



Research Article

Effect of window glass area on optimum insulation thickness and environmental analysis

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ABSTRACT

This research highlights the significance of insulation and glazing area to increase energy efficiency in buildings and reduce fuel consumption and environmental pollution. With the proper combination of window glass area and insulation in the wall, heating and cooling loads and therefore fuel consumption and emissions can be notably reduced. Therefore, the basic goal of this study is to numerically research the impact of window glass area on insulation thickness, fuel consumption and emissions under dynamic thermal conditions for south orientation in the climate of Elazığ, Turkey and to fill knowledge gap in this field. For this goal, the window glass area on the wall which has different insulation thicknesses was enhanced from 0% to 100% with an increase of 10%. The annual heating and cooling loads were computed employing an implicit finite difference procedure taking into consideration that the window is single-glazing and double-glazing. The annual heating loads obtained were used for the optimization of insulation thickness. The results indicate that the heating load in 20 mm insulated wall for single glazing is acquired to be 177.57, 236.79, 317.51 and 398.23 MJ/m² year for values 0%, 20%, 40% and 60% of the glazing area, respectively while it is obtained to be 177.57, 114.24, 88.24 and 76.81 MJ/m² year for double glass. It is observed that choosing smaller glazing areas in insulated walls containing a single-glazed window results in less heating load. It is also observed that at lower values of insulation thickness, the large double-glazing area on the south facade notably reduces heat loss. It is revealed that the increment in the glazing area for single glass induces an additional heating load, fuel consumption and emissions.

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INTRODUCTION

Today, the energy consumption in the world makes contribution to environmental pollution and greenhouse gas emissions. Industry, construction, agriculture and

transportation sectors are the sectors which contribute the highest to energy consumption [1]. The constructions are liable for roughly 40% of yearly energy consumption in the world. Most of this energy consumed is used for

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heating, cooling, air conditioning and lighting [2]. Due to the decrease in energy resources in the world, energy savings should be achieved by reducing the energy consumed in buildings in an effort to ensure thermal comfort. The building envelope is one of the most significant parameters impressing thermal comfort and energy saving [3]. Windows are often the weakest element of buildings in terms of energy savings. About one-third of a building's energy loss is due to windows. But, they are indispensable elements in building applications as they beautify the appearance of buildings and allow daylight to enter. In the past, while it was thought that the size of the windows should be small in terms of thermal comfort, window sizes were increased with double glazing applications. Thus, both thermal comfort and energy savings have improved significantly [4]. Large glazed windows can reduce the use of artificial lighting by allowing more daylight into the space. However, they can also increase the heat gain or loss of the building. This causes an increase in the heating or cooling load and thus energy consumption increases. Therefore, it is necessary to determine the ideal window area by providing a balance between daylight supply and minimum energy consumption [5]. Low-emissivity coated glasses have high reflectance in the near-infrared spectrum and high transmittance in the visible region. They are usually placed on the outer surface of the inner glass of the glazing system and have a low emissivity (approximately 0.1–0.2) to decrease radiative heat transfer to the outside [6,7].

It is seen that there are many works in the literature on optimizing the wall insulation thickness of buildings. In a great many of these works, the degree-day (DD) or degree-hour (DH) method, which is an elementary and rough model, is used [8–25]. Among these studies, Dombayci et al. [11] specified the optimum insulation thickness (OIT) of the external wall by employing the heating DD concept. Çomaklı and Yuksel [12] researched the OIT for Turkey's three coldest cities by employing the DD values. Özkahraman and Bolattürk [13] computed the energy savings by employing porous tuff stone in the exterior walls of buildings. Their study indicated that OIT of tuff stone was found to be 15 cm. Bolattürk [14] computed OIT by employing the DD method for building exterior walls. In another study, Bolattürk [15] used the DH method. Kaynaklı [16] determined yearly heating energy requirement by employing long term measurements. Then, he calculated the OIT by using optimization model for five different types of fuel. Yu et al. [20] analysed the OIT by taking into consideration the effect of solar radiation based on the DD analysis. Shahid et al. [25] analysed the impact of cooling DD value and base temperature on the OIT [23]. Durmaz et al. [26] estimated the OIT for submarines. Özel and Pıhtılı [27] determined the OIT applying to external walls by considering heating and cooling DD values.

Dynamic heat transfer models should be used to obtain more accurate results. Numerical and analytical methods used for this purpose are available in the literature [28–39].

Among these studies, Al-Sanea and Zedan [35] researched the dynamic thermal properties of building walls composed of one, two and three insulation layers with the same thermal mass. Al-Sanea et al. [36] specified the OIT for cavity walls under steady periodic conditions employing the climate conditions of Riyadh. Al-Sanea et al. [37] studied impact of electricity tariff on the OIT in building walls under dynamic thermal conditions. Daouas [38] computed the OIT according to various wall orientations by employing an analytical method in Tunisian climate.

The impact of window glazing on thermal behavior has been examined by several researchers. Zengin and Kontoleon [40] analyzed the effect of glazing rate, orientations and zone aspect ratio on the heat flux through the surfaces of a building zone. Kontoleon and Zengin [41] also analyzed the rate of glazing surfaces to the total wall surface for different orientations. They investigated the impact of indoor temperature settings on heat gain or heat loss. Kontoleon and Bikas [42] studied the effect of the percentage of glazed openings and the type of glazing on indoor temperatures and energy efficiency. Shahid and Karimi [43] investigated the building envelope transmittance value with parameters such as orientation, shading devices, projection factor, glass type and window-wall ratio. Ozel and Ozel [44] investigated the thermal performance of walls which are containing windows by taking into consideration different structure materials. However, these works do not contain the optimal insulation thickness.

In the literature, it is observed that the heat transfer from the windows is generally neglected when the OIT is specified. There are very few works on the optimization of the insulation thickness of the walls involving the windows. Arıcı and Karabay [45] specified the optimum air layer thickness of double-glazed windows using the DD method. Derradji et al. [46] determined the OIT of external walls containing windows in the region of Algiers, Algeria by using the heating and cooling DDs. Özkan and Onan [47] studied the effect of changing the window and external wall areas on the building's heating energy need and OIT with the P1-P2 method. In these studies, it is seen that the DD method, which is a rough and easy model under static conditions, is used. To get highly accurate conclusions, the heat transmission loads through the wall must be computed by employing a dynamic method based on the implicit finite difference (IFD) process. The impact of glazing area on OIT for different wall directions was previously researched by taking into consideration heating and cooling loads by Ozel [48]. In this study, unlike the previous one, it is aimed to investigate the effects of the glazing area on OIT, fuel consumption and emissions, considering only heating loads. Also, none of the studies in literature include the impact of glass area on fuel consumption under dynamic thermal conditions. This research emphasizes the importance of insulation and glazing area to increase energy efficiency and reduce environmental pollution in buildings. Measures taken to reduce emissions benefit both

human health exposed to air pollution and preventing climate change. Therefore, this research will contribute to the fight against climate change caused by emissions by reducing fuel consumption and emissions. One of the most effective solutions to reduce greenhouse gas emissions against climate change is energy efficiency. With the proper combination of window glass area and insulation in the wall, heating and cooling loads and therefore fuel consumption and emissions can be significantly reduced. Therefore, the basic goal of this study is to fill this information gap and to numerically research the impact of glass area on insulation thickness, fuel consumption and emissions under dynamic thermal conditions for south orientation in the climate of Elazığ, Turkey. The current article also includes heating and cooling loads for each month of the year according to glazing area, type of glazing and wall insulation. For this objective, the wall's glazing area is raised from 0% to 100%, and the annual transmission loads are computed individually for single-glazed and double-glazed windows. Then, the optimization of the insulation thickness and its environmental effects are examined for different GAP values.

MATERIALS AND METHODS

To investigate the effect of window glass area on insulation thickness and fuel consumption, the present analysis is based on the numerical solution of heat transmission through opaque and transparent surfaces, which are given flow chart in Figure 1. Firstly, the heat transmission loads are computed according to rising insulation thickness and percentage of glazing area in case the window is single glazing and double glazing. Secondly, the optimum thicknesses of insulation, energy savings and payback periods for %0, %20, %40 and %60 values of the glazing area are computed. Finally, the impacts of thermal insulation on the environment were investigated for values %0, %20, %40 and %60 of the glazing area.

