ANALYSIS OF OPTIMUM INSULATION THICKNESS FOR EXTERNAL WALLS AT DIFFERENT ORIENTATIONS BASED ON REAL-TIME MEASUREMENTS

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In this study, the optimum insulation thickness was calculated for the heating season for external walls in the different directions of a building. For this reason, a building used for housing in Istanbul, Turkey was taken as -model. The indoor and outdoor temperatures, along with the interior and exterior surface temperatures of the building's external walls, were continuously measured using thermocouples and recorded in four different directions throughout the year. The effects of solar radiation, which vary based on the direction, were assessed for the heat transfer through the external walls. The results of this study indicate that the optimum insulation thickness for the north, south, west, and east facing walls should be 6.47, 2.87, 6.97, and 6.98 cm, respectively, based on the differences in the amount of solar radiation exposure of the walls in the different directions. The optimum insulation thickness of the building's external wall was calculated as 5.25 cm, regardless of its direction. An economic analysis of the thermal insulation cost was conducted using the P_1-P_2 method, and then the payback periods were calculated. The heating energy consumption of the building designed using the optimum insulation thicknesses, as identified separately based on the direction, decreased by 17%, compared to the present building with 3 cm of thermal insulation.

Key words*: Optimum insulation thickness, insulated external walls, heating energy, orientations*

1. Introduction

The concept of energy has become crucial as energy sources rapidly decrease and CO_2 emissions into the atmosphere resulting from energy use increase. Considering the winter conditions in Turkey, it should be noted that the major portion of the energy consumed in buildings is used for heating purposes. The energy consumption in buildings can be significantly decreased through the optimum insulation thickness and with the proper insulating materials, as well as through improvements in the windows and joineries, and the use of an efficient heating system. The "TS 825 Standard on Thermal Insulation in Buildings" was put into force to offer a solution to minimizing the energy consumption in Turkey. Thermal insulation increases the initial investment cost of a building. However, this investment cost is paid back in the short term as the energy consumption of the building decreases. The outdoor temperature, heat transfer coefficient, and material cost are the parameters to consider when choosing an insulating material. When the thickness of the insulation increases, the consumption of the heating and cooling energy decreases. An optimum insulation thickness exists for insulation applications, at which the total investment cost is minimized [1]. Although some studies on the optimum insulation thickness of a building's external walls have been undertaken, the number of studies conducted on the optimum insulation thickness of the external walls, which varies according to the direction of the wall, is quite limited in the literature. Sanea and Zedan [2] used a dynamic time-dependent model based on an implicit finite-volume method to compute the annual transmission losses through a wall under steady-periodic conditions for the climatic conditions of Riyadh. Daouas [3] calculated the optimum insulation thickness, energy saving, and payback period for a typical wall structure based on both cooling and heating loads. He calculated optimum insulation thickness 10.1 cm, energy saving 71.33% and a payback period 3.29 years. It was noted that the wall orientation has a small effect on the optimum insulation thickness, but a more significant effect on energy saving, which reaches a maximum value of 23.78 Tunus Dinar/m^2 in the case of an eastward facing wall. Özel [4] examined the relationship between insulation and a building's cooling requirement in Antalya, Turkey. Accordingly, the lowest insulation value (3.10 cm) for the cooling season was seen to be in the north facade, whereas the maximum insulation thickness was stated in the east and west facades. As a result, the north facade was designated as the most economical among the others. Taking the speed and direction of the wind into account, Axaopoulos et al. [5] conducted a study to determine the optimum insulation thickness according to the directions and building materials during the heating and cooling seasons. As a result of calculations based on three different building materials and different directions, they observed that the optimum isolation thickness varies between 7.10 and 10.10 cm. Özkan et al. [6] developed software in accordance with the TS 825 standard. The effects of the change in window and external wall areas on the building's heating energy requirement and optimum insulation thickness were examined. Özel and Pıhtılı [7] set the optimum insulation thicknesses for five cities in Turkey, using the heating and cooling degree days figures. Özkan and Onan [1] determined the optimum insulation thickness for two different fuel types and two different insulating materials, based on the P_1-P_2 economic analysis method for four different degree-day regions in Turkey. Furthermore, they analyzed the relationship between the optimum insulation thickness and CO_2 and SO_2 emissions released into the atmosphere based on the fuel type. Kürekçi et al. [8] calculated the optimum insulation thickness, energy saving, and payback periods for two different fuels and five different insulating materials in 81 cities in Turkey through a life-cost analysis using the heating degree-day figures. Bolattürk [9] used five different fuel types to compute the optimum insulation thickness and payback periods for 16 cities in four climatic zones of Turkey. Bolattürk [10] calculated the optimum insulation thickness on the building's external walls in the first climatic zone of Turkey, based on the annual heating and cooling loads, and determined the payback periods using the P_1-P_2 method in another study. Gürel and Daşdemir [11] calculated the optimum insulation thicknesses and energy saving in Aydın, Edirne, Malatya and Sivas cities of Turkey. EPS and XPS were selected as the insulating materials for the external wall. The results indicate that the optimum thickness varies between 0.036 and 0.10 m, with an energy saving between 12.08 and 58.28 TL/m^2 and a payback period between 1.50 and 2.52 years. Dombaycı et al. [12] used two different insulating materials and five different fuel types, and computed the optimum insulation thickness for Denizli, Turkey. Kaynaklı [13] used the outdoor temperature values between the years 1992 and 2005, and calculated the degree-hour values for the heating season, determining the optimum insulation thickness for Bursa, Turkey, based on these values. Kaynaklı et al. [14] conducted some analyses to determine the optimum insulation thickness to be applied to external walls. They included the effects of solar radiation on the outdoor temperatures in their calculations, and considered the heating and cooling energy requirements together for an optimization of the heat insulation thickness. Onan [15] investigated the existing building stock in Turkey depending on such parameters as the height and area. A model building was created covering all of these buildings. The results showed that the optimum insulation thickness varies between 3.21 and 7.12 cm, the energy saving varies between 9.23 and 43.95 US$/m^2, and the payback period varies between 1 and 8.8 years depending on the region.

