The life cycle assessment related to insulation thickness of external walls of the airport

Okan Kon and Ismail Caner*

Department of Mechanical Engineering,
Engineering Faculty,
Balikesir University,
Cagis Campus 10145 Balikesir, Turkey
Email: okan@balikesir.edu.tr
Email: ismail@balikesir.edu.tr
*Corresponding author

Abstract: In this study, energy savings to be gained by the insulation of the external walls of airport buildings are examined according to Turkish Building Insulation Standard (TS 825) which is renewed in December 2013. In addition, life cycle total (LCT) cost and life cycle savings (LCS) are calculated. Unlike the residences, the airport buildings indoor temperatures should be 20°C during the heating period according. The optimum insulation thickness was determined for the external walls of the airport buildings. The degree-of-day method is used in calculations. Optimum insulation thickness is the lowest polyurethane insulation material in the highest glass wool insulation material. The optimum insulation thickness is calculated as 0.044–0.090 m for the polyurethane insulation material and 0.122–0.233 m for the glass wool insulation material. Also, extruded polystyrene (XPS) insulation material was found between 0.062–0.125 m.

Keywords: life cycle assessment; LCA; TS 825; insulation; energy saving.

Reference to this paper should be made as follows: Kon, O. and Caner, I. (2019) 'The life cycle assessment related to insulation thickness of external walls of the airport', *Int. J. Sustainable Aviation*, Vol. 5, No. 2, pp.158–173.

Biographical notes: Okan Kon graduated from the Mechanical Engineering Department, Balikesir University in 2000. He completed his Master's degree in 2004 and Doctorate degree in 2014 at the same university. Since 2001, he has been working from the Department of Thermodynamics. He works on buildings energy systems.

Ismail Caner graduated from the Mechanical Engineering Department, Balikesir University, in 2011. He completed his Master's degree in 2014. He has been working from the Department of Thermodynamics. He has been continuing his PhD education in the same university since 2014. He works on energy efficiency of buildings.

This paper is a revised and expanded version of a paper entitled 'Energy saving and life cycle cost analysis related to insulation thickness of external walls of the airport' presented at International Symposium on Sustainable Aviation 2018, Rome, Italy, 9–11 July 2018.

Copyright © 2019 Inderscience Enterprises Ltd.

1 Introduction

Insulation is one of the preventions that reduces heat exchange from buildings' external walls, roofs, floors and plumbing to reduce the energy that spend to cooling in summer and heating in winter. In our existing buildings it is made by applying thermal insulation materials to roof, floor, and external walls (Değirmenci, 2010). The walls have the most area in the building envelope. The height of the building increases, the heat loss increases due to the growth of the wall surface area. Therefore, the external walls are required to be insulated to prevent heat loss and sustain the thermal comfort (Aydın, 2011). For this reason, the selection of the insulation material and the determination of the insulation thickness are very important. The most important parameters in the selection of insulation material are its thermal conductivity and price (Yu et al., 2009). As the thickness of the insulation increases, the heat gains and losses will be significantly reduced however the insulations costs will also increase. In this case, the optimum thickness of the insulation should be determined by cost analysis (Dağıdır and Bolattürk, 2011).

The heat transfer coefficients calculated by the thickness of the structural components and the heat convection coefficients are very important parameters in the energy consumption of buildings. The most effective component in terms of energy saving in the building components is the insulation layer and with this insulation layer, the heat transfer coefficient of the structural element, for example the external wall, can be reduced. This will reduce the energy consumption. However, as the insulation thickness increases, the insulation cost (insulation material, labour cost, etc.) will increase. Therefore, it would be appropriate to use the optimum insulation thickness, which is the minimum cost of energy cost and total insulation cost. The life cycle cost approach for the long-term is used to calculate the optimum insulation thickness. Energy costs are calculated by using interest and inflation rates.