Heat Transmission Through Opaque Surfaces

A composite wall consisting of layers that have different thermophysical properties is indicated schematically as in Figure 2. The one-dimensional equation related to the transient heat transfer may be described by the following equation:

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j} \frac{\partial T_j}{\partial t} \tag{1}$$

where α represents thermal diffusivity and is expressed as $\alpha=k/(\rho.c)$. ρ , c and k also represent the density, the specific heat and the thermal conductivity, respectively. It is assumed that these thermal properties are constant. It is considered that thermal contact between layers is excellent, and is expressed by the following equations:

$$T_j = T_{j+1} \tag{2}$$

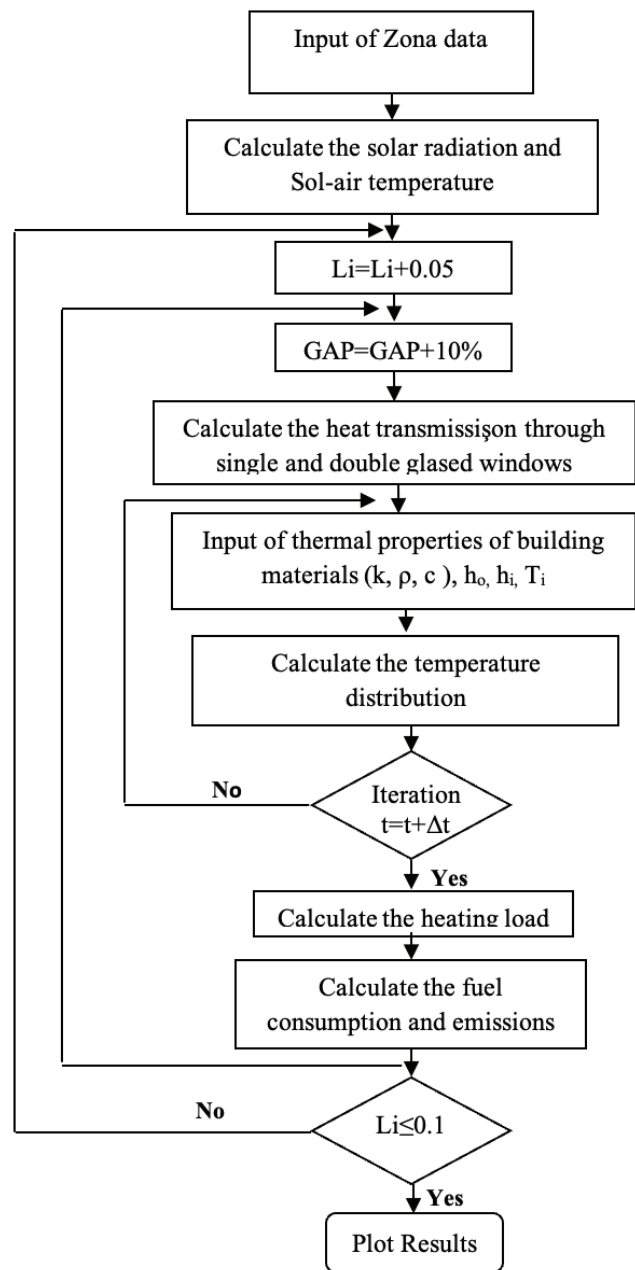


Figure 1. Flow chart.

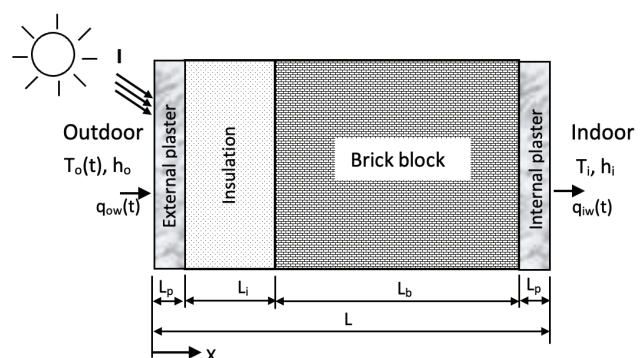


Figure 2. A multilayer composite wall [48] [created by author].

$$k_j \frac{\partial T_j}{\partial x} = k_{j+1} \frac{\partial T_{j+1}}{\partial x} \tag{3}$$

The wall's initial and boundary conditions are expressed as follows [49]:

$$T_j(x,0) = F_j \tag{4}$$

$$-k_1 \left(\frac{\partial T}{\partial x} \right)_{x=0} = h_o(T_o(t) - T_{x=0}) + a_o \cdot I(t) \tag{5}$$

$$-k_N \left(\frac{\partial T}{\partial x} \right)_{x=L} = h_i(T_{x=L} - T_i) \tag{6}$$

The initial condition, F_j represents a uniform temperature that is selected as arbitrary across the wall. h_o and h_i represent external and internal convective coefficients, respectively. T_i denotes the inner air temperature. T_o denotes the outer air temperature. I and a_o represent solar radiation and the outdoor wall surface's solar absorptivity, respectively. The total solar radiation (I) incident upon a surface at any moment can be computed by

$$I = I_D + I_d + I_R \tag{7}$$

Where I_D , I_d and I_R represent the direct radiation, the diffuse sky radiation and the solar radiation reflected upon the surface from surrounding surfaces, respectively. The detailed computing procedures of equation 7 are imputed by reference [50].

Differential equations and boundary conditions have been previously solved in MATLAB by employing the IFD method, and the computing transactions are available in detail in the source given by [51,52]. It has previously been indicated that the numerical solution is in good harmony with the analytical solution [52]. Thus, the temperature distribution along the thickness of the wall was obtained by

the numerical solution. The instantaneous heat transmission is computed following as:

$$q_{iw} = h_i(T_{x=L} - T_i) \tag{8}$$

Heat Transmission Through Transparent Surfaces

The solar radiation and the temperature difference between inner and outer thermal environments cause heat transmission through window glass. Direct, diffuse and reflected solar radiations can come to the outer surface of the window. Some of these radiations are transmitted directly through the glass, some are reflected and some are absorbed. As shown in Figure 3a, heat transfer through a single-glazed window is given by Threlkeld [49].

$$q_{i,sg} = F_s \tau_D I_D + \tau_d I_d + \tau_R I_R + (U/h_o)(F_s a_D I_D + a_d I_d + a_R I_R) + U(T_o - T_i) \tag{9}$$

$$U = 1/[(1/h_i) + (1/h_o)] \tag{10}$$

In the above equation, F_s represents the window surface's sunlit fraction. The heat transfer through the double-glazed window shown in Figure 3b can be computed as [53–55]:

$$q_{i,dg} = F_s \tau_{(1,2)D} I_D + \tau_{(1,2)d} I_d + \tau_{(1,2)R} I_R + (U/h_o)[F_s \alpha_{(1of2)D} I_D + \alpha_{(1of2)d} I_d + \alpha_{(1of2)R} I_R] + U[(1/h_o) + (1/h_a) + (1/h_i)](F_s \alpha_{(2of2)D} I_D + \alpha_{(2of2)d} I_d + \alpha_{(2of2)R} I_R) + U(T_o - T_i) \tag{11}$$

$$U = 1/[(1/h_i) + (1/h_a) + (1/h_o)] \tag{12}$$

In the above equation, h_a represents the heat transfer coefficient of the air gap between the glass sheets. The transmittance, reflectivity and absorption for a single glass layer are computed as follows [49,55–57]:

$$\tau = [(1-r)^2 a]/[1-r^2 a^2] \tag{13}$$

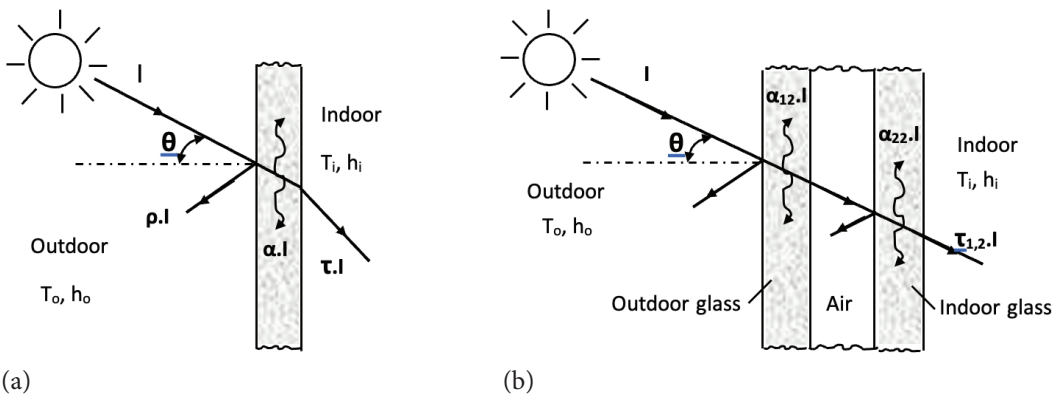


Figure 3. Heat Transmission from window with a) single glass b) double glass [48] [created by author].