The P_1-P_2 economic analysis method was used to determine the optimum insulation thickness, depending on the direction, for a building in Istanbul, Turkey within the scope of the present study. The outdoor and indoor temperatures, as well as the interior and exterior surface temperatures of the external wall, were measured from four directions and recorded using a data logger. The building's interior and exterior surface temperature data, which have been measured for the entire year, were used, and a model was created in accordance with the TS 825 standard [16]; in addition, after the optimum insulation thicknesses were determined based on the directions, the energy saving and payback periods were calculated. The optimum insulation thickness was found to be 6.47, 2.87, 6.92, and 6.98 cm for the north, south, west, and east, respectively..

2. Measurement and Evaluation

The model building we focused on in our study is located in Istanbul, Turkey. According to the average of many years, the outside temperatures of Istanbul are at a minimum of -6.1 °C in the heating season and 35 °C in the cooling season. The building consists of two normal floors, a ground floor, and a basement. Architectural drawings of the model building are shown in Fig. 1. The surface area of the building's exterior wall is 898 m^2. The window areas are 57.50, 121.00, 32.30, and 32.30 m^2 for the north, south, east, and west, respectively. The interior surface, indoor, exterior surface, and outdoor temperatures of an existing building were measured for the entire year from all directions. Thermocouples were installed on the interior and exterior surfaces, and in the indoor and outdoor areas of the building's external wall, to measure the temperatures simultaneously. The temperature values of the measured surfaces were used in the heat loss calculations.

The thermocouples used to measure the indoor temperatures were installed to center the story height within the rooms to avoid being affected by any heat sources. The thermocouples used to measure the outdoor temperatures were situated in an outdoor area to avoid having any contact with the windows and external walls at all facades, and to allow exposure to the heat flow through the external walls. The installation of the thermocouples used to measure the temperatures is illustrated in Fig. 2. Expandable Polystyrene (EPS) is used as an insulation material, a thermoplastic product that is lightweight, strong, and offers excellent thermal insulation, making it ideal for the packaging and construction industries.

