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Energy-Performance Evaluation with Revit Analysis of Mathematical-Model-Based Optimal Insulation Thickness

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Abstract: This study investigates the optimum insulation thickness value using MATLAB Optimization Toolbox based on a mathematical model for sandwich walls that are formed with different insulation-building materials by different fuel types for a particular city located in the second climatic region of Turkey. In the second stage of study, using the BIM-based Revit simulation program, a building was designed with the same building-insulation materials under the same climate conditions. The six different wall performances were compared for the designed building. The study proposes a comprehensive approach by combining technical and economic factors in the sustainable design of buildings. The computational results indicate that using different energy alternatives has a significant impact on the air quality in residential areas. The lowest value is reached when natural gas is used. The energy cost savings change from 7.56 to 14.12 TRY/m^2 for external walls. While payback periods vary between 2.15 and 3.76 years for external walls, the lowest period for all wall types is obtained for electricity, which has a high cost. The optimum insulation thickness for 10 years of lifetime varies between 0.02 and 0.16 m. This study reflects that the highest optimal insulating thickness is reached when electricity is utilized as the energy source for all wall types. According to the Revit analysis, the lowest energy consumption of 21,677 kWh during one year using natural gas was obtained for a building material of porous light brick and an insulation material of glass wool.

Keywords: optimum insulation thickness; energy efficiency; environmental impact

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1. Introduction

The efficient use of energy, as well as conservation of it, is vital in order to avoid economic and environmental problems. Heat insulation is one of the most significant stages towards developing policies related to energy efficiency on a global scale. Residential areas, consuming around 30–35 percent of the total energy in Turkey, possess a significant energy-saving potential, thus drawing an increasing amount of attention [1]. Although insulation is an application that increases the initial investment cost, it contributes to the energy conservation and overall economy depending on the payback period calculated through the initial cost and energy conservation.

Considering that fossil energy sources are quickly depleted, it is vital for a building to provide thermal comfort using the minimum amount of energy. To reduce the heating energy consumption to a minimum level, thermal insulation must be as high as possible. Providing thermal comfort in buildings at optimum conditions is enforced by the standards and regulations related to the construction industry. First, the "Regulation on Heat in Buildings" was put into force by the Ministry of Public Works and Settlement on 8 May 2000 [2]. Later, the "TS 825 Thermal Insulation Standard" [3,4] came into force following a revision since 14 June 2000 [5]. Nowadays, the compulsory criteria are applied for providing thermal comfort in newly built houses by using these standards and regulations. These regulations and standards clearly indicate that reaching thermal comfort in buildings is directly related to the thermal features of the materials utilized as construction

elements and/or components at appropriate thickness levels. Similarly, the majority of the research conducted on energy conservation cover the required actions towards conservative consumption of energy sources. Such actions aim for conservation of the energy being spent on the heating and cooling loads of buildings [6]. The economic dimension of the improvement is investigated through research considering parameters such as the life of the building, reduction of energy cost, insulation application, and change of heating systems [7].

To resist heat flow, thermal insulation materials or their combinations are primarily utilized. A heat insulator is a weak thermal-conductive material with a lower thermal conductivity coefficient. Insulation is utilized to prevent thermal loss or promote energy savings in construction and manufacturing operations. Though its main purpose is economic, it also provides a more precise personal conservation and a check of operating temperatures. It prevents condensation on cold superficies and the corrosion that follows. These materials are porous and have a large number of dormant air cells [8,9]. Thermal insulation for building external walls is regarded as one of the more efficient methods of reducing energy usage for heating or cooling in buildings at a time when the demand for electricity is rising because of the increasing human population, sustained demand for comfortable living circumstances, and development and expansion projects. Furthermore, rising energy costs and the negative environmental impact of power plants overall support measures to significantly decrease energy usage. Air pollution such as SO_2, CO, CO_2, and dust grains are also reduced by insulation systems. Furthermore, insulation improves interior thermal convenience by lowering the thermal losses or savings from buildings to the environment during hot and cold months, respectively [10,11].

The thickness of insulation is determined by a variety of factors, including the building type, function, orientation, shape, insulation-building materials, cost, fuel type, climatic circumstances, and performance of air conditioning [12]. Thermal insulation in building exterior envelopes affects energy consumption, methodologies for choosing the optimal insulating thickness for diverse wall styles, thermal insulation materials, and their implementation in building external walls. The exterior walls account for 50 percent of heat loss in buildings, followed by doors and windows (20 percent), roofs (20 percent), and the foundation walls and basement (10 percent). The electricity and heating bills can be cut in half with energy savings provided by a building's thermal insulation, ensuring more effective utilization of energy sources [13]. Though the thermal savings and losses diminish as the insulation thickness increases, the total insulation cost, including installation and material expenses, increases as well. As a result, most investigators have defined the optimal insulating thickness in relation to expenses [14–16].

Many studies have been reported in the literature about the optimal insulation thickness depending on the degree-day methodology to predict the conduction loads under constant circumstances. Alsayed et al. computed the optimum insulating thickness in building external walls based on a life-cycle cost investigation with diverse degree-days. The conclusions showed that for all occasions, the optimum thickness changed from 0.4 to 9 cm [17]. Accordingly, Hasan applied the optimal thickness for a Palestine city. It was calculated to result in savings of up to USD21/m^2 of wall field for polystyrene and rock wool. Payback durations changed from 1.3 to 2.3 years for polystyrene and from 1 to 1.7 years for rock wool [18]. In Sudan, Khalid et al. modelled diverse climatic regions; they defined optimal thickness changes from 0.041 to 0.006 mm for different kinds of wall and diverse insulating materials. The annual mean energy conservation varied from USD13.1 to 0.4/m^2 [19]. For Athens in Greece, Axaopoulos et al. performed a study and mentioned that the optimal thickness changed between 0.234 and 0.112 m. Furthermore, for their results, the CO_2 rate declined by 72.2–63.2 percent depending on the location and structure of the wall [20]. Yu et al. analyzed a few diverse insulation materials' cost efficiency in China's moist sub-tropical climatic region to obtain the optimal thickness. Payback periods changed between 4.7 and 1.9 years throughout a 20-year period while the optimal thickness of foamed polyurethane, expanded polystyrene, and extruded polystyrene changed be-

tween 0.236 and 0.053 m [21]. In Iran, Ziapour et al. conducted research on a novel external envelope for buildings in provinces in three diverse climatic zones. The payback time and optimal thickness were analyzed from the findings for the chosen provinces. The payback duration was reported to be 0.33, 0.49, and 0.57 years, respectively, while the optimal thickness was 16.35, 11.95, and 10.6 cm, respectively [22]. By utilizing P_1–P_2 financial methodology, Vincelas et al. evaluated seven common insulating materials applied in five different wall structures for buildings situated in Cameroon. The most appropriate wall was found to be 9 cm extruded polystyrene. Depending on the type of wall, the payback period, optimum thickness, and the energy savings were reported to be between 0.91–2.21 years, 8.2–10 cm, and USD44–50 /m^2, respectively [23]. In Malaysia, Shekarchian et al. computed some common insulation materials' optimum thickness values [24]. As the most efficient insulation material, fiberglass urethane having an optimal thickness (2.2 cm) could obtain an energy conservation of USD1.8 /m^2. In Greece, Kontoleon and Tzoulis calculated optimal thicknesses by taking the primary directions into account. The findings displayed that the extruded polystyrene's optimal thickness ranged from 7.5 to 10 cm depending on the external wall directions [25]. Other studies on the assessment of optimal insulating thickness on the external walls depending on the degree-day analysis and life-cycle cost concept with the inclusion of the effect of different energy resources, diverse insulation materials, and climate zones have been performed by references [26–28]. For China's moist sub-tropical climate zone, Huang et al. investigated a novel improved aerogel super-insulating material to maintain financial advantages and energy conservation in thermal insulating implementations. The super-aerogel insulating material was tested against the four most-commonly used insulating materials in implementations. For the zone researched, the aerogel's optimal thickness was determined to be 3.70 mm. Additionally, the greenhouse gas emission degradation potency was greater than that of the four diverse insulating materials when the novel material's thickness was increased [29]. For a characteristic wall structure, Daouas computed the optimal insulating thickness, payback period, and energy savings depending on both heating and cooling loads. The author computed the optimal insulating thickness to be 0.1 m, the payback period to be 3.29 years, and the energy savings to be 71.33 percent. It was discovered that the wall direction had little impact on the optimal insulating thickness, but a larger impact on energy savings, which could reach a maximal of TND23.78 per m^2 in east-oriented walls [30]. In Qatar, Al-Khawaja calculated the energy costs for insulating materials, solar irradiation, and optimal insulation thickness [31]. Akash and Mohsen investigated energy savings by insulating with polystyrene, rock wool, and air gaps. Air gap, rock wool, and polystyrene were found to save 5.4, 34, and 36 percent of energy, respectively [32]. In Saint Petersburg, Murgul and Pukhkal investigated the insulation of historical buildings. It was remarked that isolation should be applied from the inside in order to preserve the historical buildings' exterior structure and appearance. As a result, the authors discovered that using extruded polystyrene prevents condensation in buildings. They reported insulating materials with a water-vapor permeability of at minimum 12 m^2 hPamg1 prevent condensation [33]. In southern Sweden, Tettey et al. investigated the impact of various external wall insulation mechanisms on primary energy use in a building. As insulation, they utilized glass wool, rock wool, and expanded polystyrene. According to their calculations, rock wool performs 17 percent better than expanded polystyrene, and there is no important variance between glass wool and the other materials [34]. In China's five diverse climatic zones, thermal insulation materials' optimal thicknesses for extruded polystyrene and expanded polystyrene were investigated in research led by Zhu et al. [35]. The cooling and heating times were noted at the same time. When the annual energy cost of two different insulating materials of identical thickness was compared, it was determined that XPS is more advantageous than EPS [35]. Nyers et al. investigated the optimal energy-financial thickness of heat insulation layers for a building envelope. The financial modelling is divided into two sections: energy and economic. The model's economic component contains algebraic formulas, investment, usage periods, and savings [36]. In Cameroonian buildings, Ghislain

and Cyrille Vincelas presented comparative research for calculating the most cost-effective integration of building envelope and optimal insulating material thickness for energy conservation. The degree-day notion was utilized to calculate the building's transmission loads for annual cooling. Furthermore, in economic analysis, the P_1–P_2 methodology was utilized to identify the optimal insulating material thickness, payback period, and energy savings for buildings [23]. Singh et al. computed the optimal insulating thickness, payback periods, and life-cycle savings in India's composite climatic zone using life-cycle cost analysis [37].