$$\rho = r + r[(1-r)^2 a^2] / [1-r^2 a^2] \quad (14)$$

$$\alpha = 1 - r - [(1-r)^2 a] / [1-ra] \quad (15)$$

In the above equation, r represents the component reflectivity and may be found from the Frensel relations as follows:

$$r = \frac{1}{2} \left[\frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')} + \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')} \right] \quad (16)$$

Where θ denotes the incidence angle of the sun's rays. Its detailed calculation procedures are available in the reference [49]. θ' represents the refraction angle and is computed as follows:

$$\theta' = \sin^{-1}(\sin \theta / n) \quad (17)$$

In the above equation, n represents the refraction index of the glass. The absorption coefficient symbolized by a is computed as follows:

$$a = \exp\left(-K.L / \sqrt{1 - (\sin^2 \theta / n^2)}\right) \quad (18)$$

In the above equation, K denotes the extinction coefficient. L is the thickness of the glass. Transmissivity and reflectivity for double-glazed windows have been shown by Parmelee as following [49]:

$$\tau_{1,2} = (\tau_1 \tau_2) / (1 - \rho_1 \rho_2) \quad (19)$$

$$\rho_{1,2} = \rho_1 + (\tau_1^2 \rho_2) / (1 - \rho_1 \rho_2) \quad (20)$$

Where subscript 1 represents the first glass sheet while subscript 2 represents the second glass sheet. Also, the solar absorption in each sheet of glass is as follows:

$$\alpha_{1of2} = [1 - (\rho_1 + \tau_1)][1 - \rho_2(\rho_1 - \tau_1)] / [1 - \rho_1 \rho_2] \quad (21)$$

$$\alpha_{2of2} = [1 - (\rho_2 + \tau_2)]\tau_1 / [1 - \rho_1 \rho_2] \quad (22)$$

Daily and Yearly Total Heating and Cooling Transmission Loads

The research is carried out on the fifteenth day of every month of the year. Firstly, the instantaneous heat loads through the wall and window are determined as above. Daily transmission loads for the wall and window are computed by integrating instant load over a one-day (24 h) as follows:

$$Q_i = \int_0^{24h} q_i dt \quad (23)$$

Also, yearly total heating and cooling loads are acquired individually by adding the daily heating and cooling loads for the winter and summer periods.

The Glazing Area Percentage (GAP)

GAP is determined by accounting for heat transfer through external walls and windows. The window frame area is not taken into consideration in this analysis. When only the glass area is taken into account, GAP is calculated as [42,44]:

$$GAP = \frac{A_g}{A_t} \cdot 100 = \frac{A_g}{A_g + A_w} \cdot 100 \quad (24)$$

In the above equation, A_g and A_w represent glass and wall areas, respectively. Using this definition, the heating or cooling transmission loads can be computed for single and double glass with increasing glazing area percentages from 0% to 100% with a 10% increment as follows:

$$Q_{loss} = Q_{ig} \cdot GAP + Q_{iw} \cdot [1 - GAP] \quad (25)$$

or
gain

Where Q_{iw} and Q_{ig} represent the daily total loads of wall and window (for single or double-glazed), respectively.

Cost Analysis for Optimum Thickness of Insulation

Most of the studies available in the literature have calculated the OIT by taking something into consideration the heat gains and losses from only external walls. In this investigation, the OIT was computed by paying regard to the heat transmission not only through the exterior walls but also through the windows. The annual cost of energy for heating per unit area, (CA) is computed as follows [33]:

$$C_A = (Q_{loss} \cdot C_F) / (H_u \cdot \eta_s) \quad (26)$$

where Q_{loss} is the annual heat loss of the insulated wall as regards glass area percentage (kWh/m²). C_F , H_{uand} and η_s represent the fuel's cost (\$/kg), the fuel's lower heating value (kJ/kg) and the heating system's efficiency, respectively. The overall cost is determined as follows:

$$C_t = PWF \cdot C_A + C_{ins} \cdot L_{ins} \quad (27)$$

where C_{ins} and L_{ins} denote the insulation material's cost per unit volume (\$/m³) and the insulation thickness (m), respectively. Besides, PWF represents the Present Worth Factor. PWF value for the N years lifetime is calculated as follows [33,48]:

$$PWF = [(1+r)^N - 1] / [r(1+r)^N], \quad \begin{cases} i > g & r = (i-g)/(1+g) \\ i < g & r = (g-i)/(1+i) \end{cases} \quad (28)$$

$$PWF = N / (1+i), \quad i = g \quad (29)$$

The energy savings per unit area are determined by the divergence between the total cost of an uninsulated wall and the total cost when the wall was insulated to the optimum thickness. It may be computed as follows [33,48]:

$$S_e = \left(\frac{((Q_{loss})_{un} - Q_{loss}) \cdot C_F}{H_u \cdot \eta_s} \right) PWF - C_{ins} \cdot (L_{ins})_{opt} \quad (30)$$

Where $(Q_{loss})_{un}$ represents the annual total heat loss in the wall without insulation as regards the percentage of glass area (kWh/m²). Annual energy saving (A_s) is computed as follows [33]:

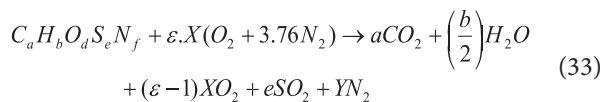
$$A_s = \frac{((Q_{loss})_{un} - Q_{loss}) \cdot C_F}{H_u \cdot \eta_s} \quad (31)$$

The payback period (p_b) may be computed as below [28,42]:

$$PWF(p_b) = \frac{C_i \cdot (L_i)_{opt}}{A_s}, \quad p_b = \frac{\ln(1 - r(C_i \cdot (L_i)_{opt} / A_s))}{\ln(1 / (1 + r))} \quad (32)$$

The Fuel Consumption and Emissions

The combustion equation of fuel is as follows [33,58]:



If the above chemical reaction is balanced based on the principle of conservation of mass, the constants specified by X and Y are determined as follows:

$$X = a + e + (b / 4) - (d / 2), \quad Y = (f / 2) + 3.76 \cdot \epsilon \cdot X \quad (34)$$

The CO₂ and NO₂ emission rates of combustion products which are result from the combustion of 1 kg of fuel may be computed as follows [33]:

$$M_{CO_2} = (a CO_2) / M \equiv kg \ CO_2 / kg \ fuel \quad (35)$$

$$M_{SO_2} = (e SO_2) / M \equiv kg \ SO_2 / kg \ fuel \quad (36)$$

M denotes fuel mol weight and may be computed as follows:

$$M = 12a + b + 16d + 32e + 14f \quad kg / kmol \quad (37)$$

Total CO₂ and SO₂ emissions are determined based on annual fuel consumption as follows:

$$M_{CO_2} = \frac{44a}{M} M_F, \quad M_{SO_2} = \frac{64e}{M} M_F \quad (38)$$

The annual fuel consumption is computed as follows [33]:

$$M_F = Q_{loss} / H_u \cdot \eta_s \quad (39)$$

RESULTS AND DISCUSSION

In this research, the impact of glass area on insulation thickness and fuel consumption was numerically investigated for a south-oriented wall in Elazig province which is located in Turkey’s Eastern Anatolia zone and has a latitude of 38.41°N and a longitude of 39.14°E. The wall structure consists of external plaster which has 20 mm thickness, an insulation layer which has variable thickness, brick block which has 200 mm thickness and internal plaster which has 20 mm thickness. The insulation thickness is increased from 5 mm to 100 mm at every 5 mm interval. The windows consist of single glass with a thickness of 3 mm and double glass with air gaps, each layer of which is 3 mm thick. For this aim, the window glass area on the wall which has different insulation thicknesses is risen from 0% to 100% with a ratio of 10%, taking into account the single glazing and double glazing. Yearly heat loads through the wall were numerically obtained under dynamic thermal conditions. Thermophysical characteristics of materials which are used in the structure of the wall are imputed in Table 1 [28]. It is assumed that the variation of thermal properties of materials given in Table1 is negligible. Yearly heating loads through the opaque wall and window glass are employed as input data in the cost analysis to specify the OIT over the 20-year life of the building. The parameters used for OIT and environmental analysis are imputed in Table 2.

