Insulation Thickness of Elastomeric on the Total Cost in Tabriz city in Heating Condition

Table 5. Optimum Insulations Thicknesses in Tabriz City in Heating Condition

Insulation Material	Optimum Thickness (cm)
Glass Wool	11.39
Stone Wool	10.26
Polyurethane	4.8
Elastomeric	3.2

Effects of insulation thickness of glass wool and stone wool on the total costs in Tehran city in both heating and cooling conditions are presented in Figs. (10-15). Investigation of investment-savings method demonstrates that utilizing polyurethane and elastomeric insulations is economically impractical in Tehran city. Regarding high initial investments of these insulations, the minimum total costs over building lifetime happens at thickness of zero. Accordingly, walls without these insulation materials are preferred in both heating and cooling conditions. The results of optimization of insulations thicknesses in Tehran city in heating, cooling, and both heating and cooling conditions are achieved in Table 6. The calculation of optimized insulations thicknesses in both heating and cooling conditions is carried out by Eq. (5). The payback periods of stone wool and glass wool as insulations with optimized thicknesses are 6.7 and 6.94 years, respectively.

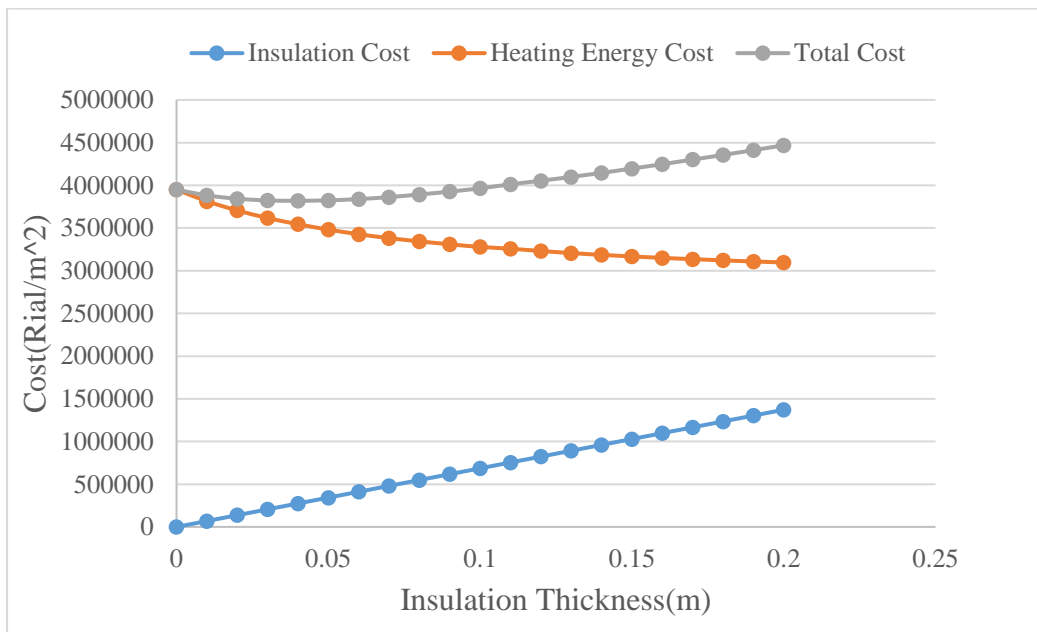


Fig. 10. Effect of Insulation Thickness of Glass Wool on the Total Cost in Tehran city in Heating Condition