Depending on the top cooling loads for a present residence in the Lahore region of Pakistan, Siddique et al. identified the optimal insulating thickness on roofs and exterior walls [38]. For a residence in the Amman region of Jordan, Malek and Hamdan utilized MATLAB simulation to compute the optimal insulating thicknesses in order to decrease the expense of the consumed heating load [39]. In Cameroon's hot and cold tropical climates, Nematchoua et al. presented the most cost-effective and optimal thermal insulation thickness for buildings. Economic modelling was utilized to compute the optimal insulating thickness, payback period, and energy savings over the building's lifetime of 22 years [40]. Jraida et al. performed research to identify the optimal insulating thickness in six provinces in six diverse climatic zones of Morocco. Optimum insulation thicknesses for extruded polystyrene were determined as 5.7 cm, 2.3 cm, 4.1 cm, 7.7 cm, 5.2 cm, and 3.7 cm for Errachidia, Marrakech, Ifran, Fez, Agadir, and Tangier, respectively [41]. Baniassadi et al. determined the optimal insulating thickness for diverse climatic regions of Iran. The optimal thickness was found to be greater than 6.0 cm in cold regions [42]. Changsha, Chengdu, and Shaoguan were the three provinces in China's cold winter and hot summer zones where Liu et al. (2015) determined the ideal insulating thicknesses. The ideal insulation thicknesses for extruded polystyrene ranged from 5.3 cm to 6.9 cm, whereas those for expanded polystyrene varied between 8.1 cm and 10.5 cm [43]. Barrau et al. computed the optimal insulating material thickness considering a diverse lifespan of the insulation and building materials. The conclusions of this research display that varying the building's lifetime from twenty to fifty years raises the optimal insulating material thickness. Additionally, varying the optimization attributes from financial to ecological priorities greatly affects the conclusions [44]. Derradji et al. carried out research to examine a model structure's optimal insulating material thickness both experimentally and numerically. Different characteristics such as the building envelope structure, fuel kind, and window field were studied [45]. In the Tripoli region of Libya, Alghoul et al. examined the effect of electrical prices on building cooling and heating energy usage, as well as insulating material thickness [46]. In Algeria's south, Marif et al. investigated the thermal efficiency of external and internal wall insulation for buildings. The authors came to the conclusion that there was no variation between external and internal wall insulation, except that the internal superficies' temperature decreased much more quickly when internal insulation material was used [47]. Sagbansua et al. researched the insulation optimization of energy-efficient building envelope alternatives for sustainable cities [48]. Some studies have also introduced the concept of insulation thickness optimization, as well as multi-objective optimization [49–51].

Heat loss from the building envelope is significant, so thermal insulation material on the building envelope is also critical. An optimal level of insulation thickness applied on the building envelope results in a much lesser thermal load transmission. In Turkey, a brief summary of the studies pertaining to optimum insulation thickness utilizing diverse insulating materials is given in Table 1. In this table, the total expense is the sum of the insulation and energy expenses. The insulation material's cost increases linearly with the insulation material's thickness. The insulating material thickness with the minimum total expense is taken as the optimal insulating thickness. In these studies, optimal insulation thicknesses were investigated by considering the climatic information of a certain region and using diverse energy sources. Depending on whether the region is warmer or colder, the climate data directly affects the amount of energy usage and thus the amount of detrimental gas emissions spread to the environment [52].

Table 1. A brief summary of studies in Turkey pertaining to optimum insulation thickness.

Authors	Fuel Type	City in Turkey	Methodology	Insulation Material	Opt. Insulation Thickness
Yüksel and Comaklı [28]	Fuel oil	Erzurum	-	Styrofoam	0.10 m calculated
Dombaycı [53]	Coal	Denizli	-	Expanded polystyrene	0.095 m calculated
Onan [54]	Natural gas	İstanbul	P_1–P_2	EPS	0.0525 cm calculated
Gürel and Daşdemir [55]	Fuel oil, natural gas	Aydın, Edirne, Malatya and Sivas	LCC	EPS, XPS	0.036–0.10 m calculated
Bolatturk [56]	LPG, electricity, fuel oil, coal, natural gas	Four cities for each of DD zones in Turkey (in total, 16 cities)	LCC	Polystyrene	For heating, they change in a broad range (between 0.019 and 0.172 m) relying on provinces and utilized energy source type
Dombayci et al. [57]	LPG, electricity, fuel oil, coal, natural gas	Denizli	LCC	Rock wool, Expanded polystyrene	For EPS, 0.259–0.076 m depending on fuel type For rock wool, 0.138–0.032 m depending on fuel type
Bolatturk [26]	For cooling, electricity For heating, natural gas	Mersin, Izmir, Iskenderun, Hatay, Antalya, Adana, Aydin,	P_1–P_2	Extruded polystyrene	0.016–0.027 m for HDHs and 0.032–0.038 m for CDHs
Yuksel and Comakli [10]	Coal	Erzincan Kars, Erzurum	LCC	Styrofoam	0.085 m, 0.107 m, 0.105 m
Kaynakli [58]	LPG, fuel oil, coal, natural gas, electricity,	Bursa		Rock wool (for basement), fiberglass (for external walls and for ceiling)	0.124 m and 0.053 m depending on fuel type
Sisman et al. [59]	Coal	Erzurum, Izmir, Eskisehir, Bursa	LCC	Rock wool	0.033, 0.047, 0.061, and 0.080 m (for walls)
Ucar and Balo [60]	LPG, natural gas, electricity, fuel oil, coal,	Elazig, Kocaeli, Agri, Aydin	P_1–P_2	Extr. polystyrene, foamboard 3500, fiberglass, foamboard 1500	0.0764–0.0106 m depending on fuel type and city
Ucar and Balo [61]		Bitlis, Mersin, Elazig, Sanliurfa,	P_1–P_2	Rock wool, nil siding, expanded and extruded polystyrene	0.01 and 0.076 depending on CDDs or HDDs, fuel type, and insulation material
Kallioglu [62]	Natural gas, fuel oil, coal	Diyarbakir		EPS and XPS	0.068 and 0.083 m calculated

When the literature is examined in detail, different methods have been used to determine and evaluate the optimum insulation thickness [63–65]. However, in order to evaluate the efficiency of optimum insulation thickness in terms of energy consumption, the combination of the P_1–P_2 method and Revit was used for the first time in the literature in this study. In this respect, an original study was carried out to guide the applicability of the results obtained in this study in real designs with the support of Revit, a simulation that gives highly accurate results. Revit analysis was supported with different side simulations. The building renders were obtained using Lumion software. The sample building model was made in the Autodesk Revit 2021 program. Then, a building energy

model was created over the alternatives. Sample building analyses were conducted via Autodesk Green Building Studio. Modeling was carried out with BIM-based design tools and energy analyses were performed with Green Building Studio and Revit. Optimum designs were determined by comparing the different alternatives created. The effect of the created wall layers on the energy loads of the building was investigated. In this way, the most effective wall combinations were determined using simulations when the optimum insulation thickness was used for the study region.

The first part of this study provides economic and environmental analysis through mathematical-model-based calculations. In these analyses, the payback period and optimal insulating thickness are computed for four energy resources (fuel oil, coal, natural gas, and electricity). XPS and glass wool are used as insulation materials in a building envelope designed as a sandwich wall. Porous light brick, gas concrete, and bims are used as construction materials. In a city with the hottest climatic conditions located in the second climatic region of Turkey, analyses were applied considering the degree-day region value. In the second part, a building with sandwich walls was designed in the climate conditions of the second region with Revit simulation. When natural gas is utilized as an energy source, the energy consumption amounts of the building were investigated using the optimum thicknesses of insulation materials calculated according to the second region. The energy performances of the building designed without insulation and with optimum insulation thickness were compared.