Table 1. Thermophysical properties of building materials, and cost of insulation [48] [created by author]

Material	k (W/m K)	ρ (kg/m ³)	c (J/kg K)	C ₁ (\$/m ³)
Brick block	0.620	1800	840	—
Extruded polystyrene	0.029	35	1213	304.23
Cement plaster	0.720	1865	840	—

Table 3. Indoor design temperatures selected for the representative day of each month [48] [created by author]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ti (°C)	20	20	20	22	23	23	23	23	23	22	20	20

Table 2. The parameters used in calculations [48] [created by author]

Parameter	Value
C_r	0.3777 \$/kg
H_u	29.307×10^6 J/kg
η_s	% 65
Chemical formula of Coal [58]	$C_{7.078}H_{5.149}O_{0.517}S_{0.01}N_{0.086}$
Interest rate, i	% 8.75
Inflation rate, g	% 7.50

The external environment temperatures of Elazig were ensured from the meteorological data of the years 2010-2020 [59]. As in Table 3, fixed inside air temperatures were chosen for each month's 15th day. The solar absorption of the opaque wall was chosen to be 0.8. The combined convection coefficients for the outer and inner wall surfaces were assumed as 22 and 9 W/m²K, respectively [31]. In this work, clear plate glass was chosen as the glass type. For this type of glass, the refractive index (n) was received as 1.526 and the extinction coefficient (K) was taken as 6.85 m-1. It is assumed that the sunlit fraction (Fs) was 1. The thickness of the air gap between the double glazing was chosen as 6 mm. The heat transfer coefficient of the air gap was received to be 5.56 W/m²K [53].

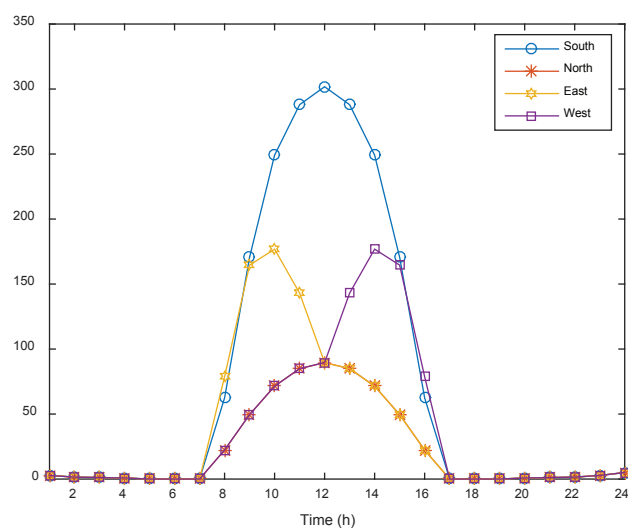
In this study, a Matlab program was comprehensively developed to perform numerical calculation. With the help of this program, heat transmission loads through walls and windows, OIT, fuel consumption and emissions are computed depending on many parameters.

Figure 4(a) and (b) show the incident solar radiation's hourly variation in all wall directions for Jan. 15 and Jul. 15, respectively.

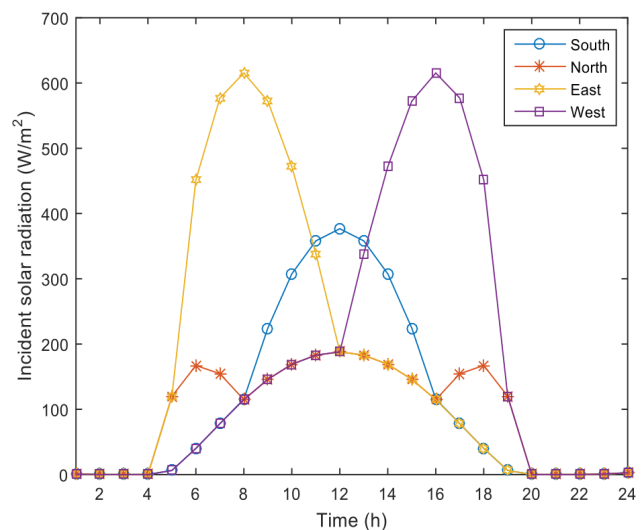
It is observed that in summer, the incident solar radiation's highest value is received as 615.36 W/m² at 8:00 hour in the east direction and at 16:00 hour in the west direction while in winter, it is acquired to be 301.77 W/m² at noon (12:00 hour) in the south direction. On the other part, the incident solar radiation's highest value for Jul. 15 and Jan. 15 occurs at 8:00 and 10:00 hours, respectively in the east direction and at 16:00 and 14:00 hours, respectively in the west direction while it is acquired at noon (12:00 hour) in the south and north directions. It is obvious that in summer, the south facade does not receive the maximum radiation because the sun is too high in the sky, while in winter, it receives the maximum radiation because the sun is at a much lower altitude [60]. These results were found to be in good agreement with previously obtained results [7,60].

Figure 5 presents the incident solar radiation's highest values for all months in different orientations. It is revealed that the east and west directions give maximum solar radiation in July while the south orientation gives in September [48]. It is also revealed that the lowest solar radiation is acquired in the north orientation for all months. Particularly, south walls provide large solar heat gain and eliminate heat losses in winter, while in summer the solar heat gain is relatively small and limits unwanted gain. The most desirable external wall orientation is south and therefore, the south direction is selected in this study.

In case the wall is insulated, as the GAP is increasing, heating and cooling transmission loads are increasing for single glass. However, as the GAP is increasing, the heating transmission load on the wall consisting of a double-glazed window is increasing for January month while it is decreasing for February month. In addition, as the GAP



(a)



(b)

Figure 4. Hourly variation of incident solar radiation for all wall orientations: (a) in January 15 (b) in July 15.

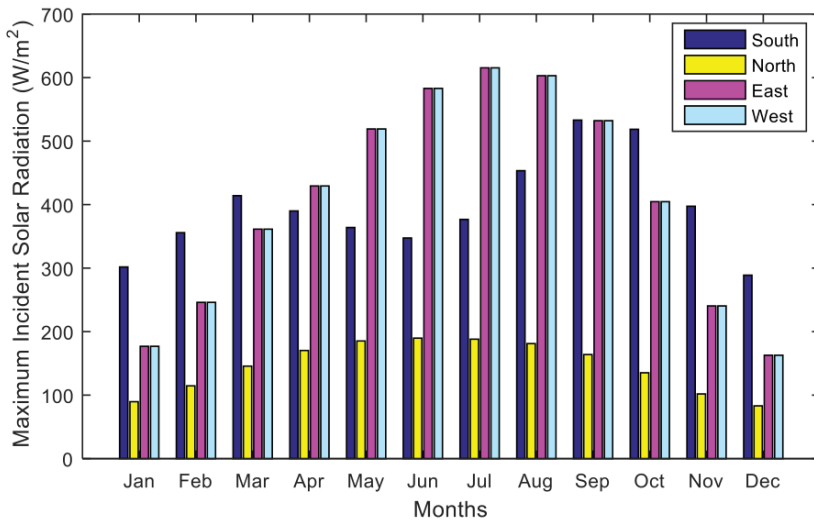


Figure 5. Maximum values of incident solar radiation according to months for all wall orientations [48] [created by author].