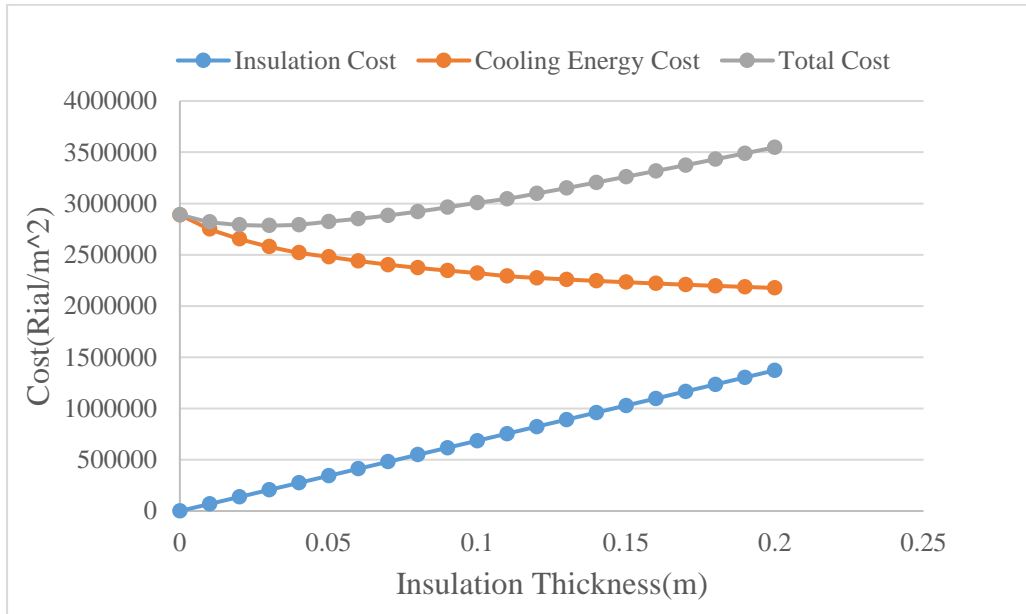


Fig. 11. Effect of Insulation Thickness of Glass Wool on the Total Cost in Tehran city in Cooling Condition

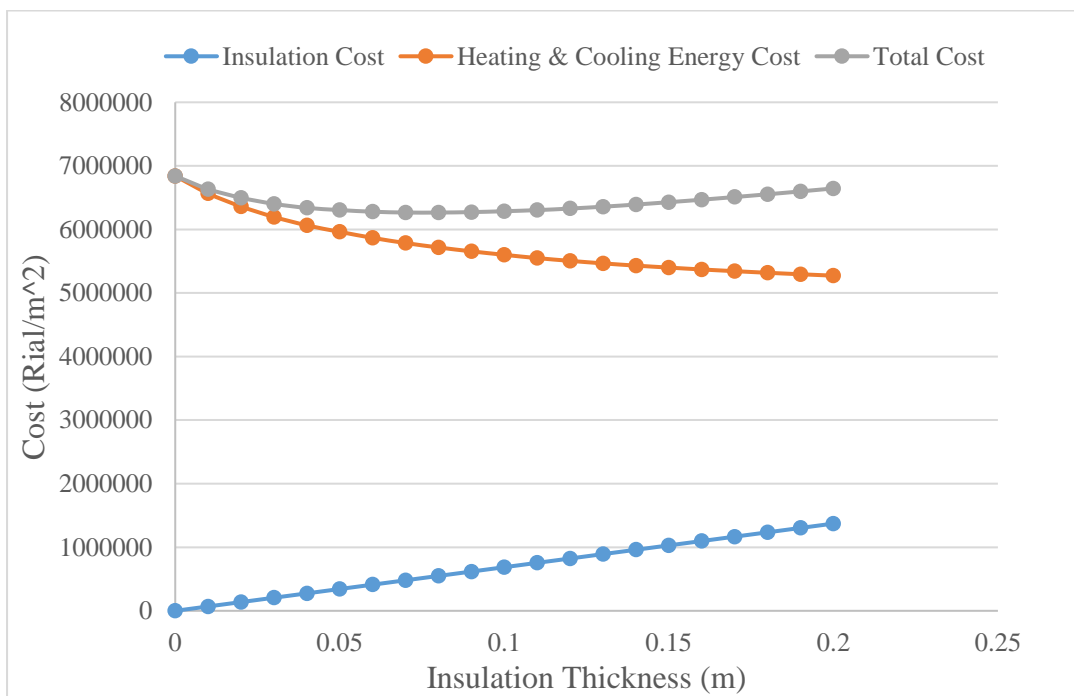


Fig. 12. Effect of Insulation Thickness of Glass Wool on the Total Cost in Tehran city in both Heating and Cooling Conditions