2. Materials and Methods

A systematic framework for optimization of insulating material thickness is improved from Hasan [18] and then performed for a city. The optimization depends on the life-cycle cost evaluation. Life-cycle savings of the buildings insulated are calculated for different regions in this study. Generalized formulas for choosing the optimum insulating material thickness as a function of thermal wall resistance and degree-days are produced. In this study, the analysis method in Hassan's study was applied to a different region and then supported with Revit analysis.

2.1. Calculations for Building Performance with Sandwich Design

In this study, a building with sandwich external walls is designed in the second climatic region according to TS 825 of Turkey. The TS 825 standard defines the calculation rules for determining the heating energy need in buildings and comparing them with the allowable limit values. The U-value determined for the building's shell is an important parameter describing the energy need of the building. TS 825 describes the minimum requirements for U-values for the roof, facade, windows, and base plate of new buildings and buildings to be renovated. The climatic regions and location of the analyzed building according to TS 825 of Turkey are displayed in Figure 1.

2.1.1. Calculating Heat Loss

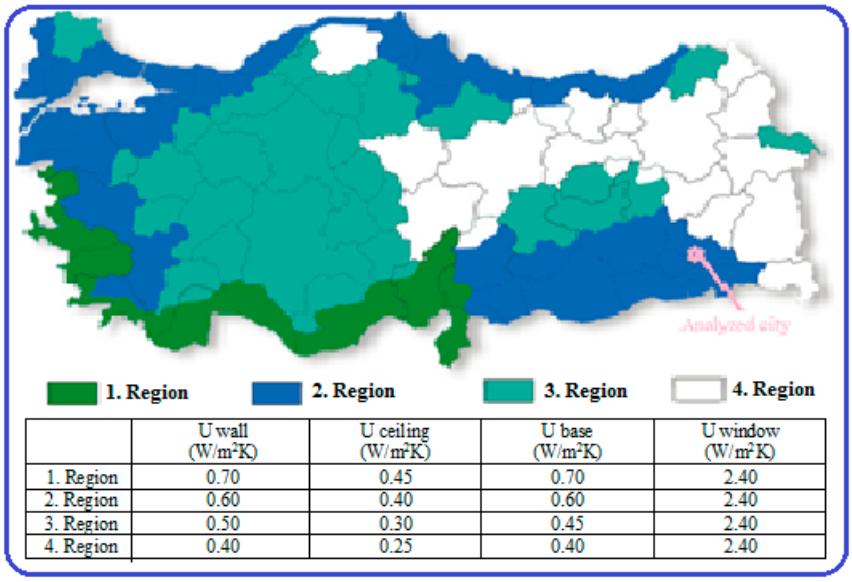
Heat loss in buildings occurs, in the majority of cases, through the building's external walls, ceiling, windows, and basement. In this study, heat loss calculations are made assuming heat loss occurs through the external walls. The thermal loss per unit field of external walls is

$$q = U \cdot (T_b - T_0) \quad (1)$$

The yearly thermal loss per unit field (q_A) can be calculated utilizing the formula [32,66–68];

$$q_A = 86,400 \times DD \cdot U \quad (2)$$

where DD = degree-day (°C day).



	U wall (W/m²K)	U ceiling (W/m²K)	U base (W/m²K)	U window (W/m²K)
1. Region	0.70	0.45	0.70	2.40
2. Region	0.60	0.40	0.60	2.40
3. Region	0.50	0.30	0.45	2.40
4. Region	0.40	0.25	0.40	2.40

Figure 1. The climatic regions and location of the analyzed building according to TS 825 of Turkey [3].

The yearly energy amount (E_A) required for heating is calculated approximately by dividing the yearly thermal loss by the performance of the combustion system due to the thermal loss through a unit area of the external wall. The efficiency of the distribution system as well as that of the combustion system also affects the amount of annual energy.

$$E_A = \frac{86,400 \times DD \cdot U}{\eta} \tag{3}$$

For a typical wall, the total thermal transmittance (the amount of heat passing per unit time from 1 m^2 of the building element consisting of different material layers) can be calculated by

$$U = \frac{1}{R_{int} + R_w + R_{ins} + R_{ext}} \tag{4}$$

where R_{int} and R_{ext} are the thermal resistances of the internal and external surfaces, respectively. R_w is the total thermal resistance of the non-insulated wall layers. R_{ins} is the insulation material's thermal resistance:

$$R_{ins} = \frac{x}{k} \tag{5}$$

where k and x are the thermal conductivity and insulation materials' thickness, respectively.

$$U = \frac{1}{R_{tw} + R_{ins}} \tag{6}$$

where R_{tw} is the total of R_i, R_w, and R_d thermal resistances. The amount of yearly energy needed for heating can be computed through the formula below:

$$E_A = \frac{86,400 \times DD}{\left(R_{tw} + \frac{x}{k}\right)\eta} \tag{7}$$

A typical representation of the external wall utilized in this paper is provided in Figure 2. Physical features of the materials utilized in such walls can be found in Table 2.

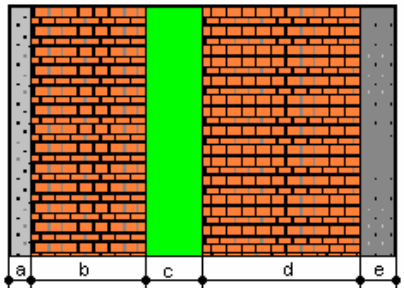


Figure 2. Sandwich wall model used for calculations (a. External plaster; b. Building material; c. Insulation material; d. Building material; e. Internal plaster).

Table 2. Thickness, thermal conductivity, and thermal resistance values of the materials used in building design.

	Material	Thickness	Thermal Condictivity (W/m K)	R (m^2 K/W)
a	Internal plaster (lime-based)	0.02	0.87 [4]	0.023
b	Construction materials (internal)			
	Porous light brick	0.085	0.33 [4]	0.257
	Gas concrete	0.085	0.18 [4]	0.472
	Bims block	0.085	0.156 [4]	0.544
c	Insulation materials			
	XPS	*	0.028 [4]	
	Glass wool	*	0.04 [4]	
d	Construction materials (external)			
	Porous light brick	0.13	0.33 [4]	0.393
	Gas concrete	0.13	0.18 [4]	0.722
	Bims block	0.13	0.156 [4]	0.232
e	Exterior Plaster (cement-based)	0.03	1.4 [4]	0.021

The "*" sign denotes the optimum insulation thickness to be calculated in the study, taking into account different energy sources and all other parameters.

There are several methodologies for decreasing this air-conditioning load, but one stands out: designing and selecting the proper building external wall and its elements. The thermal properties of the building external wall, particularly the heat resistance of the insulating material utilized, influence the energy and thermal efficiency of buildings. The main factor influencing the efficiency of a thermal insulating material is the thermal conductivity coefficient, which displays the capability of heat to move through a given material because of a temperature variation. Thermal insulating material utilized in building envelopes aids to decrease the building's energy need. It develops thermal comfort and, when utilized correctly, lowers the building's operating expenses.

Using an appropriately constructed external wall and its elements stands out among the many options to lower the air-conditioning load. The energy and thermal efficiency of buildings is influenced by the thermal properties of the building envelope, especially the utilized insulation's heat resistance [66–69]. Buildings with thermal insulation in their walls and roofs consume less energy overall. When used properly, it enhances thermal comfort and decreases the building's running costs.

2.1.2. Annual Energy Cost

Yearly energy expense of heating per unit field can be calculated through the formula below [70–74]:

$$m_{fA} = \frac{86,400 \times DD \cdot m_y}{\left(R_{tw} + \frac{x}{k}\right) H_U \cdot \eta} \quad (8)$$

where H_U (J/kg) is the base thermal value of the fuel type determined while m_y (TRY/kg) is its price.

2.1.3. Optimization of Insulation Thickness

Life-cycle cost analysis is utilized to calculate the optimal insulating thickness. The total heating cost needs to be evaluated along with the lifetime period (N) and present-value factor (PWF). PWF depends on the interest (i) and inflation (g) rates. Considering the inflation and interest rates, the real interest rate (r) and PWF values can be calculated as below [70–74]:

$$\text{if } i > g,\ r = \frac{i-g}{1+g}$$

$$\text{if } i < g,\ r = \frac{g-i}{1+g}$$

$$PW = \frac{(1+r)^N - 1}{r(1+r)^N} \tag{9}$$

The lifetime period of N is considered to be ten years. The Turkish lira was used in the calculation as the monetary unit. For an insulating cost C_{ins} (TRY/m^2), insulation material cost C_y (TRY/m$^{3)}$, and insulation thickness x,

$$Cins = Cy{\cdot}x \tag{10}$$

Consequently, the total heating expense of an insulated building can be calculated using the LCCA method composed of the total of all expenses related to the system as below [70–74]:

$$C_t = C_A P_1 + C_y x \tag{11}$$

or

$$C_t = \frac{86400{\cdot}DD{\cdot}C_f{\cdot}P_1}{\left(R_{tw} + \frac{x}{k}\right){\cdot}H_U{\cdot}\eta} + C_y{\cdot}x \tag{12}$$

The net energy savings for heating (S) can be computed utilizing the formula below:

$$S = C_A P_1 - P_2 C_{ins} \tag{13}$$

or

$$S = \frac{86400DDC_f}{\left(R_{tw} + \frac{x}{k}\right)H_U\eta}P_1 - P_2 C_y x \tag{14}$$