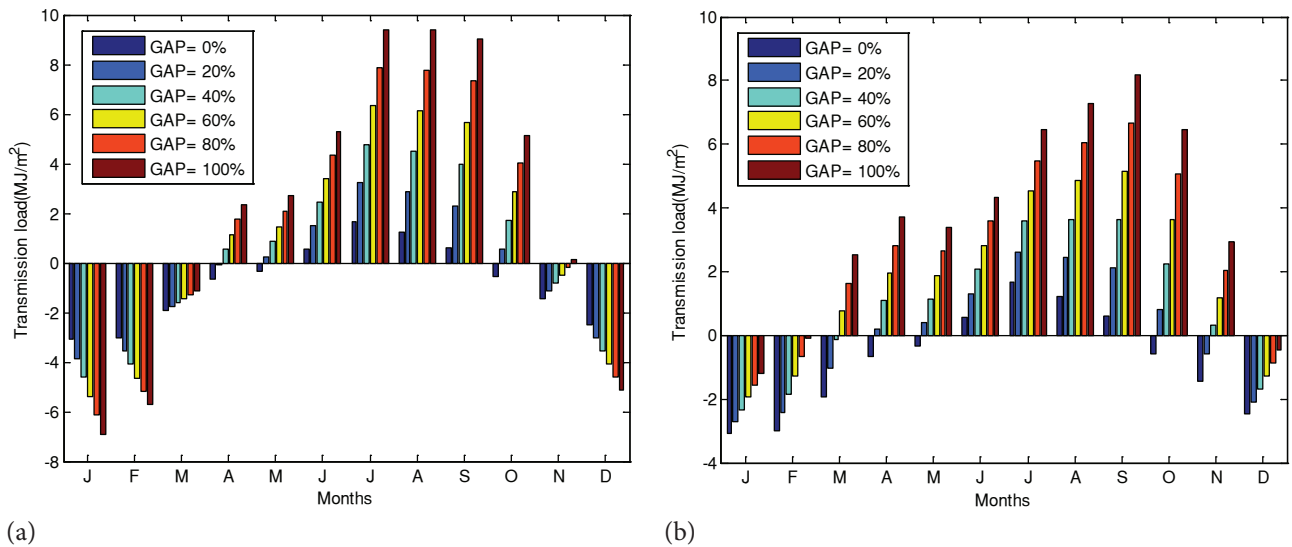


Figure 6. Daily total cooling and heating transmission loads for the 15th day of each month with respect to different GAP values in uninsulated wall for a) single glass and b) double glass.

is increasing, the cooling transmission load is increasing for the walls consisting of single and double-glazed windows.

Figure 8(a) and (b) show the trends of annual heating loads with respect to insulation thickness for various GAP values in the wall consisting of single-glazed and double-glazed windows, respectively. The annual heating load is determined considering the months in which the heating load occurs. It is revealed that heating transmission loads for all GAP values decline as the insulation thickness rises. This decline in the heating load of wall consisting of a single-glazed window is acquired to be 82.25%, 54.19%, 34.55% and 20% for 0%, 20%, 40% and 60% values of GAP,

respectively. Whereas, this decrease for wall consisting of a double-glazed window is acquired to be 82.25%, 76.86%, 69.29% and 57.89%. It is seen that double glazing provides a greater reduction in heating load. Additionally, the results show that at larger glazing ratios, the insulation thickness has less impact on the heating load. This result is consistent with previously reported using P1-P2 method under different climate conditions [47].

The heating load in 20 mm insulated wall for single glazing is acquired to be 177.57, 236.79, 317.51 and 398.23 MJ/m^2 year for values 0%, 20%, 40% and 60% of the GAP, respectively while it is obtained to be 177.57, 114.24, 88.24

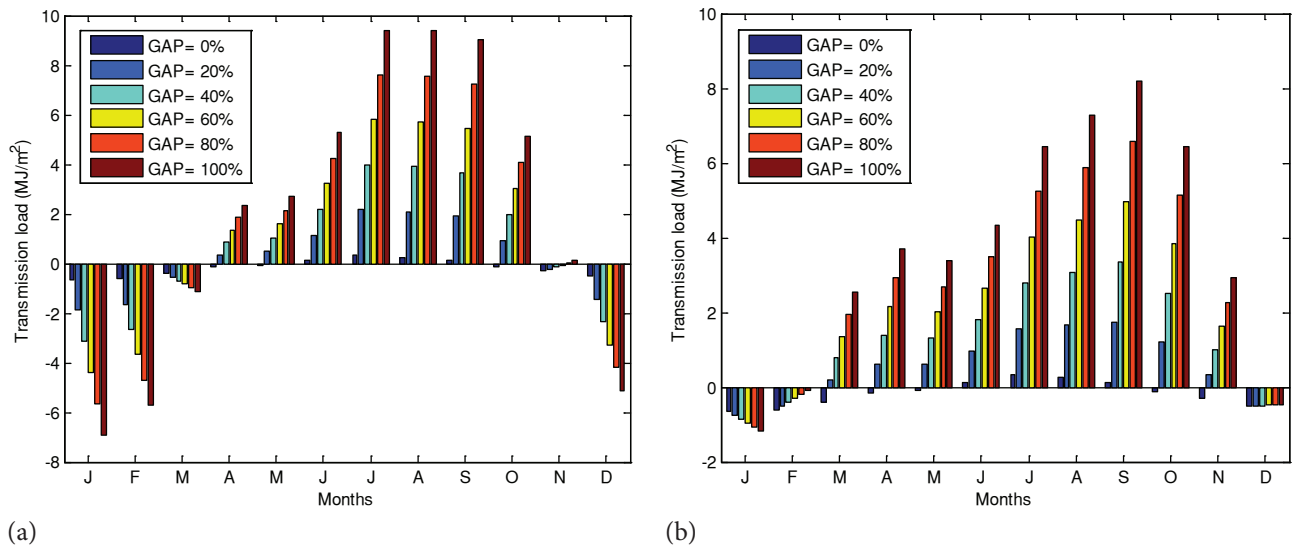


Figure 7. Daily total cooling and heating transmission loads for the 15th day of each month with respect to different GAP values in 6 cm insulated wall for a) single glass and b) double glass.

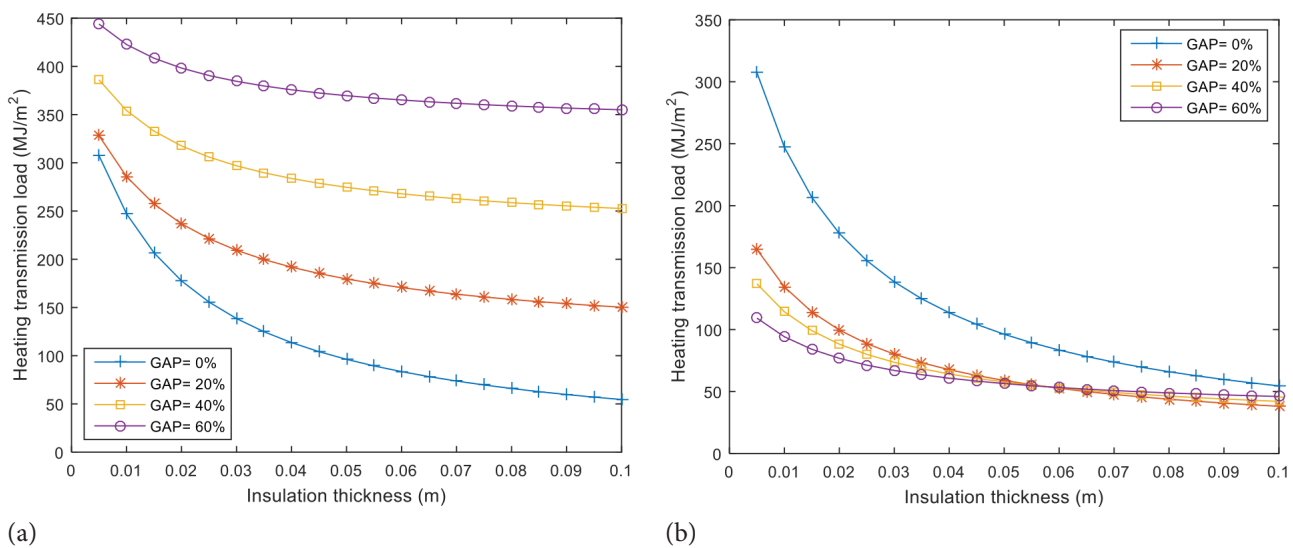


Figure 8. Yearly heating transmission loads according to increasing insulation thickness and glazing area percentage (GAP) for a) single glass and b) double glass.