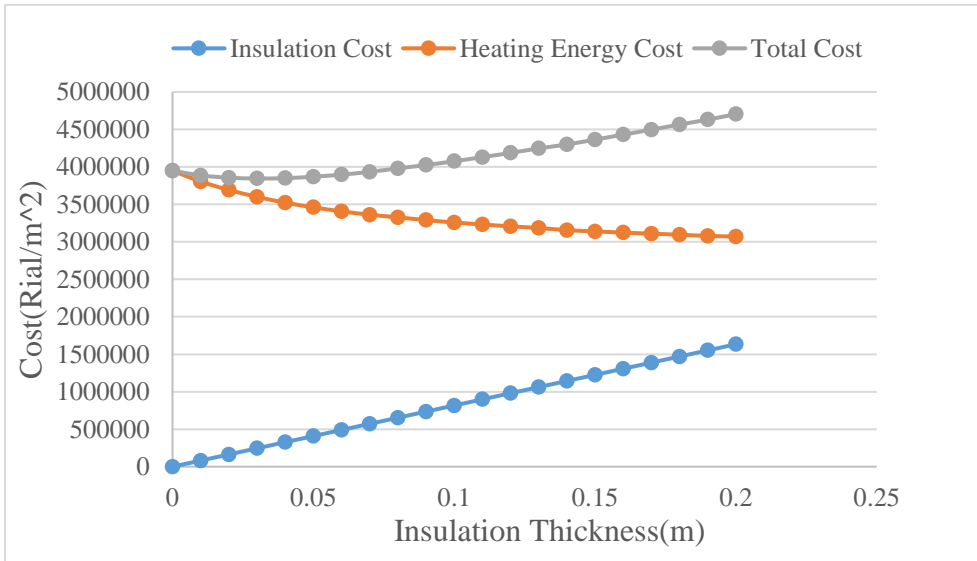


Fig. 13. Effect of Insulation Thickness of Stone Wool on the Total Cost in Tehran city in Heating Condition

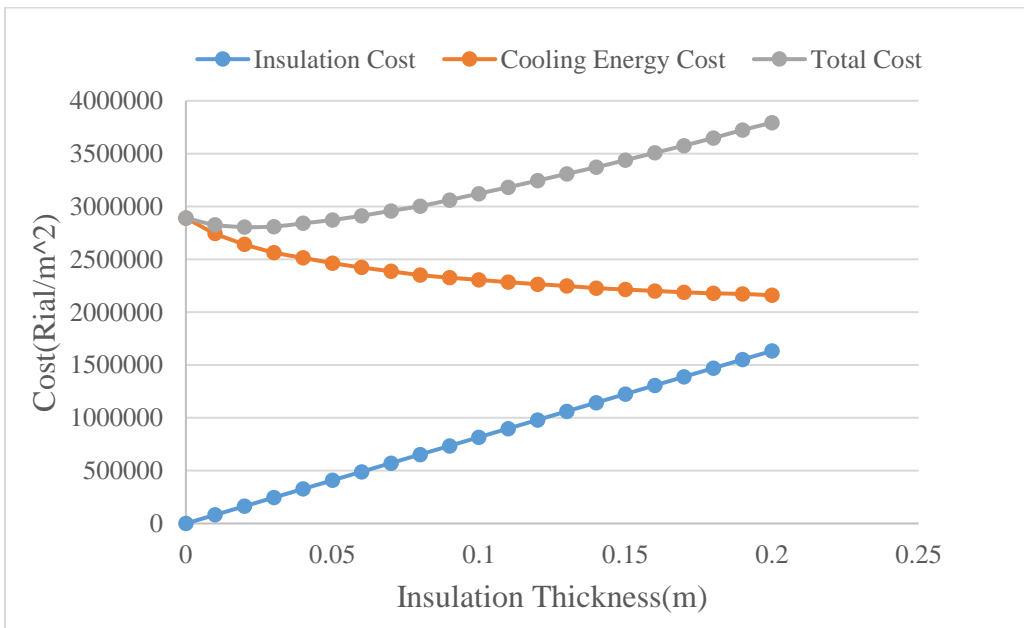


Fig. 14. Effect of Insulation Thickness of Stone Wool on the Total Cost in Tehran city in Cooling Condition