Alghoul et al. (2016) have calculated the optimum insulation thickness of external walls for the city of Tripoli in Liberia. The calculations have been made according to the degree-day method and life cycle cost analysis. Polystyrene have been used as an insulation material and electricity were used as an energy source which has different prices. Al-Khawaja (2004) has determined the optimum insulation thickness for the external walls of buildings in hot countries. To calculate the value of solar radiation, the temperature of the sun-air has been used. In Qatar, the external wall insulation thicknesses for cooling have been calculated. Wallmate, fibreglass, and polyurethane have been used as insulation material and electricity has been used as an energy source. Arslanoglu and Yigit (2017) have investigated the parameters that affect optimum insulation thickness using the theoretical-Taguchi combined method. An L16 (43 * 22) orthogonal array has been chosen as a design plan for parameters; wall, insulation, fuel type, heating degree-day (HDD) and lifetime. The results have been analysed using signal-to-noise (S/N) ratio and analysis of variance method. As an insulation material, extruded polystyrene (XPS), expanded polystyrene, glass wool, and polyurethane have been used. Natural gas, coal, fuel oil, and LPG have been used as a fuel. According to TS 825 for four climate zones; Istanbul, Ankara, Izmir and Erzurum provinces have been selected. Bolattürk (2006), in Turkey for cities that in four different climate zones which are Iskenderun, Adana, Antalya, Aydın, Manisa, Trabzon, Istanbul, Mardin, Istanbul, Izmir, Eskisehir, Nevsehir, Erzincan, Hakkari, Ağrı and Ardahan, for the optimum insulation thickness of external walls, energy saving and payback period have been calculated. Coal, natural gas, fuel oil, LPG and electricity have been used as fuel and polystyrene was considered as insulation material. In Gölcü et al. (2006), when coal and fuel oil used for heating in the buildings located in Denizli, Turkey, calculated the optimal insulation thickness for external walls, the payback period and, energy savings. Jraida et al. (2017) have calculated optimum insulation thickness, energy saving and payback period were for Agadir, Tangier, Fes, Ifrane, Marrakech and Errachidia cities of Morocco. Calculations have been made for XPS, cork, glass wool insulation materials depending on electricity. Life cycle cost analysis method has been used. Kaynakli (2011) has investigated the effect of optimum insulation thickness of the external walls, interest and inflation rate, lifetime, energy price, heating and cooling loads of the building, wall structure, properties of insulating materials. Life cycle total cost (LCT) analysis has been used in the calculations. Dombaycı et al. (2006) have calculated the optimum insulation thickness of the external walls for the city of Denizli in Turkey. As a fuel; coal, natural gas, LPG, and fuel-oil and as an insulation material; expanded polystyrene and rock wool were used. The optimisation is based on a life cycle cost analysis. Kurekçi (2016) has calculated the optimum insulation thickness for 81 city centre in Turkey. As a fuel, natural gas, coal, fuel oil, and LPG and as an insulation material; XPS, expanded polystyrene, glass wool, rock wool, and polyurethane have been used. The optimum insulation thicknesses have been calculated for heating, cooling and for both heating and cooling periods. Degree-day method and LCT analysis have been used in the calculations. The optimum insulation thickness for the external wall, roof, and the floor has been calculated for the heating period, the cooling period and for both heating and cooling period by Kon (2014). The calculations have been made according to the measured and calculated heat transfer coefficient and the performance coefficient of cooling (COP) value for the sample building. For optimum insulation thickness calculations, degree-day method and LCT analysis have been used. Mahlia et al. (2007) have calculated the optimum insulation thickness of the cooling period has been found for the external walls of commercial buildings that have air-conditioned system. The study has been made in Malaysia that a warm and humid country. Life cycle cost analysis and P1-P2 method have been used for optimum insulation thickness calculation. Fibreglass-urethane, fibreglass (solid), urethane (solid), perlite, XPS and urethane (roof terrace) have been used as an insulation material, and electricity has been used as a fuel. Uçar and Balo (2009) in Turkey for cities that in four different climate zones which are Ağrı, Elazığ, Kocaeli and, Aydın, calculated the optimum insulation thickness of the external walls, energy saving and payback period for five different fuels and different insulation materials such as; foam board 3,500, foam board 1,500, XPS and fibreglass. The amount of net energy savings has been determined by using P1-P2 method. Ulaş (2010) has calculated the optimum insulation thickness for the school building for four different climate zones which specified in TS 825. As an energy source; natural gas, fuel oil, and lignite and as an insulation material; glass wool, expanded polystyrene, and XPS have been used. The fuel consumption of the uninsulated and optimally insulated school building; and carbon dioxide emission that were released to the atmosphere have been calculated. In Akyüz et al. (2017), the application of thermal insulation on the walls and roof of the Hasan Polatkan Airport terminal building have been investigated from energy, environment and cost aspects. This study determined the optimum insulation thickness and assessed its effects on environmental performance based on energy flows. Environmental payback periods were calculated depending on the optimum insulation thickness. The life cycle assessment (LCA) method has been used to assess. In Yu et al. (2009), the optimum thicknesses of five insulation materials including expanded polystyrene, XPS, foamed polyurethane, perlite and foamed polyvinyl chloride have been calculated with a typical residential wall using solar-air cooling and HDDs analysis and P1-P2 economic model. LCTs, life cycle savings (LCSs) and payback periods have been calculated based on life cycle cost analysis. Four typical cities of Shanghai, Changsha, Shaoguan and Chengdu have selected subzone of hot summer and cold winter zone in China, respectively. Electricity has been used as an energy source. Dağıdır and Bolattürk (2011) have calculated optimum insulation thicknesses according to the cooling and heating load by taking into account the effect of solar radiation for İzmir province. The optimum insulation thicknesses, energy savings and payback periods required for the external walls of the building in İzmir were determined by using economic data such as interest, inflation, and life.