and 76.81 MJ/m² year for double glass. On the other hand, The heating load in 60 mm insulated wall for single glazing is acquired to be 83.49, 170.63, 267.89 and 365.15 MJ/m² year for values 0%, 20%, 40% and 60% of the GAP, respectively while it is obtained to be 83.49, 52.58, 52.92 and 53.26 MJ/m² year for double glass. It is observed that in south facing wall, as GAP rises, the heating loads for single glazing increase. The results show that increasing the glazing area for single glazing results in an additional heating load. This conclusion is consistent with conclusion obtained under the environmental conditions of the Greek region [41]. It is seen that when GAP rises, the heating

transmission load for double glazing declines at insulation thickness's smaller values while it increases at bigger values of insulation thickness. It is revealed that the heating loads for different GAP values of a 50 mm insulated wall consisting of a double-glazed window approach each other and are almost the same for insulation thicknesses from 55 mm to 65 mm. In high insulation thicknesses, it is revealed that for double glazing, the heating load rises as the GAP rises, as in single glazing. It is revealed that for an insulated wall consisting of a double-glazed window, the heating loads are significantly reduced for different GAP values when compared to single-glazed. Using double-glazed instead of

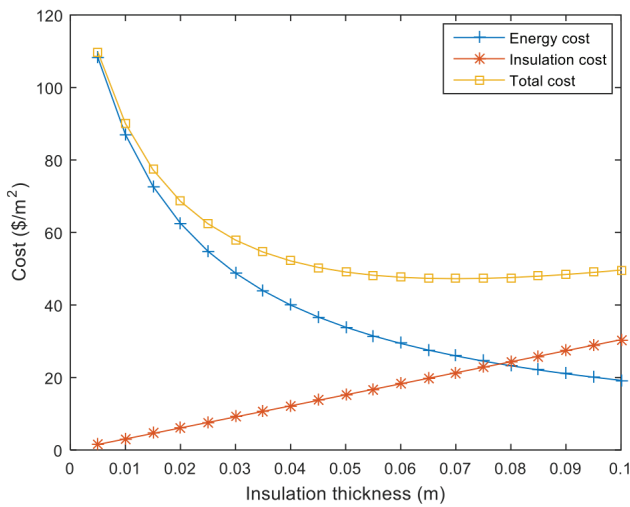


Figure 9. Variation of costs to insulation thickness for GAP=0 value in a south-oriented wall with single glass.

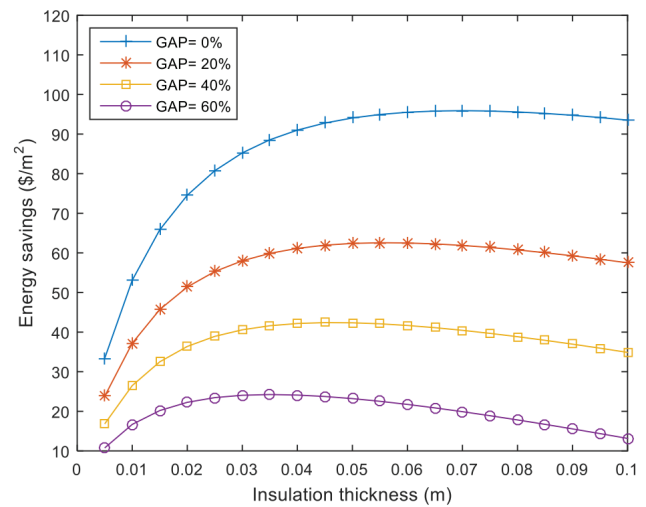


Figure 10. Effect of insulation thickness on energy savings for different GAP values in a south oriented wall with single glass.

single-glazed in a 50 mm insulated wall reduces the heating load by 67.17%, 78.98% and 84.72% for 20%, 40% and 60% GAP values, respectively.

For south orientation, it is observed that In winter, double glazing of windows increases the heat gain compared to single glazing while in summer, double glazing of windows reduces heat gain as seen in Reference [60]. This situation, explained above for winter conditions, can be attributed to the fact that double glazing increases heat gain compared to single glazing in winter. It is revealed that the larger double-glazing area on the south facade significantly reduces heat loss in winter.

Figure 9 demonstrates the trends of costs to insulation thickness for GAP=0% in a wall in the south direction. It is revealed that as the thickness of insulation rises, the cost of insulation linearly rises while the cost of energy decreases. The sum of insulation cost and energy cost gives the total cost. The insulation thickness where the total cost is minimum gives OIT. The impression of insulation thickness on energy savings for various GAP values of a wall in the

south direction is shown in Figure 10. It is revealed that the energy saving decreases as GAP increases.

The optimum thicknesses of insulation, energy savings and payback periods for various values of the GAP according to type of glazing are illustrated in Table 4. It is revealed that when the GAP rises, OIT and energy-saving decline for south wall while the payback period rises. The conclusions show that the GAP values have a notable effect on OIT, energy saving and payback period. It is revealed that OITs for single glazing are acquired as 70, 55, 45 and 35 mm for 0%, 20%, 40% and 60% values of the GAP, respectively while they are acquired as 70, 45, 35 and 25 mm for double glazing. It is seen that the OIT decreases as GAP increases for both glass types. This result is consistent with those acquired by other studies using the DD method [46,47] under different climate conditions. Also, the similar conclusions are obtained by using both heating and cooling transmission loads [48]. For example, it is seen in Reference 46 that the OIT for a wall including a double-glazed window is 23 mm for 10% and 10 mm for 50% by using cooling DD in Algiers.

Table 4. The OIT, energy savings and payback periods for different values of GAP

Glazing Type	GAP	OIT (m)	Energy savings (\$/m ²)	Payback period (years)
Single glazing	0%	0.070	95.90	3.30
Single glazing	20%	0.055	62.56	3.85
Single glazing	40%	0.045	42.39	4.47
Single glazing	60%	0.035	24.23	5.63
Double glazing	0%	0.070	95.90	3.30
Double glazing	20%	0.045	56.88	3.53
Double glazing	40%	0.035	28.09	5.05
Double glazing	60%	0.025	14.50	6.37