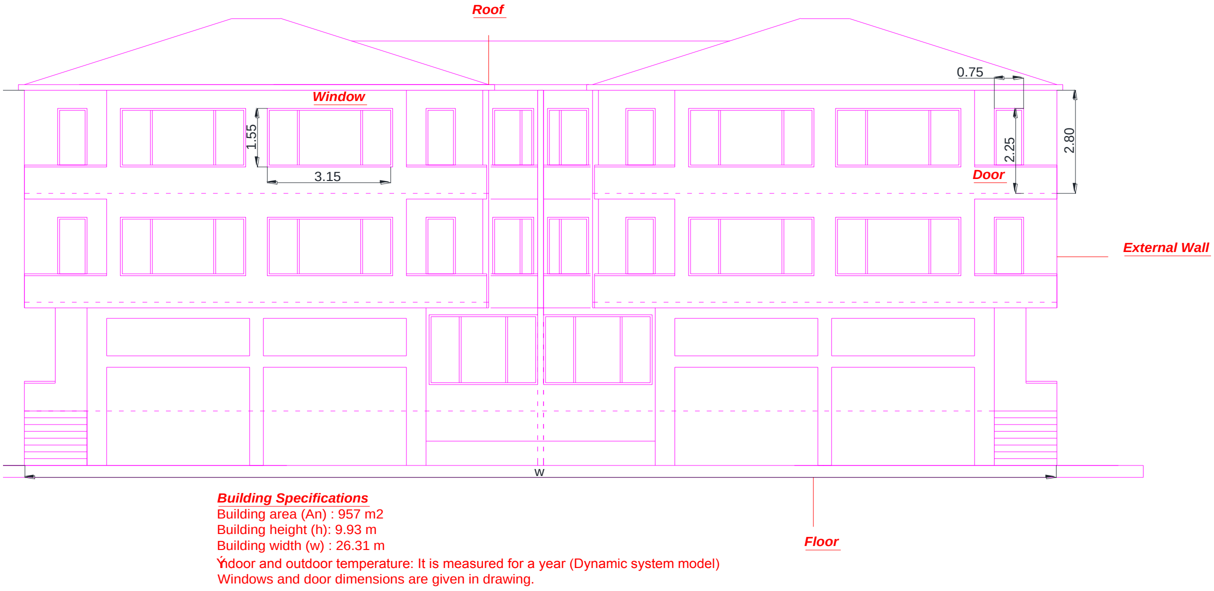

Figure 1. Front view of the building

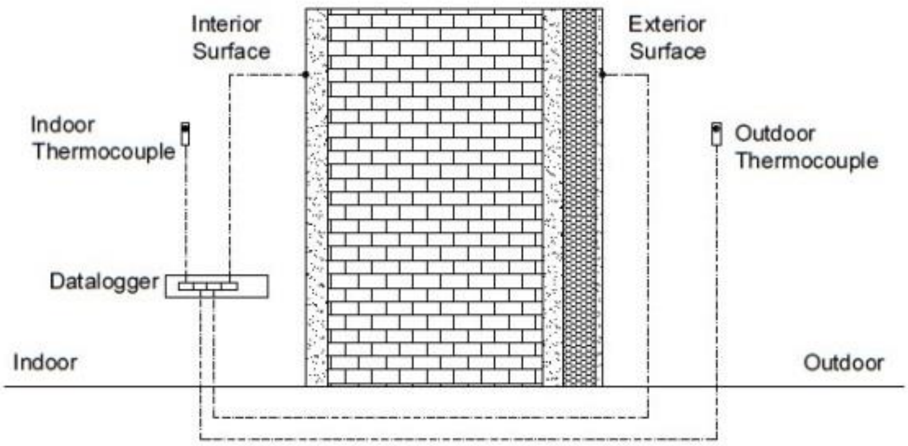

Figure 2. The installation of the thermocouples

Four-piece 4-channel data loggers were used for the temperature measurements. Type-K thermocouple probes were used with the data loggers, whose accuracy is ±0,30 °C within the related range of measurements. The coldest day was determined as January 10, and the hottest day as August 18, according to the measurements recorded during the entire year. Figure 3 shows graphically the changes in temperature of the exterior surfaces according to the time from all directions for January 10, which was the coldest day of the year. The figure shows that the temperature of the external walls has the lowest value at 06:30, and the highest value at 14:00 in all directions.