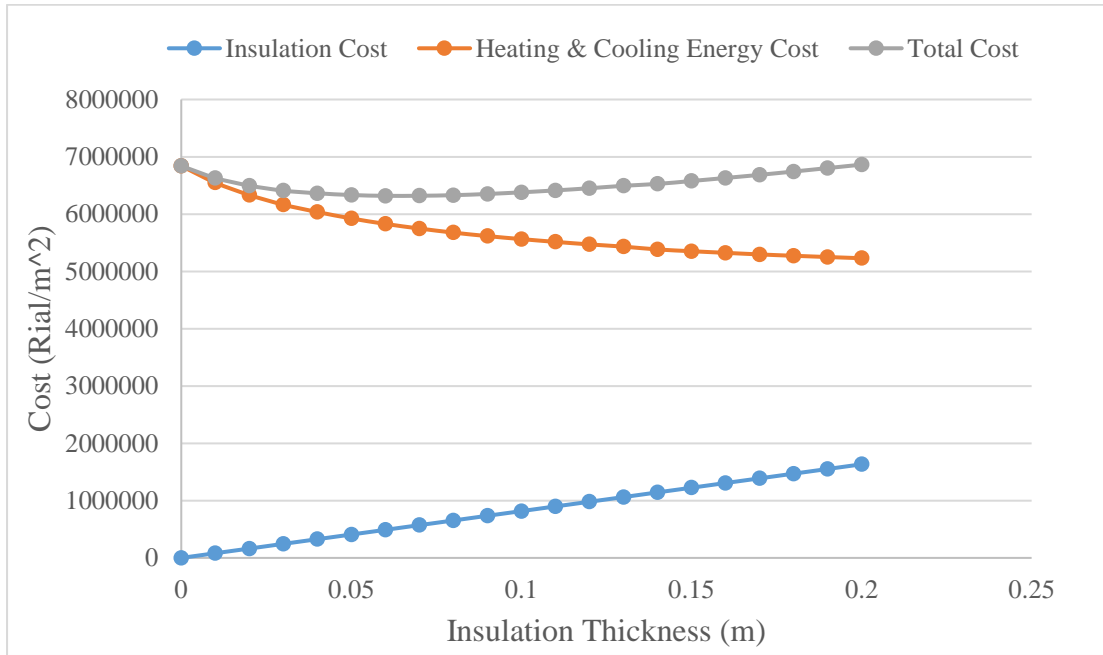


Fig. 15. Effect of Insulation Thickness of Stone Wool on the Total Cost in Tehran city in both Heating and Cooling Conditions

Table 6. Optimum Insulations Thicknesses in Tehran City in Heating, Cooling, and both Heating and Cooling Conditions

	Heating	Cooling	Heating and Cooling
Insulation Material	Optimum Thickness (cm)	Optimum Thickness (cm)	Optimum Thickness (cm)
Glass Wool	4.4	2.68	8.13
Stone Wool	3.33	2.38	5.93

3.2 Energy Savings

Apart from optimization of insulation thickness, investigation of energy savings is one of the most significant methods in order to compare insulation materials in aspect of energy consumption. As mentioned, increasing insulation thickness in external walls reduces heating and cooling loads of the building. Heating or cooling energy savings with respect to insulation thickness for all examined insulations and climate zones are shown in Figs. (16-19). Results depict that polyurethane is the most effective insulation material in order to save energy. Elastomeric, Stone wool, and glass wool are placed in next orders, respectively.