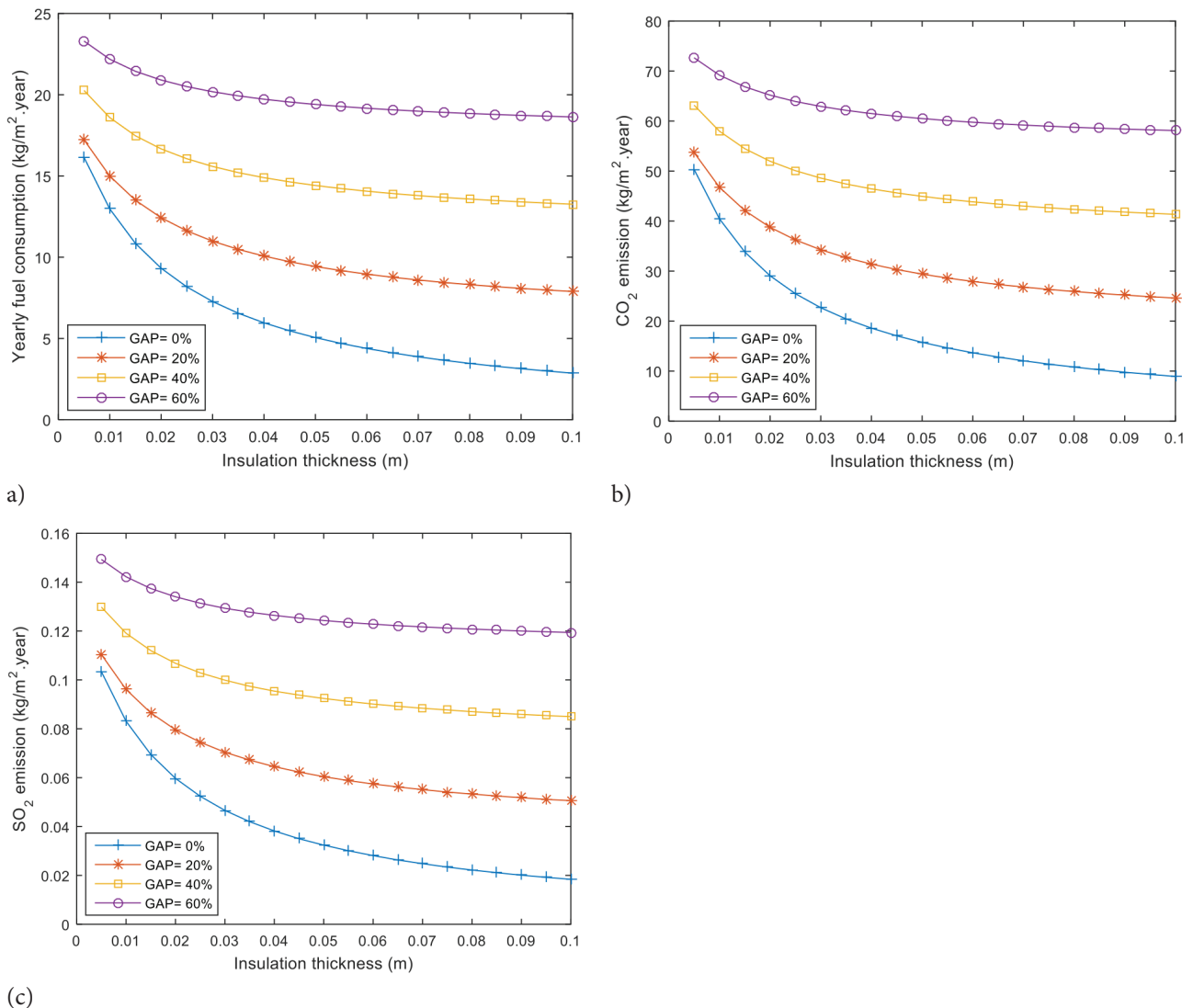


Figure 11. Variations of the yearly fuel consumption and, CO₂ and SO₂ emissions according to insulation thickness for different GAP values in a south oriented wall with single glass.

The thermal insulation’s environmental impacts are also researched for different values of the GAP. Figure 11(a-c) shows fuel consumption and emissions trends according to insulation thickness and various GAP values for the single glazing in the south direction. It is revealed that the annual fuel consumption and emissions decrease for all GAP values depending on increasing insulation thickness. This decline in the wall consisting of a single-glazed window is acquired as 82.25%, 54.19%, 34.55% and 20% for 0%, 20%, 40% and 60% of the glazing area, respectively. It is obvious that this decrease is the same as the decrease in heating load, as seen in Figure 7a. The results show that if the wall consisting of a single-glazed window is insulated with the OIT, fuel consumption and emissions are reduced by 76.02%, 46.73%, 27.77% and 14.46% for values 0%, 20%, 40% and 60% of the glass area, respectively. However, it is seen that fuel consumption and emissions increase as GAP

rises. For example, at 6 cm insulation thickness, yearly fuel consumption was obtained as 4.3826, 8.9574, 14.0630 and 19.1686 kg/m².year for 0%, 20%, 40% and 60% of the glazing area, respectively. It is seen that the increment in the glazing area for single glass induces additional heating, fuel consumption and emissions. It is observed that insulation is more effective in the lower glazing areas. These results acquired are found to be in good agreement with previously reported using P1-P2 method under different climate conditions [47].

CONCLUSION

In this work, the effect of window glass area on insulation thickness and fuel consumption is researched numerically for the south orientation under dynamic thermal conditions in the climate of Elazığ, Turkey. For this goal, the

window glass area on the wall which has different insulation thicknesses is enhanced by %10 from %0 to %100. The results showed that as the glazing area percentage increases, the heating transmission load for single glazing increases in all wall insulation thicknesses. It is seen that choosing smaller glazing areas in insulated walls containing a single-glazed window results in less heating load.

The results also showed that as the glazing area percentage rises, the heating transmission load for double glazing declines at minor values of the insulation thickness and becomes almost the same for approximately 6 cm insulation thickness. It is observed that at lower values of insulation thickness, the large double-glazing area on the south facade significantly reduces heat loss in winter from the point of energy efficiency.

It is seen that the increment in the glazing area for single glass induces additional heating, additional fuel consumption and emissions. Besides, it is obvious that double glazing can provide a greater reduction in terms of insulation thickness, heating load, fuel consumption and emissions.

The conclusions demonstrate that the glazing area and type of glazing have a notable effect on heating and cooling loads, the optimum insulation thickness, fuel consumption and emissions.

As a result, it appears that with the appropriate combination of design parameters such as window glass area, glazing type and wall insulation, heating and cooling loads and therefore fuel consumption and emissions can be substantially reduced. The reduction in heating and cooling loads results in lower building operating costs. Therefore, the results acquired in this work will be helpful from the point of energy efficiency in the selection of glass type, the glazing area and insulation thickness when designing building exterior walls. In addition, this work will contribute to the fight against climate change caused by emissions by reducing fuel consumption and emissions. Besides, both heat loss and fuel consumption; and hence emissions, can be reduced by changing the window glass of existing buildings to double glazing and applying insulation to the walls from the outside.

It is revealed that some findings acquired in this work are supported by the results that were acquired in different climate zones in the literature. The same methodology can be replicated to other kinds of buildings (residential or commercial). Additionally, the study can be also expanded for different climatic regions, different building orientations, different insulation materials and advanced glazing materials using the same methodology, and presented in another study.

Since this study focuses on the effect of wall insulation and glazing area on heating and cooling loads and hence fuel consumption and emissions, the daylight factor is not taken into account in this study. The effect of artificial lighting on energy consumption can also be investigated in another study.

AUTHORSHIP CONTRIBUTIONS

Meral Özel: Investigation, methodology, software, analyzing and interpreting the data, discussion, writing original draft, review and editing.

Serhat Şengür: Investigation, analyzing and interpreting the data, discussion, writing original draft, review and editing.

DATA AVAILABILITY STATEMENT

The authors confirm that data supporting the findings of this study are available within the article.

CONFLICT OF INTEREST

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

ETHICS

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

REFERENCES

- [1] Pargana N, Pinheiro MD, Silvestre JD, Brito J. Comparative environmental life cycle assessment of thermal insulation materials of buildings. *Energy Build* 2014;82:466–481. [\[CrossRef\]](#)
- [2] Omer AM. Energy, environment and sustainable development. *Renew Sustain Energy Rev* 2008;12:2265–2300. [\[CrossRef\]](#)
- [3] Oral GK. Appropriate window type concerning energy consumption for heating. *Energy Build* 2000;32:95–100. [\[CrossRef\]](#)
- [4] Karabay H, Arıcı M. Multiple pane window applications in various climatic regions of Turkey. *Energy Build* 2012;45:67–71. [\[CrossRef\]](#)
- [5] Ghisi E, Tinker J. Optimising energy consumption in offices as a function of window area and room size. 7th International IBPSA Conference. Rio de Janeiro, Brazil; 2001 p. 13–15.
- [6] Tsai DC, Chang ZC, Kuo BH, Chen EC, Huang YL, Hsieh TJ, et al. Thermal stability and optical properties of low emissivity multilayer coatings for energy-saving applications. *Ceram Int* 2020;46:7991–7997. [\[CrossRef\]](#)
- [7] Kontoleon KJ. Dynamic thermal circuit modelling with distribution of internal solar radiation on varying façade orientations. *Energy Build* 2012;47:139–150. [\[CrossRef\]](#)
- [8] Hasan A. Optimizing insulation thickness for buildings using life cycle cost. *Appl Energy* 1999;63:115–124. [\[CrossRef\]](#)