Airports are more complex in terms of area of use and structural envelope than other buildings. The energy consumption of these structures is also high. The most important application of energy saving is the insulation of the structural envelope. The highest amount of heat transfer is caused by external walls with the highest surface area. Therefore, the insulation of the external walls is very important for energy saving. The life cycle cost approach for energy saving is important for insulation.

The purpose of this work investigates the savings in energy consumption by insulation to be applied to the external walls of the airport which be built at five different climate zones according to TS 825. Life cycle cost calculations are made for long-term energy consumption. Optimum insulation thickness was calculated for the external walls of the airport depending on the life cycle cost calculations. In the literature, the energy savings to be obtained by the isolation of the external walls of the dwellings have been examined. In this study, the energy savings that will occur with the insulation of the external wall of the airport buildings were examined. For dwellings, indoor air temperature is 19°C according to Turkish insulation standard TS 825. However, the indoor temperature in the airport buildings is 20°C. This situation can make a difference in energy consumption.

2 Methodology

2.1 Degree-day method

In this study, calculations were made according to the degree-day method and life cycle cost analysis for long years. The degree-day method is the sum of the differences between the indoor temperatures of the buildings and the outdoor temperatures. The degree-day values are calculated separately for the heating and cooling period. In this study, indoor temperature was taken as 20°C for heating period and 22°C for cooling period. The temperature values given for each climate zone and for each month separately were taken from Turkish insulation standard TS 825. Table 1 shows that heating and cooling degree-day values. Cooling degree-day values are not found for 3rd, 4th and 5th zones because of the average air temperatures for all months are below 22°C. Degree-day values calculations are as follows (Kon, 2014; Ulaş, 2010, Gültekin and Kadıoğlu, 1996):

$$\text{If } (T_o \leq T_i) \quad HDD = 30\sum_{1}^{12}(T_i - T_o) \tag{1}$$

$$\text{If } (T_o > T_i) \quad HDD = 0 \tag{2}$$

$$\text{If } (T_o > T_i) \quad CDD = 30\sum_{1}^{12}(T_o - T_i) \tag{3}$$

$$\text{If } (T_o \leq T_i) \quad CDD = 0 \tag{4}$$

2.2 Calculation of energy consumption

Total transmission rate through unit area is (Alghoul et al., 2016):

$$q = U.\Delta T \tag{5}$$

The amount of heat transmitted annually through the unit area depending on the value of HDD in heating season is:

$$q_H = 0.024 \cup HD \tag{6}$$

The amount of heat transmitted annually through the unit area depending on the value of cooling degree-day (HDD) in cooling season is (Alghoul et al., 2016):

$$q_C = 0.024 \cup CDD \tag{7}$$

Annual heating energy requirement per unit area is:

$$E_H = \frac{q_H}{\eta} \tag{8}$$

Annual cooling energy requirement per unit area is:

$$E_C = \frac{q_C}{COP} \tag{9}$$

Annual heating energy load equation is (Alghoul et al., 2016; Jraida et al., 2017):

$$E_H = \frac{0.024.U.HDD}{\eta} \tag{10}$$

Annual cooling energy load equation is (Alghoul et al., 2016; Jraida et al., 2017):

$$E_C = \frac{0.024.U.CDD}{COP} \tag{11}$$

Calculation of degree-day is:

$$DD = \frac{CDD}{COP} + \frac{HDD}{\eta} \tag{12}$$

where CDD is cooling degree-day, HDD is HDD, COP is cooling performance coefficient and η is heating system efficiency. Optimum insulation thickness equation is (Alghoul et al., 2016):