The total heating cost over an N-year period is converted to present value by multiplying it by P_1. The P_1 factor is defined as the ratio of lifetime fuel savings to first-year fuel savings. P_1 is impacted by the inflation rate "d" in addition to the interest rate "I". The P_2 factor is defined as the ratio of the additional capital investment's life-cycle expenses to the initial capital investment [71]. The equations for P_1 and P_2 are as follows:

$$P_1 = \left[\frac{1+g}{g-i}\right][1 - ((1+i)/(1+g))^N] \tag{15}$$

$$P_2 = 1 + P_1 M - R_v(1+g)^{-N} \tag{16}$$

The optimum net energy savings can be calculated by maximizing Equation (14). Thus, the optimal insulating thickness is calculated by treating Equation (14) as the objective function and utilizing MATLAB Optimization Toolbox. The payback period N_p can be calculated through the formula below [70–74]:

$$N_p = \frac{\ln[1 - \frac{\left(P_2 C_y H_u \eta \left(R_{wt} + R_{wt}^2 k\right)(g-i)\right)}{86400DDC_f(1+g)}]}{\ln[(1+i)/(1+g)]} \tag{17}$$

2.1.4. Calculation of the Fuel Consumption Process

Burning fossil fuels such as natural gas, petroleum, and coal causes a massive amount of hazardous gases such as CO_2 and SO_2 resulting in environmental problems. Such gases (CO_2 in particular) cause an increase in the earth's temperature by holding the solar rays that are reflected back by the earth. Consequently, climatic changes throughout the world occur in the long run. Sulfur-based chimney-gas emission joins with water particles in the air to form sulfuric acid, which causes acidic rain. Such rain destroys plants and structures. Taking necessary insulation precautions reduces the heating demand of buildings and hence reduces the amount of chimney gas that would in turn be released to the environment. The general chemical function for burning fuels is provided below [70–74]:

$$C_aH_bO_dS_eN_f + \alpha A(O_2 + 3.76N_2) \rightarrow aCO_2 + \left(\frac{b}{2}\right)H_2O + BO_2 + eSO_2 + DN_2 \quad (18)$$

where A, B, and D are constants calculated through the functions below:

$$A = a + \left(\frac{b}{4}\right) + e - \left(\frac{d}{2}\right) \quad (19)$$

$$B = (\alpha - 1)[a + \left(\frac{b}{4}\right) + e - (\frac{d}{2})] \quad (20)$$

$$D = 3.76\alpha\left[a + \left(\frac{b}{4}\right) + e - \left(\frac{d}{2}\right)\right] + \frac{f}{2} \quad (21)$$

The emission rate caused by burning 1 kg of fuel is

$$M_{CO_2} = \frac{aCO_2}{M} = \text{kg } CO_2/\text{kg fuel} \quad (22)$$

$$M_{SO_2} = \frac{eSO_2}{M} = \text{kg } SO_2/\text{kg fuel} \quad (23)$$

Stating the right-hand side of the functions above in terms of annual fuel consumption, the total emission amounts of CO_2 and SO_2 can be computed utilizing the below functions:

$$M_{CO_2} = \frac{44a}{M}m_y \quad (24)$$

$$M_{SO_2} = \frac{44e}{M}m_y \quad (25)$$

where M is the molecular weight of the fuel computed by the function below:

$$M = 12a + b + 16d + 32e + 14f \quad (26)$$

Prices, heat values, and performances of the fuels utilized in the computations are provided in Table 3.

Table 3. Prices, heat values, efficiencies, and chemical formulas of the fuels [35,36].

Energy Type	Hu × 10^6 (j/kg)	ηS	Unit Price [TRY/kWh]	Chemical Formula
Coal	25.122	0.65	1.78×10^{-9}	$C_{7.078}H_{5.149}O_{0.517}S_{0.01}N_{0.086}$
Natural gas	34.542	0.93	4.19	$C_{1.05}H_4O_{0.034}N_{0.022}$
Fuel oil	40.614	0.80	4.36×10^{-9}	$C_{7.3125}H_{10.407}O_{0.04}S_{0.026}N_{0.02}$
Electricity	3.6	0.99	24.01	-

2.2. Revit Analysis

One of the cloud-based services is Green Building Studio. It allows building performance simulations to be conducted for improving energy efficiency and for working earlier in the design process towards carbon neutrality. It helps to expand the potential of traditional methods to construct high-efficiency buildings at a fraction of the time and expense. To perform energy simulation for comprehensive architectural models and conceptual forms generated in Revit, Energy Analysis for Autodesk Revit is utilized. Revit is a simulation program that calculates and analyzes U-values in its interface. The outcome of the simulation is used to consider the usage and consumption of building resources and then to iterate the designs to boost their sustainability ratings. In Revit, the energy model developed from the Revit building model can be shown, so the energy model used for analysis can be validated and viewed.

Lumion is a 3D rendering simulation program. It is completely compatible with most CAD and 3D programs. In this study, a building is designed in the second climatic region according to TS 825 of Turkey. The designed building is created in six types using the material properties defined in Table 4. Natural gas is selected as an energy source. The building renders obtained using Lumion software and the building's 3D view obtained using Revit are displayed in Figure 3. The designed building types according to different building and insulation materials are listed in Table 5.

Table 4. The building information of the analyzed structure.

Building Information	
Carrier System:	Masonry Construction
Number of Floors:	Ground Floor
Story Height:	3 m
Dimensions:	10 m × 10 m
Gross Area:	100 m^2
Net Area:	87 m^2

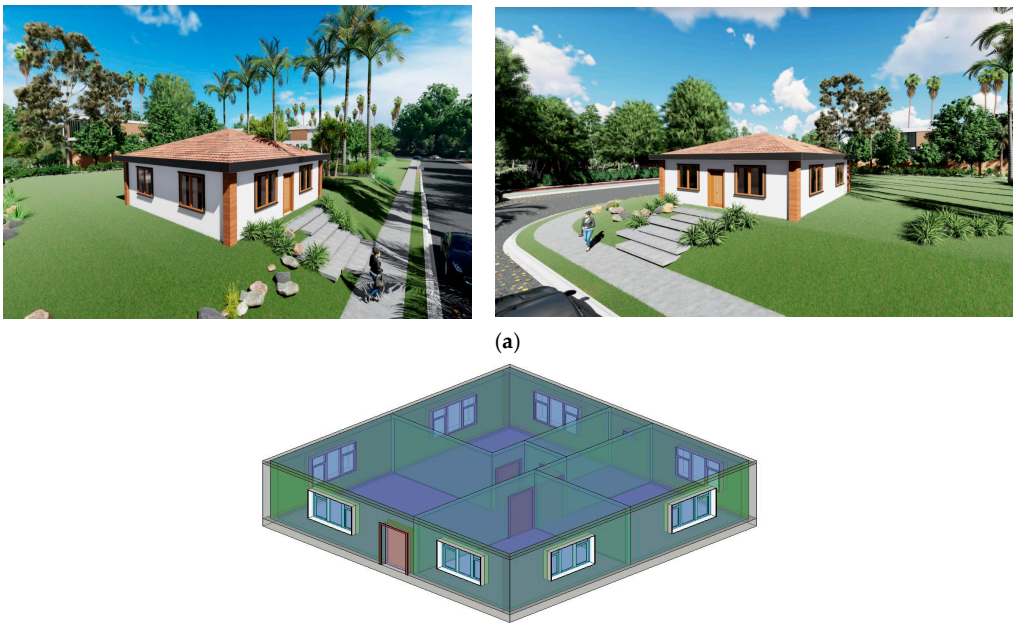


Figure 3. (**a**) The building renders obtained from Lumion software; (**b**) The building 3D view obtained from Revit.

Table 5. The designed building types according to different building and insulation materials.

Type 1	Internal plaster (lime-based)	Porous light brick	XPS (0.04 m)	Porous light brick	Exterior Plaster (cement-based)
Type 2	Internal plaster (lime-based)	Porous light brick	Glass wool (0.06 m)	Porous light brick	Exterior Plaster (cement-based)
Type 3	Internal plaster (lime-based)	Gas concrete	XPS (0.03 m)	Gas-concrete	Exterior Plaster (cement-based)
Type 4	Internal plaster (lime-based)	Gas concrete	Glass wool (0.05 m)	Gas-concrete	Exterior Plaster (cement-based)
Type 5	Internal plaster (lime-based)	Bims block	XPS (0.02 m)	Bims block	Exterior Plaster (cement-based)
Type 6	Internal plaster (lime-based)	Bims block	Glass wool (0.04 m)	Bims block	Exterior Plaster (cement-based)
Type 2	Internal plaster (lime-based)	Porous light brick	Glass wool (0.06 m)	Porous light brick	Exterior Plaster (cement-based)

3. Results and Discussion

3.1. LCCA (Life-Cycle Cost Analysis)

It should be noted that insulation does not eradicate thermal transfer; rather, it reduces it. The thicker the insulating material, the slower the thermal transfer, but the higher the insulation cost. As a result, an optimal thickness of insulation is required, which corresponds to the lowest integrated cost of insulation and thermal loss. Insulation costs increase linearly with thickness, whereas thermal loss costs decrease exponentially. The total expense, which is the insulation's sum and lost-heat costs, reduces first, reaches a minimal value, and then begins to rise. The insulation material's optimal thickness is the thickness that corresponds to the lowest total cost, and this is the recommended insulation thickness to be installed. When the insulation material is selected, and the only factor to be identified is the most cost-effective thickness, the debate about the optimal thickness is viable. However, there are several alternatives, and selection can be somewhat complicated because each insulation material has a different thermal conductivity, service life, and installation cost [53,73].