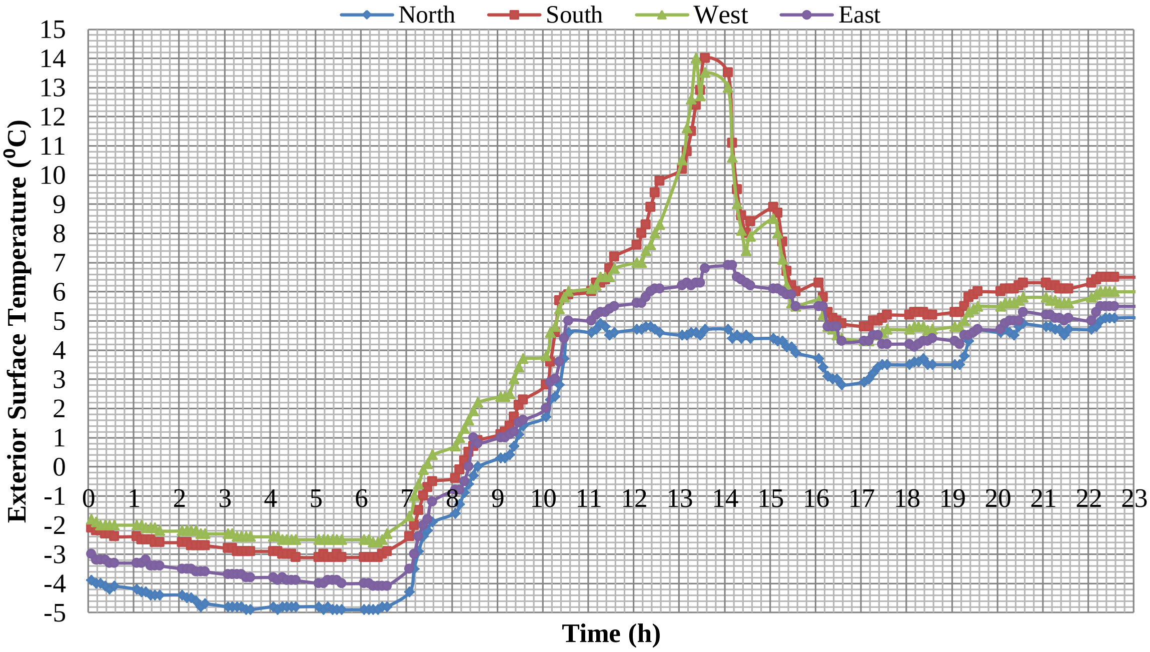

Figure 3. January 10th exterior surface temperature-time

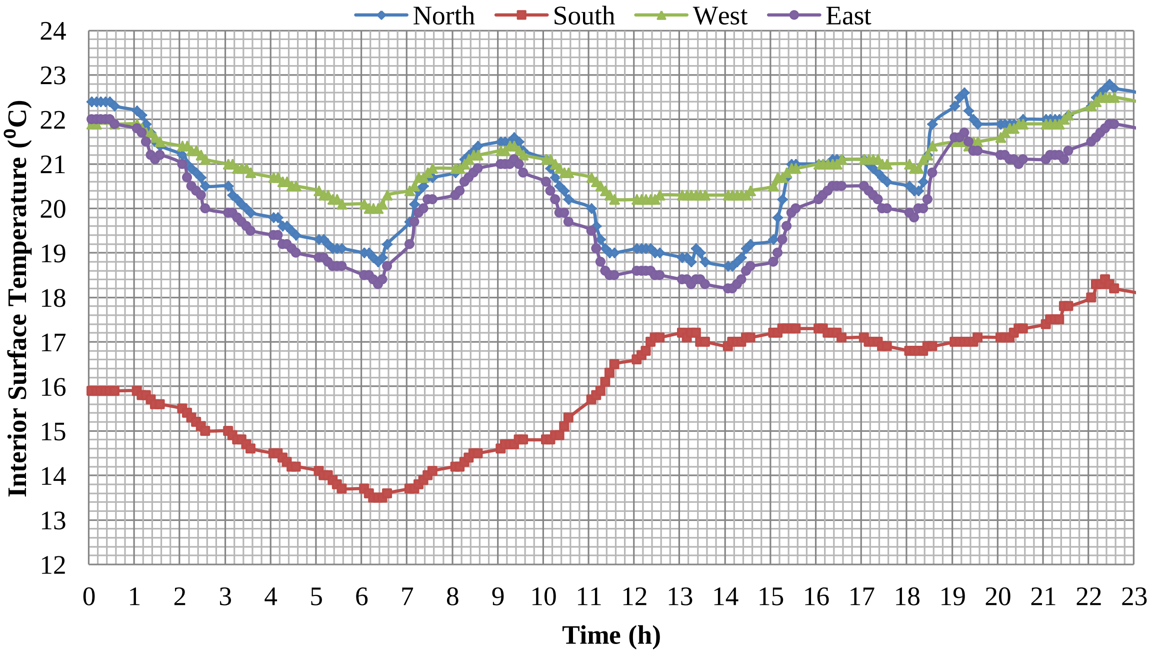

Figure 4. January 10th interior surface temperature-time

Figure 4 shows graphically the changes in temperature of the interior surfaces according to the time from all directions for the same day, January 10, the coldest day of the year. The figure indicates that the interior surface has minimum temperature values at 06:30 in all directions, with the lowest value being for the south facade in particular.

3. Heat Load for External Walls

In Turkey, the insulation thickness used in buildings is limited by the heating energy requirements in the TS 825 standard [16]. This method is similar to DIN 4108, and the method defined in DIN was adapted to Turkey. The annual heating energy requirements and sub-equations are shown in Tab. 1. The descriptions and formulas are shown in the table, respectively. The assumptions used in Eqs. (1) through (9) are also shown in Tab. 2. Values of the monthly average solar radiation intensity of the solar radiation are taken from the TS 825 standard [16] and shown in Fig. 5.