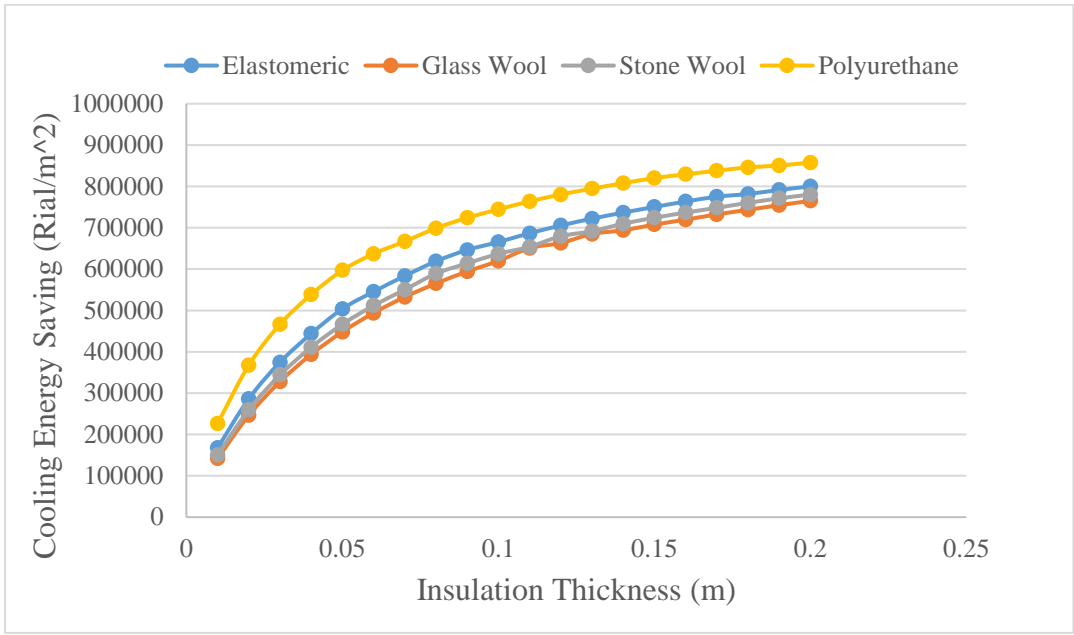


Fig. 16. Comparison of Cooling Energy Savings of Studied Insulation Materials in Bandar Abbas city