This study covers the determination of the optimal insulating thickness for building performance designed with sandwich walls in the second climatic region. The thickness values are calculated for four types of energy source used in heating and two insulating materials. Life-cycle cost analysis is utilized in the calculations. The optimal insulating thickness values for external walls and the resulting amount of annual savings along with payback durations are computed for buildings located in the second climatic region when XPS and glass wool are used as the insulating material. Since the most widely used thermal insulation materials in the insulation of buildings in Turkey are XPS and glass wool, they were preferred in this study. The optimal insulating thickness is computed by considering inflation and interest ratios using life-cycle cost analysis. Life-cycle cost analysis is the operation of compiling all expenses that the producer or owner of an object will incur over its lifespan. The impact of insulation thickness on the total energy expense over a 10-year lifetime is displayed in Figure 4. The heating savings were taken into account in calculating the optimum insulation thickness, since the analyzed region is more exposed to cold climate conditions throughout the year. Increasing the insulating thickness applied on the buildings' external walls decreases the heating load and heat loss as a result. Consequently, the fuel cost decreases as well. On the other hand, increasing the insulation thickness results in higher insulating costs. However, increasing the thickness causes a decrease in the total cost composed of the heating and insulating cost up to a certain point where the optimum insulation thickness is reached. After this point, further increasing the thickness starts to increase the total cost along with the unnecessary increase in insulating expense.

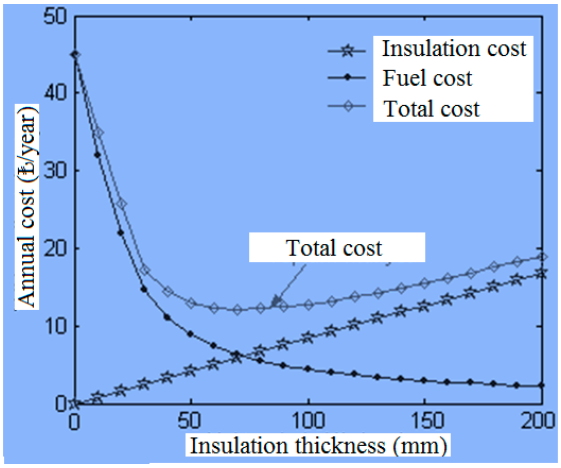


Figure 4. Total cost and impact of insulation thickness.

The optimal insulation thicknesses computed for the wall types utilized in this paper are provided in Table 6 for diverse energy sources. The payback durations and energy cost savings calculated depending on fuel and insulating materials for wall types are provided in Tables 7 and 8, respectively. Table 8 indicates the energy cost savings depending on the energy source and insulating material. The optimum insulation thickness for a 10-year lifetime varies between 0.02 and 0.16 m (for XPS, between 0.02 and 0.11 m; for glass wool, between 0.04 and 0.16 m) while the annual heating cost savings lie within a range of 7.56 to 14.12 TRY/m^2 (for XPS, between 7.56 and 12.84 TRY/m^2; for glass wool, between 7.57 and 14.12 TRY/m^2) depending on different wall types. The payback period is determined to be between 2.15 and 3.76 years (for XPS, between 2.15 and 3.38 years; for glass wool, between 2.27 and 3.76 years). The highest energy savings for the sandwich building performance is realized when electricity is used as the energy source and glass wool as the insulating material. Moreover, CO_2 emission levels in the four cities investigated in this study are computed for four fuel types (coal, fuel oil, natural gas, electricity). The lowest energy savings from external walls are obtained when natural gas is utilized as an energy source and extruded polystyrene is utilized as insulating material in a bims wall.

Table 6. Optimal insulating thickness depending on fuel and insulating materials for wall types.

	Optimal Insulating Thickness (m)							
	Extruded Polystyrene				**Glass Wool**			
	Coal	**Natural Gas**	**Fuel Oil**	**Electricity**	**Coal**	**Natural Gas**	**Fuel Oil**	**Electricity**
Porous light brick	0.05	0.04	0.07	0.11	0.08	0.06	0.10	0.16
Gas concrete	0.04	0.03	0.06	0.10	0.07	0.05	0.09	0.14
Bims	0.04	0.02	0.05	0.09	0.06	0.04	0.09	0.14

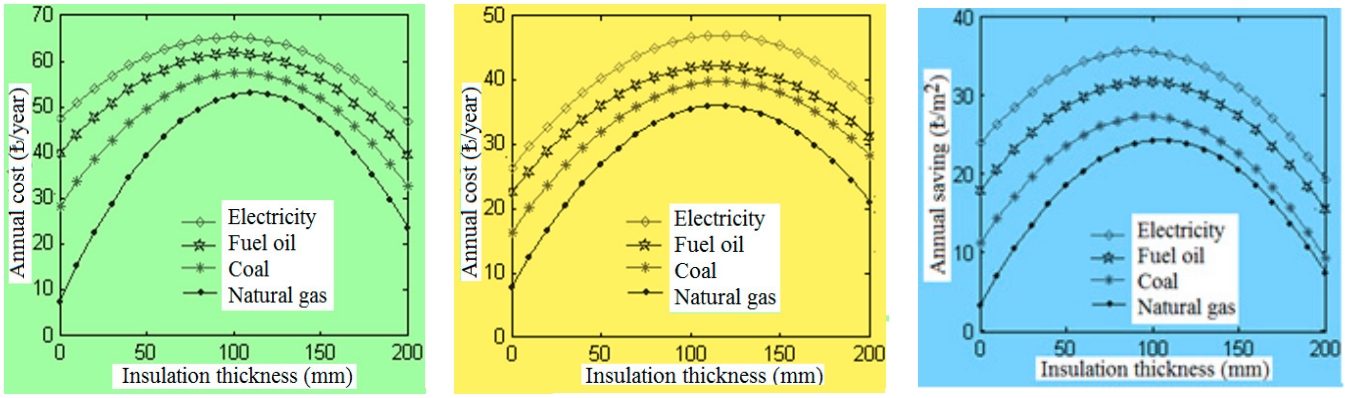
Table 7. Payback duration depending on fuel and insulating materials for wall types.

	Payback Period (Years)							
	Extruded Polystyrene				**Glass Wool**			
	Coal	**Natural Gas**	**Fuel Oil**	**Electricity**	**Coal**	**Natural Gas**	**Fuel Oil**	**Electricity**
Porous light brick	2.69	2.89	2.48	2.15	2.82	3.06	2.62	2.27
Gas concrete	3.17	3.38	2.97	2.63	3.37	3.60	3.15	2.78
Bims	3.29	3.51	3.09	2.75	3.51	3.76	3.28	2.91

Table 8. Energy cost savings depending on fuel and insulation materials for wall types.

	Energy Cost Savings (TRY/m^2)							
	Extruded Polystyrene				Glass Wool			
	Coal	Natural Gas	Fuel Oil	Electricity	Coal	Natural Gas	Fuel Oil	Electricity
Porous light brick	8.74	7.66	9.95	12.84	9.43	8.11	10.86	14.12
Gas concrete	8.76	7.64	9.83	12.41	9.13	7.73	10.53	13.66
Bims	8.79	7.56	9.83	12.31	9.03	7.57	10.43	13.52

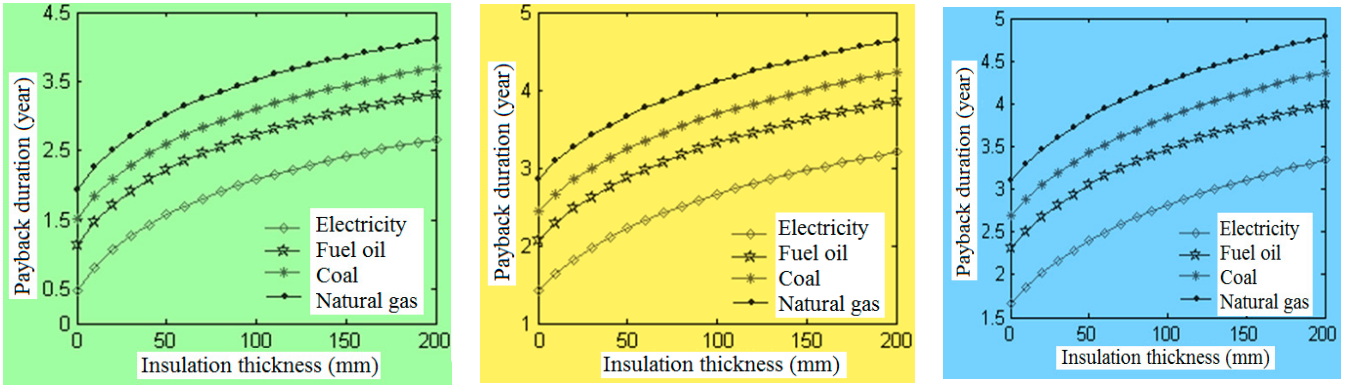
The impact of insulation thickness on annual savings for diverse wall and energy source types is presented in Figure 5. Annual savings are directly proportional to the fuel cost. The increasing cost of fuel results in increases in the amount of savings. The figure indicates that the highest savings are obtained in cases where electricity is used while the minimum savings are obtained when natural gas is utilized.