The minimum insulation thickness is calculated using Eq. (10) according to TS 825 for all regions.

$$L_s = \frac{\sum_{month} A_{ew} \lambda \Delta T}{Q_s \times 0.44 V_{gross} + \sum_{month} (\eta(\phi_{in} + \phi_s) - M \quad \Delta T \quad)} - R_{ww} \lambda \tag{10}$$

Table 1. Model calculations and their descriptions

Equation No	Formula	Description
Eq.(1)	$Q_{year} = \sum_{j=1}^{12} \left[H(T_{in} - T_{out,j}) - \eta_j (\phi_{in} + \phi_{s,j}) \right] \times t$	The annual heating energy requirements for the model buildings is calculated as given in [15]
Eq.(2)	$\phi_{s,j} = \sum_k r_j g_j I_{j,k} A_{gl,k}$	Monthly average solar energy gain
Eq.(3)	$g_j = F_w \times g_{\perp}$	g is the solar energy permeation factor
Eq.(4)	$\eta = 1 - e^{\frac{H(T_{out} - T_{in})}{(\phi_{in} + \phi_s)}}$	Unitless monthly average usage of heat gain factor (the ratio of the heat losses to the heat gains)
Eq.(5)	$H = H_{tr} + H_{ven}$	Specific heat loss (H) of the building is calculated by adding the heat loss occurred in consequence of conduction and convection (H_{tr}) to the heat loss occurred in consequence of ventilation (H_{ven}).
Eq.(6)	$H_{ven} = 0.264 \times n_a \times V_{gross}$	Heat loss occurred in consequence of ventilation
Eq.(7)	$H_{tr} = U_{ew} A_{ew} + U_{gl} A_{gl} + 0.5 U_{fl} A_{fl} + 0.8 U_{ce} A_{ce}$	Heat loss occurred in consequence of conduction and convection
Eq.(8)	$U_{ew} = \frac{1}{R_{in} + R_{cw} + R_{ins} + R_{out}}$	The wall conductance U for a typical wall that includes a layer of insulation

Eq.(9)	$$R_{ins} = \frac{L_{ins}}{\lambda_{ins}}$$	R_{ins} is the thermal resistance of the insulation layer

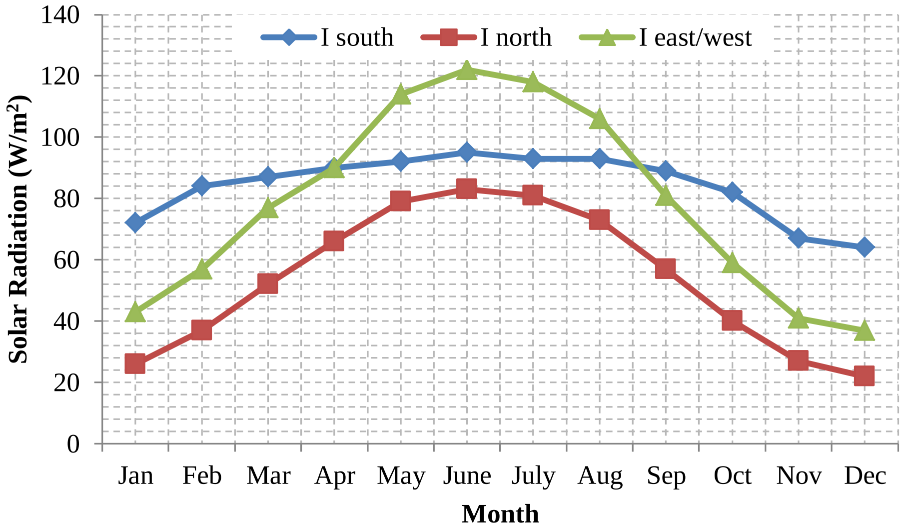

Figure 5. Monthly average solar radiation intensity used in the calculations (W/m^2)