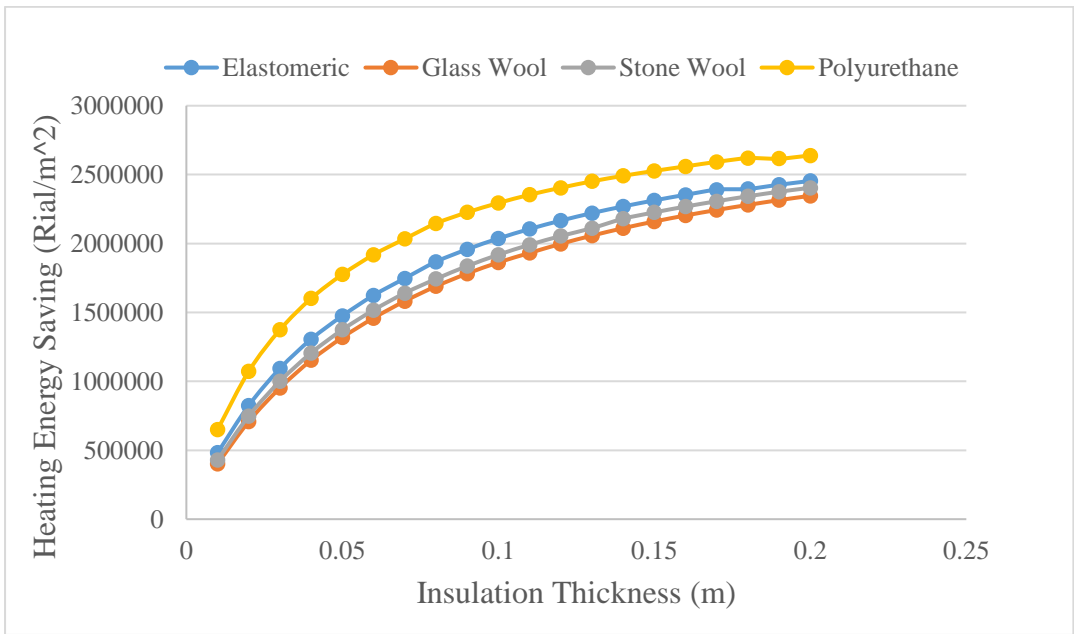


Fig. 17. Comparison of Heating Energy Savings of Studied Insulation Materials in Tabriz city

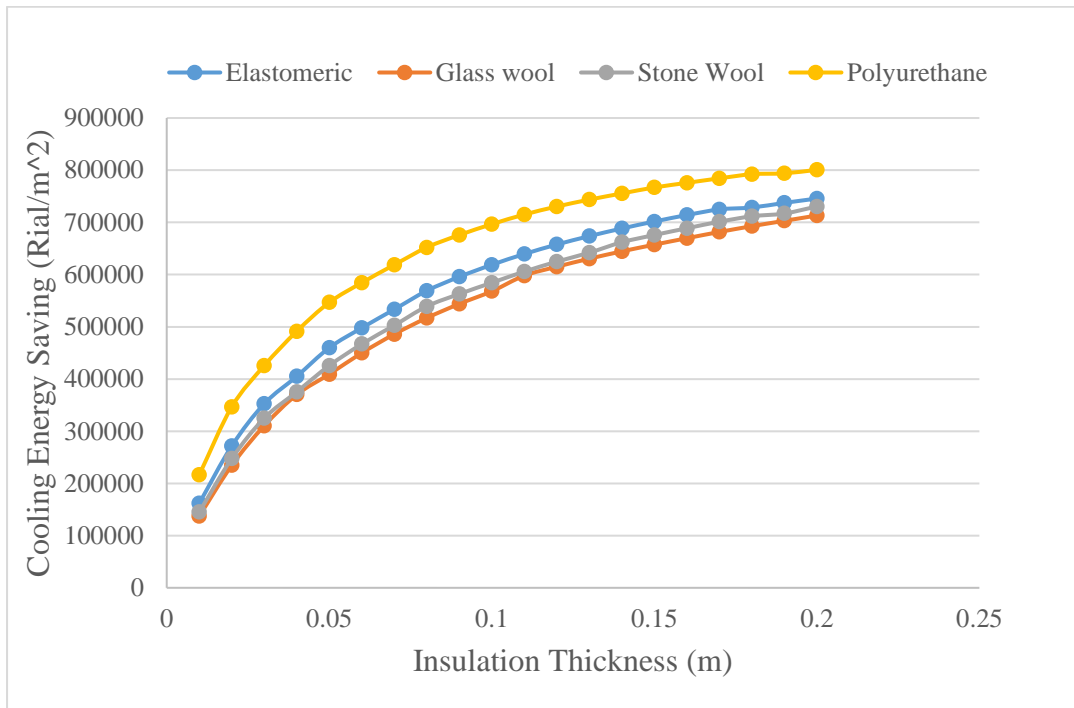


Fig. 18. Comparison of Cooling Energy Savings of Studied Insulation Materials in Tehran city