(**a**) (**b**) (**c**)

Figure 5. Impact of insulating thickness on annual savings for energy source types (extruded polystyrene insulating material): (**a**) Porous light brick wall; (**b**) Gas concrete wall; (**c**) Bims wall.

Figure 6 shows the impact of insulation thickness on the payback period for diverse external walls and fuel kinds. The payback period for 10 years of lifetime varies between 2.15 and 3.06 years for a porous light brick wall and between 2.75 and 3.76 years for a bims wall depending on the insulating material and wall types.



(**a**) (**b**) (**c**)

Figure 6. Impact of insulating thickness on payback duration for energy source types (extruded polystyrene insulating material): (**a**) Porous light brick wall; (**b**) Gas concrete wall; (**c**) Bims wall.

The correlation of SO_2 and CO_2 emission rates with the insulation thickness for external wall and fuel types are presented in Figures 7 and 8, respectively. CO_2 emission declines

when the insulation thickness is increased. When 70 mm of insulating is implemented in the wall and coal is utilized as the energy source, CO_2 emission decreases by approximately 60% in a bims wall and by 73% in a porous light brick wall. The maximum CO_2 emission is reached when coal is the energy source. Figure 8 indicates that the highest SO_2 emission occurs as a result of coal, while natural gas does not result in any SO_2 emission at all. When 70 mm of insulation is implemented in the wall, 0.0183 and 0.0151 kg/m^2 of SO_2 emission occurs in porous light brick and bims walls, respectively. The figure shows that SO_2 emission decreases when the insulation thickness is increased.

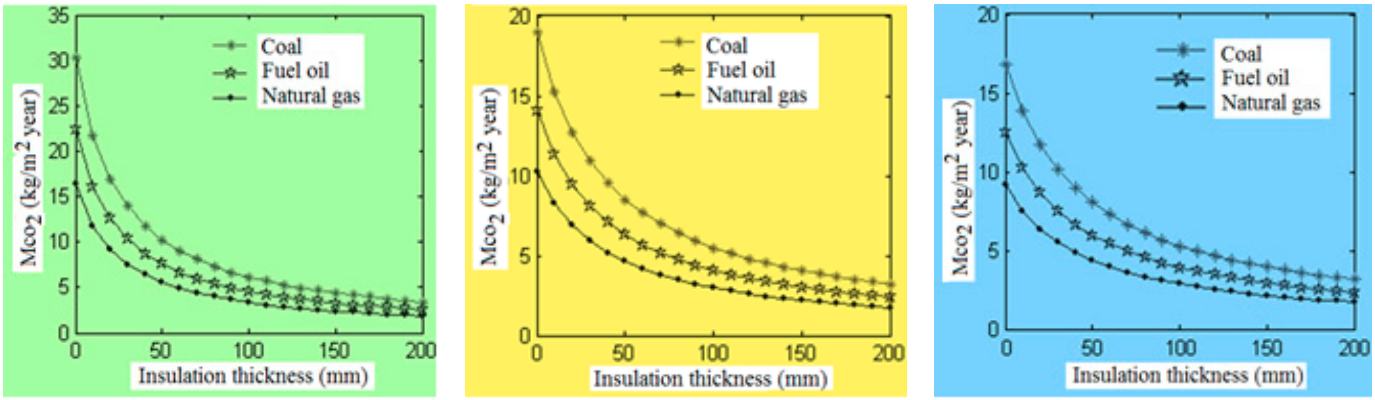


Figure 7. Correlation of CO_2 emission with insulation thickness for different fuel types: (**a**) Porous light brick wall; (**b**) Gas concrete wall; (**c**) Bims wall.

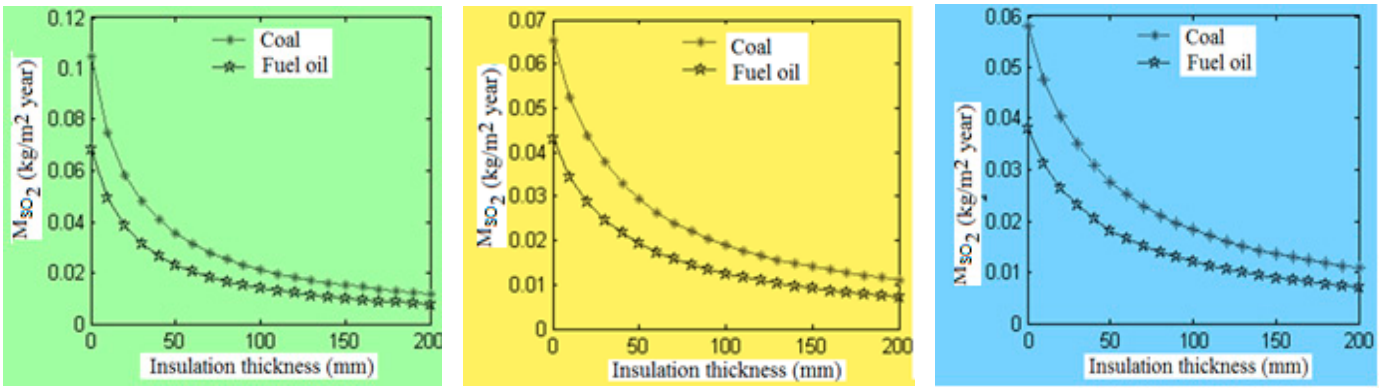


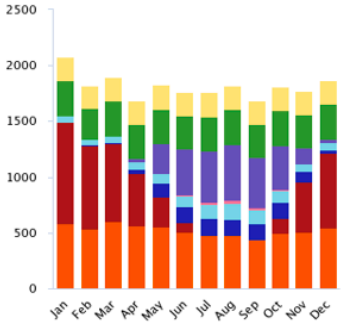
Figure 8. Correlation of SO_2 emission with insulating thickness for diverse energy source types: (**a**) Porous light brick wall; (**b**) Gas concrete wall; (**c**) Bims wall.

3.2. Energy Consumption Analysis with Revit Simulation during One Year

In this phase of the study, natural gas was taken into account as the energy source with the lowest emissions according to the first analysis. Later, when natural gas is used as an energy source for XPS and glass wool, the optimum insulation thicknesses obtained through mathematical modeling were selected as the applied thicknesses of the insulation materials. For other materials, the values used in the first analysis were taken into account. A building with sandwich exterior walls was modeled under regional conditions. Using meaningful combinations of building and insulation materials selected for the study, six different types were created. The Revit program was used for evaluation. The energy usage and energy usage intensity values of the six building types modeled according to the optimal insulation thickness were analyzed. The total energy usage is the amount of energy consumed in a year.

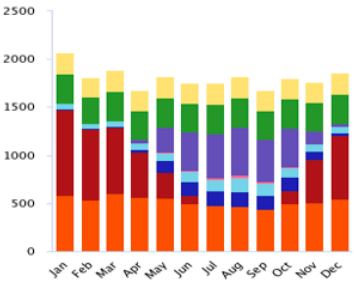
The monthly energy performance values (kWh) of the designed building types are displayed in Figure 9. Among the wall types, the total energy consumption values vary between 22,530 kWh and 21,677 kWh.

As shown in Figures 10 and 11, the highest energy consumption value through Type 5 sandwich walls was obtained at 22,530 kWh over the course of a year. For Type 5, the building material was bims blocks and the insulation material was glass wool. The maximum energy usage was observed in January, with 2256 kWh. Among the energy-consuming elements of a Type 5 building, the maximum energy consumption was found for space heating, at 1079 kWh. The minimum energy consumption of 1714 kWh was found in September. Among the energy-consuming elements of a Type 5 building, the maximum energy consumption was 461 kWh for space cooling.