Table 2. Assumptions used in model calculations

Equation No	Assumptions and Descriptions
Eq.(1)	ϕ_{in} is the average interior heat gain, 5 W/m^2 per unit usage area considered maximum as the interior gain in residences, schools, and the buildings equipped normally (such as office buildings). Monthly average outdoor temperature values and monthly average interior temperature values are calculated with a dynamic system model. The data are collected by a measurement as described above.
Eq.(2)	r is the monthly average shading factor of the transparent surfaces, considered 0.6 due to the fact that generally buildings are located around uninsulated buildings or there is shading caused by trees in Turkey I values are taken from TS 825 according to direction (k) and month (j). Values of the monthly average solar radiation intensity used for calculation of the solar radiation coming on the windows are given in Fig. 5.
Eq.(3)	F_w is the correction factor for windows and considered 0.80. $g_{\perp}$ is the solar energy permeation factor measured under laboratory conditions for the rays striking the surface vertically and is considered 0.75 for colorless insulation glass [16].
Eq.(6)	Air changing ratio (n_a) is taken constant "0.80" according to TS 825 which is similar to DIN 4108 for all regions. (Natural ventilation)
Eq.(7)	Heat transfer coefficients for ceilings, floors, and windows are shown in Tab. 3.
Eq.(8)	R_{in} and R_{out} are the inside and outside air film thermal resistances, respectively, R_{cw} is total thermal resistance of the composite wall materials without the insulation. Recommended design values for air film thermal resistances on the inner and outer surfaces of a building are R_{in} = 0.13 m^{2}K / W and R_{out}= 0.04 m^{2}K / W.
Eq.(9)	L and λ are the thickness and heat transfer coefficient of the insulation material, respectively. Heat transfer coefficient (λ or k) is taken 0.040 W/mK for EPS.

Table 3. Values of the heat transfer coefficients (W/m^{2}K)

U_{ew} (W/m^{2}K)	U_{ce} (W/m^{2}K)	U_{fl} (W/m^{2}K)	U_{gl} (W/m^{2}K)
0.61	0.65	0.60	2.50

4. Economic Analysis

The P_1-P_2 method, which is an economic analysis method, was used to calculate the optimum insulation thickness. The net energy recovery is calculated using Eq. (11) according to the P_1-P_2 method.

$$S = \Delta E\, C_f\, P_1 - C_{ins} P_2 L_{ins} A_d \tag{11}$$

The present worth factor P_1 is calculated using Eq. (12), depending on the interest and inflation rates set by the Central Bank of the Republic of Turkey [20] in 2017, during its investment life.

$$P1 = \frac{1}{d\text{-}i}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right] \tag{12}$$

Because it was agreed that the maintenance and operating costs are not included in the calculations, the P_2 value is considered to be 1.

The optimum insulation thickness depends on certain parameters, such as the price of the insulating material, the heat transfer coefficient, the efficiency of the heating system, and the type of fuel.

The economic parameters used in the calculations are illustrated in Table 4.

Table 4. Economic Parameters

Fuel cost (C_f)	0.410 \$/Nm³
Insulation unit price (C_{ins})	102 \$/m³
Interest rate (i)	0.11
Inflation rate (d)	0.0732

Accordingly, the cost of the insulating material is calculated using Eq. (13).

$$C_{insulation} = C_{ins} L_i A_d \tag{13}$$

The annual fuel cost equation for buildings that require heating is

$$C_{yf} = \frac{Qyear}{H\ \eta_b} C_f \tag{14}$$

where H (kj/Nm³), η_b, and C_f (TL/Nm³) indicte the lower heating value of natural gas, the efficiency of the heating system, and the unit price of the fuel, respectively.

$$S = -\frac{\sum_{j=1}^{12}\left[\left(M + \frac{Ad}{R_d + \frac{L_i}{k_i}}\right)\Delta T + \left(\left(e^{\frac{(M+A_d\,U_d)\Delta T}{\varphi i+\varphi s}} \text{-}1\right)(\varphi_i + \varphi_s)\right)\right]\frac{86400 \times 30}{1000}}{H\,\eta_b} C_f\, P_1 + C_{yf} P_1 - C_i\, P_2 L_i\, A_d \tag{15}$$

The optimum insulation thickness is the thickness at which the net energy recovery is at the maximum level. For this reason, the insulation thickness that evanishes the derivative of the energy recovery equation indicates the optimum insulation thickness. Accordingly, the optimum insulation thickness is calculated using Eq. (16).

$$L_{\text{opt}} = \left(\sum_{j=1}^{12} \frac{k\Delta T 2592 C_{yf} P_1}{H\eta C_i P_2} \left(1 - e^{-\frac{(M+\frac{A_d}{R_d+\frac{Li}{ki}})\times\Delta T}{\varphi i+\varphi s}} \right) \right)^{0,5} - R_d \times k_i \tag{16}$$

Here, M indicates the multiplication of the heat transfer coefficient and wall area for a 3cm insulated wall in the current situation. The parameters used in the calculation are shown in Tab. 5.