- [9] Dombayci OA. The environmental impact of optimum insulation thickness for external walls of buildings. *Build Environ* 2007;42:3855–3859. [\[CrossRef\]](#)
- [10] Sisman N, Kahya E, Aras N, Aras H. Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions. *Energy Policy* 2007;35:5151–5155. [\[CrossRef\]](#)
- [11] Dombayci OA, Golcu M, Pancar Y. Optimization of insulation thickness for external walls using different energy-sources. *Appl Energy* 2006;83:921–928. [\[CrossRef\]](#)
- [12] Comakli K, Yuksel B. Optimum insulation thickness of external walls for energy saving. *Appl Therm Eng* 2003;23:473–479. [\[CrossRef\]](#)
- [13] Ozkahraman HT, Bolatturk A. The use of tuff stone cladding in buildings for energy conservation. *Constr Build Mater* 2006;20:435–440. [\[CrossRef\]](#)
- [14] Bolatturk A. Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. *Appl Therm Eng* 2006;26:1301–1309. [\[CrossRef\]](#)
- [15] Bolatturk A. Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Build Environ* 2008;43:1055–1064. [\[CrossRef\]](#)
- [16] Kaynakli O. A study on residential heating energy requirement and optimum insulation thickness. *Renew Energy* 2008;33:1164–1172. [\[CrossRef\]](#)
- [17] Erturk M. A new approach to calculate the energy saving per unit area and emission per person in exterior wall of building using different insulation materials and air gap. *J Fac Eng Archit Gazi Univ* 2016;31:395–406.
- [18] Erturk M. A new model for exergetic optimum insulation thickness. *Int J Exergy* 2017;22:309–330. [\[CrossRef\]](#)
- [19] Erturk M, Kecebas A. Prediction of the effect of insulation thickness and emission on heating energy requirements of cities in the future. *Sustain Cities Soc* 2021;75:103270. [\[CrossRef\]](#)
- [20] Yu J, Yang C, Tian L, Liao D. A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. *Appl Energy* 2009;86:2520–2529. [\[CrossRef\]](#)
- [21] Mahlia TMI, Taufiq BN, Masjuki HH. Correlation between thermal conductivity and the thickness of selected insulation materials for building wall. *Energy Build* 2007;39:182–187. [\[CrossRef\]](#)
- [22] Kaynakli O. A review of the economical and optimum thermal insulation thickness for building applications. *Renew Sustain Energy Rev* 2012;16:415–425. [\[CrossRef\]](#)
- [23] Kurt H. The usage of air gap in the composite wall for energy saving and air pollution. *Environ Prog Sustain Energy* 2011;30:450–458. [\[CrossRef\]](#)
- [24] Mahlia TMI, Iqbal A. Cost benefits analysis and emission reductions of optimum thickness and air gaps for selected insulation materials for building walls in Maldives. *Energy* 2010;35:2242–2250. [\[CrossRef\]](#)
- [25] Shahid M, Karimi MN, Mishra AK. Optimum insulation thickness for external building walls for different climate zone in India. *J Therm Eng* 2021;10:1198–1211. [\[CrossRef\]](#)
- [26] Durmaz S, Colak AB, Mercan H, Dalkilic AS. Determination of optimum insulation thickness in submarines 2023;9:1655–1666. [\[CrossRef\]](#)
- [27] Ozel M, Pihtili K. Determination of optimum insulation thickness by using heating and cooling degree-day values. *J Eng Nat Sci* 2008;26:191–197.
- [28] Ozel M. Effect of wall orientation on the optimum insulation thickness by using a dynamic method. *Appl Energy* 2011;88:2429–2435. [\[CrossRef\]](#)
- [29] Ozel M. Thermal performance and optimum insulation thickness of building walls with different structure materials. *Appl Therm Eng* 2011;31:3854–3863. [\[CrossRef\]](#)
- [30] Ozel M. The influence of exterior surface solar absorptivity on thermal characteristics and optimum insulation thickness. *Renew Energy* 2012;39:347–355. [\[CrossRef\]](#)
- [31] Ozel M. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. *Energy Build* 2012;49:552–559. [\[CrossRef\]](#)
- [32] Ozel M. Determination of optimum insulation thickness based on cooling transmission load for building walls in a hot climate. *Energy Convers Manag* 2013;66:106–114. [\[CrossRef\]](#)
- [33] Ozel M. Thermal, economical and environmental analysis of insulated building walls in a cold climate. *Energy Convers Manag* 2013;76:674–684. [\[CrossRef\]](#)
- [34] Al-Sanea SA, Zedan MF. Optimum insulation thickness for building walls in a hot-dry climate. *Int J Ambient Energy* 2002;23:115–126. [\[CrossRef\]](#)
- [35] Al-Sanea SA, Zedan MF. Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass. *Appl Energy* 2011;88:3113–124. [\[CrossRef\]](#)
- [36] Al-Sanea SA, Zedan MF, Al-Ajlan SA, Abdul Hadi AS. Heat transfer characteristics and optimum insulation thickness for cavity walls. *J Therm Envel Build Sci* 2003;26:285–307. [\[CrossRef\]](#)
- [37] Al-Sanea SA, Zedan MF, Al-Ajlan SA. Effect of electricity tariff on the optimum insulation-thickness in building walls as determined by a dynamic heat-transfer model. *Appl Energy* 2005;82:313–30. [\[CrossRef\]](#)
- [38] Daouas N. A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads. *Appl Energy* 2011;88:156–164. [\[CrossRef\]](#)

- [39] Daouas N, Hassen Z, Aissia H Ben. Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. *Appl Therm Eng* 2010;30:319–326. [\[CrossRef\]](#)
- [40] Zengin DG, Kontoleon KJ. Influence of orientation, glazing proportion and zone aspect ratio on the thermal performance of buildings during the winter period. *Environ Sci Pollut Res* 2018;25:26736–26746. [\[CrossRef\]](#)
- [41] Kontoleon KJ, Zengin DG. Analysing Heat Flows Through Building Zones in Aspect of their Orientation and Glazing Proportion, under Varying Conditions. *Procedia Environ Sci* 2017;38:348–355. [\[CrossRef\]](#)
- [42] Kontoleon KJ, Bikas DK. Modeling the influence of glazed openings percentage and type of glazing on the thermal zone behavior. *Energy Build* 2002;34:389–399. [\[CrossRef\]](#)
- [43] Shahid M, Karımı MN. Optimization of energy transmittance through building envelope for hot dry climate. *J Therm Eng* 2022;8:595–605. [\[CrossRef\]](#)
- [44] Ozel M, Ozel C. Effect of window-to-wall-area ratio on thermal performance of building wall materials in Elaziğ, Turkey. *PLoS One* 2020;15:1–14. [\[CrossRef\]](#)
- [45] Arici M, Karabay H. Determination of optimum thickness of double-glazed windows for the climatic regions of Turkey 2010;42:1773–1778. [\[CrossRef\]](#)
- [46] Derradji L, Imessad K, Amara M, Boudali Errebai F. A study on residential energy requirement and the effect of the glazing on the optimum insulation thickness. *Appl Therm Eng* 2017;112:975–985. [\[CrossRef\]](#)
- [47] Ozkan DB, Onan C. Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey 2011;88:1331–1342. [\[CrossRef\]](#)
- [48] Ozel M. Influence of glazing area on optimum thickness of insulation for different wall orientations. *Appl Therm Eng* 2019;147:770–780. [\[CrossRef\]](#)
- [49] Threlkeld JL. *Thermal Environment Engineering*. 3rd ed. London: Pearson; 1998.
- [50] Duffie JA, Beckman WA. *Solar engineering of thermal processes*. 2nd ed. New York: John Wiley & Sons; 1991.
- [51] Ozel M, Pihtili K. Optimum location and distribution of insulation layers on building walls with various orientations 2007;42:3051–3059. [\[CrossRef\]](#)
- [52] Ozel M, Pihtili K. Investigation of the most suitable location of insulation applying on building roof from maximum load levelling point of view. *Build Environ* 2007;42:2360–2368. [\[CrossRef\]](#)
- [53] Davies MG. Useful solar gains through a south-facing window in the UK climate. *Build Environ* 1980;15:253–272. [\[CrossRef\]](#)
- [54] Kontoleon KJ, Bikas DK. The influence of the zone's indoor temperature settings on the cooling/heating loads for fixed and controlled ventilation. *Build Environ* 2006;41:75–86. [\[CrossRef\]](#)
- [55] Ozel M. Investigation of methods for minimizing heat gain and losses in the buildings with periodical temperature variation on the wall surface. *Firat Univ Nat Sci Inst* 2003.
- [56] Ozel M, Pihtili K. Investigation of effect of wall insulation thickness on window areas. *J Fac Eng Archit Gazi Univ* 2008;23:655–662.
- [57] Kılıç A, Ozturk A. *Güneş Enerjisi*. İstanbul: Kipaş Dağıtımçılık; 1983.
- [58] Yıldız A, Gurlek G, Erkek M, Ozbalta N. Economical and environmental analyses of thermal insulation thickness in buildings. *J Therm Sci Technol* 2008;28:25–34.
- [59] State Meteorological Station. Records for weather data. Turkey, 1997-2007.
- [60] Ozel M. Impact of glazing area on the thermal performance of buildings. *Int J Ambient Energy* 2022;43:2039–2055. [\[CrossRef\]](#)