Area Lights / Misc Equip / Space Cooling / Vent Fans / Pumps Aux / Space Heat / Hot Water	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Area Lights	kWh	217	196	217	210	217	210	217	217	210	217	210	217
Misc Equip	kWh	310	280	310	300	310	300	310	310	300	310	300	310
Space Cooling	kWh	0	0	0	34	264	407	459	500	448	400	139	32
Heat Rej	kWh	0	0	0	0	0	9	19	30	18	8	0	0
Vent Fans	kWh	56	53	62	67	86	101	122	143	122	98	70	63
Pumps Aux	kWh	7	7	7	33	122	144	149	149	144	149	92	34
Space heat	kWh	905	745	700	470	271	87	0	0	0	134	453	666
Hot water	kWh	585	537	604	567	555	504	483	475	442	498	508	549
Total		2080	1818	1900	1681	1825	1762	1759	1824	1684	1814	1772	1871

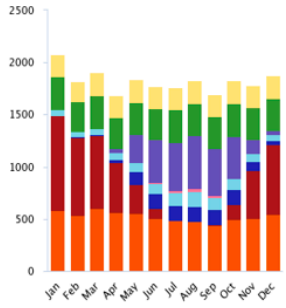
(**a**)



Area Lights / Misc Equip / Space Cooling / Vent Fans / Pumps Aux / Space Heat / Hot Water	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Area Lights	kWh	216	195	216	209	216	209	216	216	209	216	209	216
Misc Equip	kWh	309	279	309	299	309	299	309	309	299	309	299	309
Space Cooling	kWh	0	0	0	34	262	405	457	497	446	398	139	32
Heat Rej	kWh	0	0	0	0	3	9	19	30	18	8	0	0
Vent Fans	kWh	56	53	61	67	86	101	121	142	121	98	69	63
Pumps Aux	kWh	7	7	7	34	122	144	148	148	144	148	92	34
Space heat	kWh	895	737	691	466	269	83	0	0	0	133	449	658
Hot water	kWh	583	536	602	565	553	502	481	473	441	496	506	547
Total		2066	1807	1886	1674	1820	1752	1751	1815	1678	1806	1763	1859

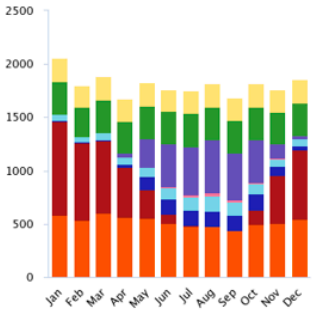
(**b**)

Figure 9. *Cont.*



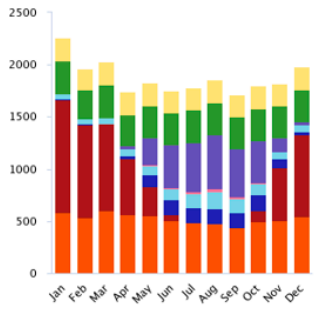
Area Lights / Misc Equip / Space Cooling / Vent Fans / Pumps Aux / Space Heat / Hot Water	Unit	Jan	Feb	Mar	Apr	May	Jun	July		Aug	Sep	Oct	Nov	Dec
Area Lights	kWh	218	197	218	211	218	211	218		218	211	218	211	218
Misc Equip	kWh	311	281	311	301	311	301	311		311	301	311	301	311
Space Cooling	kWh	0	0	0	35	265	408	460		501	450	401	141	33
Heat Rej	kWh	0	0	0	0	3	9	19		30	18	9	0	0
Vent Fans	kWh	56	53	62	67	87	102	122		143	122	99	70	63
Pumps Aux	kWh	7	7	7	34	122	145	150		150	145	149	93	35
Space heat	kWh	904	745	699	472	275	94	0		0	0	140	454	668
Hot water	kWh	587	539	606	569	557	506	485		477	444	499	509	551
Total		2083	1822	1903	1689	1838	1776	1765		1830	1691	1826	1779	1879

(**c**)



Area Lights / Misc Equip / Space Cooling / Vent Fans / Pumps Aux / Space Heat / Hot Water	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Area Lights	kWh	217	196	217	210	217	210	217	217	210	217	210	217
Misc Equip	kWh	310	280	310	300	310	300	310	310	300	310	300	310
Space Cooling	kWh	0	0	0	35	264	406	457	497	446	398	140	33
Heat Rej	kWh	0	0	0	0	2	9	19	30	18	8	1	0
Vent Fans	kWh	56	53	62	67	86	101	121	141	121	98	70	63
Pumps Aux	kWh	7	7	7	34	122	144	149	149	144	148	92	35
Space heat	kWh	883	727	684	464	272	94	0	0	0	139	446	652
Hot water	kWh	584	537	604	567	555	504	483	475	442	497	507	548
Total		2057	1800	1884	1677	1828	1768	1756	1819	1681	1815	1766	1858

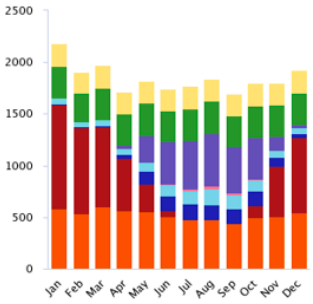
(**d**)



Area Lights / Misc Equip / Space Cooling / Vent Fans / Pumps Aux / Space Heat / Hot Water	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Area Lights	kWh	218	197	218	211	218	211	218	218	211	218	211	218
Misc Equip	kWh	311	281	311	301	311	301	311	311	301	311	301	311
Space Cooling	kWh	0	0	0	29	263	412	470	518	461	405	136	29
Heat Rej	kWh	0	0	0	0	3	9	20	32	20	9	2	0
Vent Fans	kWh	54	51	58	64	86	106	131	155	132	102	67	60
Pumps Aux	kWh	7	7	8	31	122	145	150	150	145	149	92	32
Space heat	kWh	1079	889	826	534	272	59	0	0	0	108	502	781
Hot water	kWh	587	539	606	569	557	506	485	477	444	499	509	551
Total		2256	1964	2027	1739	1832	1749	1785	1861	1714	1801	1820	1982

(**e**)

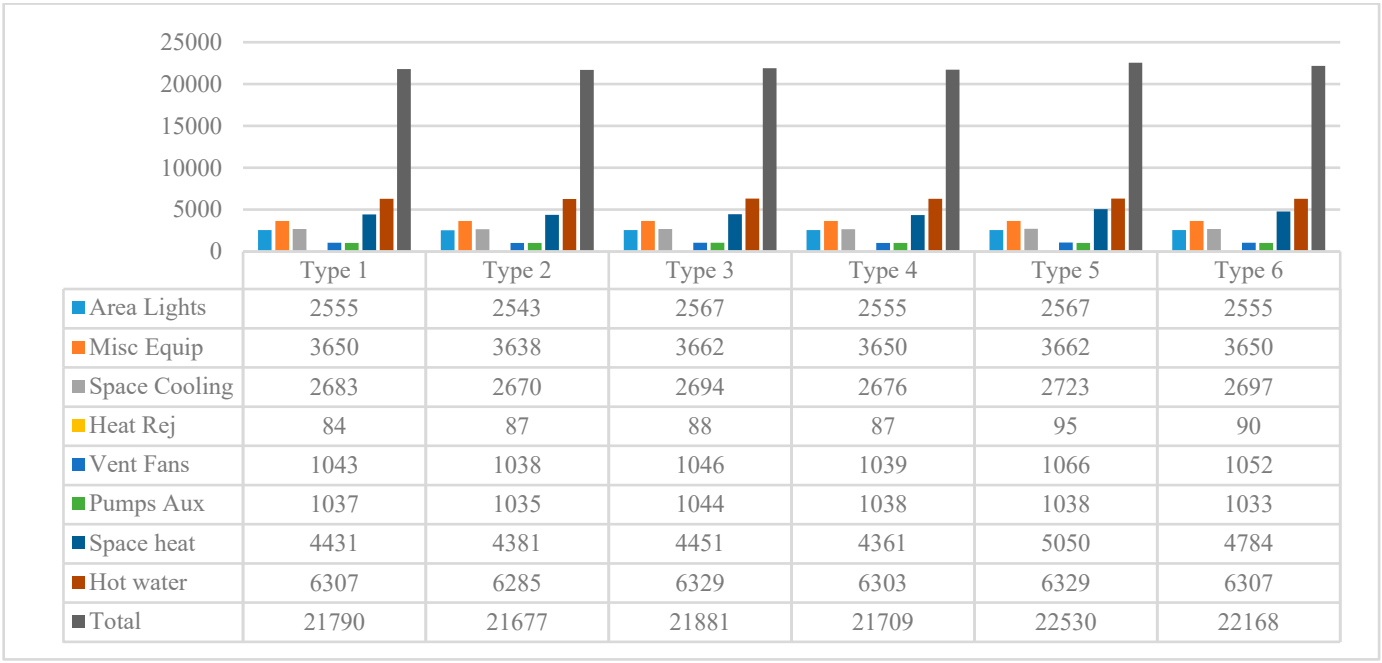
Figure 9. *Cont.*



Area Lights / Misc Equip / Space Cooling / Vent Fans / Pumps Aux / Space Heat / Hot Water	Unit	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Area Lights	kWh	217	196	217	210	217	210	217	217	210	217	210	217
Misc Equip	kWh	310	280	310	300	310	300	310	310	300	310	300	310
Space Cooling	kWh	0	0	0	31	262	409	464	509	455	401	136	30
Heat Rej	kWh	0	0	0	0	3	9	20	31	19	8	0	0
Vent Fans	kWh	54	51	59	65	85	103	128	150	128	100	68	61
Pumps Aux	kWh	7	7	7	32	121	144	149	149	144	148	92	33
Space heat	kWh	1008	834	776	508	270	62	0	0	0	114	484	728
Hot water	kWh	585	537	604	567	555	504	483	475	442	498	508	549
Total		2181	1905	1973	1713	1823	1741	1771	1841	1698	1796	1798	1928

(**f**)

Figure 9. Monthly energy performance values (kWh) of the designed building types with sandwich walsl: (**a**) Type 1; (**b**) Type 2; (**c**) Type 3; (**d**) Type 4; (**e**) Type 5; (**f**) Type 6.



	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
Area Lights	2555	2543	2567	2555	2567	2555
Misc Equip	3650	3638	3662	3650	3662	3650
Space Cooling	2683	2670	2694	2676	2723	2697
Heat Rej	84	87	88	87	95	90
Vent Fans	1043	1038	1046	1039	1066	1052
Pumps Aux	1037	1035	1044	1038	1038	1033
Space heat	4431	4381	4451	4361	5050	4784
Hot water	6307	6285	6329	6303	6329	6307
Total	21790	21677	21881	21709	22530	22168

Figure 10. Total energy consumption of designed building types.