Table 5. Account Parameters

Lifetime (N)	10 year
Naturalgas low heating value (H)	34526 kJ/Nm³
Thermal efficiency (η)	0.93
Wall thermal resistance (R_d)	0.89 m²K/W
EPS heat transfer coefficient (k_i)	0.04 W/mK

To consider an investment as profitable, the cost should be affordable, and a profit returned in the short term. Considering changes in the inflation and interest rates over time, the payback period was calculated using Eq. (17) for a thermal insulation investment of the building.

$$G = \frac{\ln\left(1 - \frac{C_i\ P_2\ L_i\ A_d\ H\ \eta\ (d-i)}{C_{yf}\ H\ \eta - C_f\ \sum_{j=1}^{12}\left[\left(M + \frac{A_d}{R_d + \frac{L_i}{k_i}}\right)\Delta T + \left(\left(e^{\frac{(M+A_d U_d)\Delta T}{\varphi i+\varphi s}} - 1\right)(\varphi_i + \varphi_s)\right)\right]\frac{86400 \times 30}{1000}}\right)}{\ln\left(\frac{1+i}{1+d}\right)} \tag{17}$$

5. Results and Discussion

As shown in Tab. 6, insulation applied to the present buildings regardless of its direction is an economically profitable investment. For the optimum insulation thickness based on the direction, the maximum energy saving and minimum payback period were observed for the north facade, where the annual saving amount is 89.38 TL/m² with an optimum thermal insulation thickness of 6.47 cm.

Table 6. Optimum insulation thickness difference according to the direction

Direction	Optimum Ins. Thickness	Energy Saving	Payback Period
North	6.47	38.65	1.64
South	2.87	-	-
East	6.98	31.96	2.04
West	6.92	32.02	2.02
Each facade	5.25	29.54	2.14

Because the optimum insulation thickness was calculated to be 2.87 cm for the south facade, where the thickness of the building's existing thermal insulation is 3 cm, according to the measurement and calculation results, the present insulation was deemed to be proper. For this reason, the energy saving and payback period were not calculated for the south facade. The ratio of window area to wall area is higher for the south facade, as compared to the other facades, and for this reason, the heat loss through the wall in this facade is smaller. The optimum heat insulation thickness of the south facade was found to be much lower than that of the other facades. Accordingly, along with the building's orientation, environmental conditions of the area, building location, the unit prices of the fuel, insulating materials, the architectural design are having great importance when determining the optimum insulation thickness. The results found in the literature were compared with those of the present study, as shown in Tab. 7.

Table 7. Comparison of the model building results data with the latest studies.

Author	Year	Optimum insulation thickness (cm)	Payback period (year)	Energy saving ($\$/m^2$)
Kucuktopcu et. al. [21]	2018	2.80	2.16	31.15
Ashrafian et. al. [22]	2016	-	6.60	34.50
Onan [15]	2014	4.94	1.26	21.60
Bektas et. al. [20]	2012	3.20	2.90	21.40
Özkan and Onan [1]	2010	7.04	2.07	32.88
Ucar et. al. [18]	2009	1.06	3.77	-
Kaynakli [13]	2008	5.30	-	8.64
Sisman et. al. [19]	2007	4.70 (Coal)	2.28	22.10
Bolattürk [9]	2006	3.60-4.70	2.10-2.52	-
Dombaycı et al. [12]	2006	-	-	-
Present study		5.25	2.14	30.09

For the calculation of the heating loads transmitted through the external walls, hourly measurement data were used. The heating energy consumption, which was calculated using the optimum insulation thicknesses determined according to the different directions, decreased by 17% in comparison to a building with 3 cm thick thermal insulation. Figure 6 shows the heating energy requirement of the model building based on the month for the optimum insulation thickness of the external walls both dependentlyand independently of the wall direction. The figure indicates a decrease in the building's heating energy requirement when the thermal insulation thickness is applied according to the direction examined.