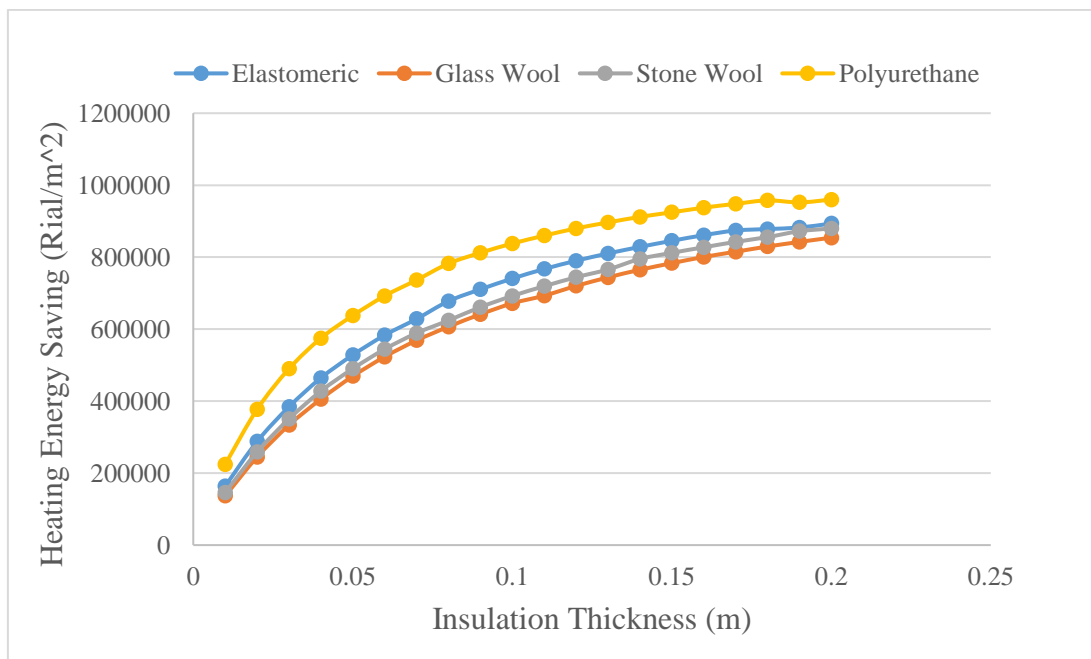


Fig. 19. Comparison of Heating Energy Savings of Studied Insulation Materials in Tehran city

4. CONCLUSION

This paper investigates the energy-economic optimization of insulations thicknesses based on total costs of insulation and energy over a lifetime of 20 years. In order to determine optimal thickness of insulations, heating and cooling loads of the modelled building are calculated in three cities in Iran with different climate zones. Insulation materials including

elastomeric, polyurethane, stone wool and glass wool with different thermal conductivities and costs are used in external walls. Furthermore, analysis of energy savings and payback periods are considered in this study. Results show that optimum insulation thickness is between 0.79 cm and 11.39 cm. Also, payback periods vary from 5.66 to 9.43 years. Investigation of insulation materials illustrate that total costs of insulation and energy will decrease by using glass wool. Analysis of energy saving demonstrates that the amount of saved energy increases when polyurethane is utilized. Elastomeric, stone wool, and glass wool are placed in next steps, respectively.

NOMENCLATURE

U	Overall Heat Transfer Coefficient (W/m ² K)
R	Thermal Resistance (m ² K/W)
A	Area (m ²)
h	Convective Heat Transfer Coefficient (W/m ² K)
L	Material Thickness (m)
k	Thermal Conductivity (W/mK)
$C_{t.H}$	Total Cost in Heating Condition (Rial/m ²)
$C_{t.C}$	Total Cost in Cooling Condition (Rial/m ²)
$C_{t.H.C}$	Total Cost in both Heating and Cooling Condition (Rial/m ²)
$C_{A.H}$	Annual Heating Cost (Rial/m ²)
$C_{A.C}$	Annual Cooling Cost (Rial/m ²)
C_y	Unit Insulation Cost (Rial/m ³)
x	Insulation Thickness
PWF	Present Worth Factor
i	Interest Rate (%)
g	Inflation Rate (%)
r	Actual Interest Rate
N	Lifetime (year)
PP	Payback Period (year)
$C_{O.ins}$	Optimized Insulation Cost (Rial/m ²)
A_{year}	The Difference Between Annual Energy Cost Without Insulation and With Optimized Insulation (Rial/m ² .year)

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