The minimum energy consumption was found for Type 2 walls as 21,677 kWh during one year. For Type 2, the building material was porous light brick and the insulation material was glass wool. Over the course of a year, the highest monthly total energy consumption was 2066 kWh in January. The lowest monthly energy consumption was 1674 kWh in April. Among the energy-using components of a Type 2 building, the maximum energy use occurred for hot water, with 565 kWh in the total monthly consumption.

In designs where climatic inputs are ignored and devoid of environmental sensitivities, different results are revealed for the same building as a result of not determining the optimum ranges for the design parameters. This causes great losses in the long term in building applications that are thought to have high gains in the short term. Simulation programs that include seasonal parameters give more accurate results in terms of long-term

gains to produce climate-sensitive and sustainable buildings. According to the results obtained, energy usage amounts in heating and cooling were found to be seasonal.

For all wall types, the maximum energy consumption areas are generally space heating, hot water, miscellaneous equipment, area lights, space cooling, vent fans, and pumps aux. Seasonally, hot water, space cooling, and space heating draw attention as the highest-energy-consumption areas. The highest values of energy consumption were determined for the periods of December–January–February among all wall types.

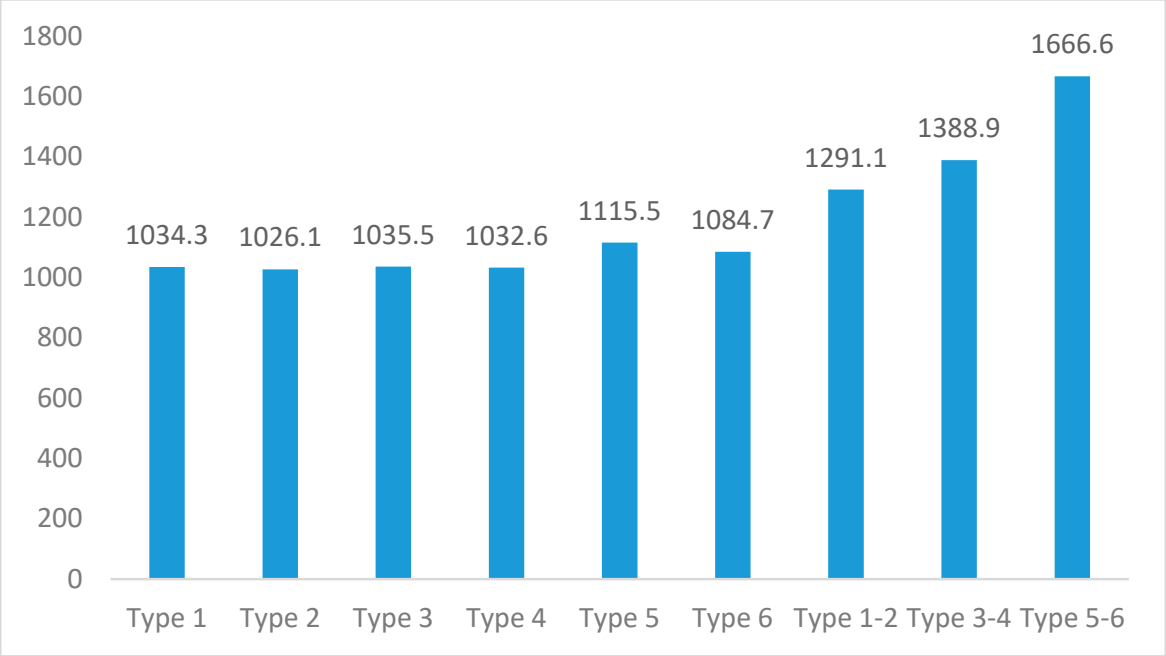


Figure 11. The energy use intensity values of the designed building types with insulation material and without insulation material.

Energy usage intensity (EUI) is a parameter calculated by dividing the annual building energy consumption by the total gross floor area and characterizes the energy use of a building in terms of its function, size, and other characteristics [74]. Among the six wall types, the minimum energy-use intensity was as 1026.1 kWh per m^2 for Type 2. The highest energy-use intensity was 1115.5 kWh per m^2 for Type 5. Among walls without insulation, the minimum and maximum energy-use intensity values found were 1291.1 kWh per m^2 and 1666.6 kWh per m^2 for Type 1–2 and Type 5–6, respectively.

4. Conclusions

Fast technological improvements and a growing population lead to increases in power consumption despite the environmental consequences. In Turkey, 34 percent of the total power usage takes place in service and residential buildings. In this research, the life-cycle cost method was utilized to optimize the thermal insulation thickness of building envelopes for energy efficiency. The expenses of insulating materials differ based on the material type. Furthermore, the wall structure, degree-days, and insulating material all have an important effect on the optimum insulating thickness. It is possible to increase or decrease the energy performance by changing the wall structure. In this paper, the optimum insulation thickness for a 10-year lifetime is calculated along with annual heating cost savings based on a sandwich wall type. A sandwich wall is one of the wall structures that can provide good energy efficiency. The payback period and energy savings for sandwich walls are calculated when different combinations of energy source and insulating material are utilized. Two commonly used materials, glass wool and XPS, were utilized as the insulation material for the purpose of this study. These materials' feasibility for

different fuel types and commercially available sizes was evaluated. In Revit simulations, the same construction and insulation materials used in the mathematical model calculations were utilized as the materials on the sandwich-formed exterior walls of this building. In the Revit analysis, the same thickness values of the building materials were used as in the mathematical model. The Revit analysis was performed for six different combinations using the optimum insulation thicknesses obtained from the mathematical analysis of XPS and glass wool.

With life-cycle cost analysis, the minimum optimum insulation thickness was obtained as 0.02 m and 0.04 m for extruded polystyrene and glass wool, respectively, when natural gas was used as the energy source and bims was used as building material.

The minimum payback period was obtained as 2.15 years and 2.27 years for extruded polystyrene and glass wool, respectively. The maximum energy cost savings was obtained as 12.84 TRY/m^2 and 14.12 TRY/m^2 for extruded polystyrene and glass wool, respectively. Electricity was used as the energy source and porous light brick was used as the building material for both of them.

From the Revit analysis, the minimum energy-use intensity value of 1026 kWh was obtained in Type 2 walls. Using the same materials, the minimum energy consumption was found as 21,677 kWh during one year. For Type 2, the building material was a porous light brick and the insulation material was glass wool.

The results indicate that the highest amount of CO_2 and SO_2 emissions are reached when coal is utilized as the energy source. On the other hand, CO_2 and SO_2 emission levels are at their lowest when natural gas is used. Thus, it can be stated that the use of natural gas has a significant impact on lowering air pollution in residential areas. The primary target of this research was to contribute to the optimum insulation thickness research with a never-before-used simulation method. Researchers, policy-makers, and practitioners need to work together in order to design energy efficiency plans in buildings and apply them in reality. Working with different wall types, different building-insulation materials, and different energy sources, this research can be detailed. Renewing existing buildings with optimum insulation so that they can consume energy efficiently and designing future energy-efficient buildings will be possible only through appropriate regulations and standards.

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Abbreviations

As	Annual total cost difference [TRY/m^2]
CA	Annual energy cost for hearing [TRY/m^2-year]
Cf	Fuel cost [TRY/kg]
Cins	Insulation material cost [TRY/m^2]
Ct	Total heating cost of non-insulated building [TRY/m^2-year]
Ct, ins	Total heating cost of insulated building [TRY/m^2-year]
DD	Degree-days [°C day]
EA	Annual energy required for heating [J/m^2-year]
g	Inflation rate [%]
Hu	Thermal value [J/kg]
i	Interest rate [%]
U	Total heat-transfer coefficient [W/m^2 K]
LCCA	Life-cycle cost analysis

N	Lifetime [year]
pp	Payback period [year]
PWF	Present-value factor
q	Thermal loss per unit field of external walls [W/m^2]
qA	Annual heating loss [W/m^2]
r	Real interest rate [%]
Rext	Outdoor thermal resistance coefficient [m^2 K/W]
Rint	Indoor thermal resistance coefficient [m^2 K/W]
Rins	Thermal resistance coefficient of the insulation material [m^2 K/W]
Rt	Thermal resistance coefficient of the brick material [m^2 K/W]
Rw	Thermal resistance coefficient of the non-insulated wall layer [m^2 K/W]
Rtw	Total thermal resistance coefficient of the non-insulated wall layer [m^2 K/W]
Rtw, ins	Total thermal resistance coefficient of the insulated wall layer
x	Insulation thickness [m]
xopt	Optimum insulation thickness [m]
k	Thermal conductivity of the insulation material [W/mK]
ŋ	Efficiency of burning system
D	Thickness [m]
M	Molecular weight of the fuel [kg/k mol]
MCO_2	Molecular weight of CO_2 [kg CO_2/kg fuel]
MSO_2	Molecular weight of SO_2 [kg SO_2/kg fuel]
mfa	Yearly energy cost of heating per unit field [TRY/year]
my	Yearly fuel consumption [kg/year]
T0	Daily temperature [°C]
Tb	Base temperature [°C]

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