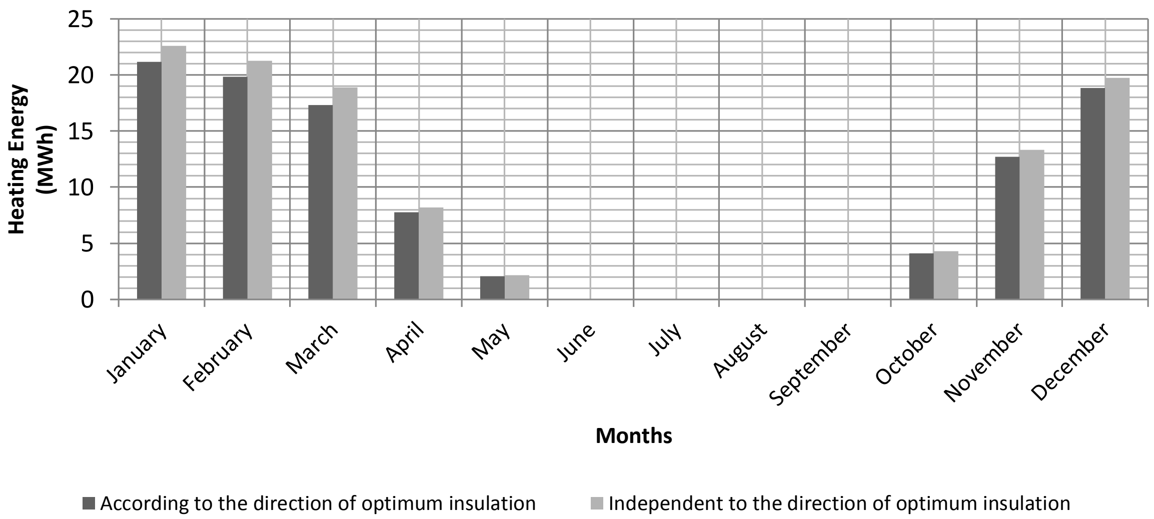

Figure 6. Heating energy requirement compared to the optimum insulation thickness

6. Conclusion

An economic analysis of the thermal insulation cost was conducted using a P_1–P_2 method, and the payback periods were calculated. Thermal insulation of 3 cm thickness was considered when calculating the optimum insulation thickness and conducting the economic analyses. Accordingly, the calculation results were evaluated using the existing thermal insulation. The energy saving and payback periods were calculated as 89.38 TL/m² and 1.64 years, 74.05 TL/m² and 2.02 years, and 73.91 TL/m² and 2.04 years for the north, west, and east facades, respectively.Considering the wall direction used, the maximum energy saving and shortest payback period were observed for the north facade, where the optimum insulation thickness was 6.47 cm and the annual saving was 89.38 TL/m² for an external wall. As a result of the measurements, 3 cm thick insulation for the south facade, where the existing thermal insulation is 2.87 cm, was considered to be proper, and for this reason, the energy saving and payback period were not determined. For the optimum insulation of equal thickness in all directions, the energy saving is 12%, and for the optimum insulation of different thicknesses based on the difference in direction, the energy saving reaches 17 %.

The majority of heat loss through the south facade of the building results from the windows, whereas only a small portion of the heat is lost through the walls. One of the reasons why the optimum insulation thickness is lower for the south facade than for the other facades is the window-to-wall ratio. It was concluded that the building's orientation, the heat transfer coefficients of the building, the insulating materials, and the architectural design should be taken into account when calculating the optimum insulation thickness.

Nomenclature

A: Area [m^2]
C: Cost [US$]
d: Inflation rate [%]
g: Solar energy permeation factor [-]
H: Specific heat loss of the building [W/K]

h: Building height [m]

i: Interest rate [%]

I: Monthly average solar radiation [W/m^2]

k: Direction [-], Heat transfer coefficient [W/mK]

L: Insulation thickness [m]

LHV: Low heating value of the fuel [kJ/Nm^3]

M: Specific heat loss excluding heat transferred from the external wall to outside [kJ], Weight [kg fuel]

M_s: Ratio of the annual maintenance and operation cost to the original first cost [-]

n: Air changing ratio [-]

N: Lifetime, payback period [year]

r: Monthly average shading factor of the transparent surfaces [-]

R: Thermal resistance [m^2K/W]

S: Net energy saving [US$/m²]

t: Time [sec]

T: Temperature [°C]

U: Heat transfer coefficient [W/m^2K]

Q: Annual heating energy requirement [J]

V: Volume [m^3]

<u>Greek Symbols:</u>

η: Average usage of heat gain factor [-]

η_b: Efficiency of the boiler/heating system [-]

ϕ: Monthly average heat gain [W]

ε: Glazing area percentage [%]

λ: Heat transfer coefficient [W/mK]

ΔE: Fuel consumption quantity difference between buildings with insulation and present insulation.

<u>Subscripts:</u>

a: air

A: Annual

avg: Average

ce: Ceiling

cw: Composite wall materials with present insulation

ew: External wall

f: Fuel

fl: Floor

gl: Glazing

in: Inside

ins: Insulation

j: Month

m: Buildings

opt: Optimum

out: Outside

s: Solar

tr: Transfer
ven: Ventilation
w: Window

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