$$x_{opt} = \left(\frac{0.024.C_e.PWF.k.DD}{C_{ins}} \right)^{\frac{1}{2}} - k.R_{wt} \tag{13}$$

where C_e is cost of electricity, PWF is present value factor, k is heat thermal conductivity of insulation material, C_i cost of insulation material, R_{wt} thermal resistance of uninsulated wall. Optimum insulation thickness is the value that makes the total life cycle cost calculation minimum. Energy saving (ES) and LCT of and LCS energy consumption equation is (Alghoul et al., 2016; Jraida et al., 2017):

$$ES = C_e \left(\left(E_H(\text{noins}) - E_H(\text{withins}) \right) + \left(E_C(\text{noins}) - E_C(\text{withins}) \right) \right) \tag{14}$$

$$\begin{aligned} LCS = {} & C_e \left(\left(E_H(\text{noins}) - E_H(\text{withins}) \right) + \left(E_C(\text{noins}) - E_C(\text{withins}) \right) \right) PWF \\ & - x.C_{ins} \end{aligned} \tag{15}$$

$$LCT = C_e \left(E_H + E_C \right) PWF + x.C_{ins} \tag{16}$$

If i < g real interest rate is (Dombaycı et al., 2006):

$$r = \frac{g - i}{1 + i} \tag{17}$$

If g < i real interest rate is (Dombaycı et al., 2006):

$$r = \frac{i - g}{1 + g} \tag{18}$$

Then

$$PWF = \frac{(1 + r)^N - 1}{r(1 + r)^N} \tag{19}$$

where i is interest rate and g are inflation rate.

2.3 Values used in calculations

For the insulation of the external walls of the airport buildings, the most commonly used insulation materials for external wall insulation are considered. These materials are XPS, glass wool (GW) and polyurethane (PU). The heat convective coefficient and prices of these insulation materials are very different. This difference is important for examining the change in energy consumption. It is important to investigate the change in energy consumption cost with a life cycle cost approach.

Electricity price was taken as 0.108 $/kWh (Uludağ Electricity Distribution Corporation, 2017). Electricity was used as an energy source for the cooling season and the cooling performance coefficient was taken as 2.5 (Kaynakli, 2011). For electricity consumption, the heating system efficiency is 0.99 (Dombaycı et al., 2006). The interest rate and the inflation rate were taken 4%, 5% respectively (Arslanoglu and Yigit, 2017). Accordingly, PWF was found 9.49. While calculating the heat transfer coefficient of the external walls, internal and external surface resistances were taken as 0.13 and 0.04

(m^2K/W) (TS 825). Table 1 presents properties of insulation materials. Table 2 shows heating and cooling degree-days. Table 3 gives external wall structural components and properties. Table 2 provides the necessary degree-day values for heating and cooling period for five different climate zones in TS 825. The first climate zone is the hottest climate zone and the fifth climatic zone is the coldest climate zone. The HDD value is 1,642 in the first climatic zone with the lowest value, and in the fifth climatic region this value is more than three times that of 5,416. In the three, four and fifth climatic zones, the cooling degree-day value was not found. In these regions, there is no need for cooling in summer. In the first climate zone, it is seen that there is a maximum need for cooling in the summer.

Table 1 Properties of insulation materials

Insulation materials	*Thermal conductivity (W/m.K)*	*Price C_{ins} (\$/m^3)*
Extruded polystyrene (XPS)	0.031	180
Glass wool (GW)	0.040	75
Polyurethane (PU)	0.024	260

Source: Kurekçi (2016)

Table 2 Heating and cooling degree-days

Zone	*Heating degree-day (HDD)*	*Cooling degree-day (CDD)*	*Degree-day (DD)*
Zone 1	1,642	555	1,889
Zone 2	2,672	176	2,770
Zone 3	3,551	--	3,587
Zone 4	4,377	--	4,421
Zone 5	5,416	--	5,471

Source: TS 825 (2013)

Table 3 External wall structural components and properties

Structural components	*Thickness (m)*	*Thermal conductivity (W/m.K)*
Internal plastering with cement and lime	0.020	1.000
Horizontal perforated brick	0.085	0.330
Insulation	x	y
Horizontal perforated brick	0.135	0.330
External plastering with cement	0.030	1.600

Source: TS 825 (2013), http://www.turgutlutuglasi.org

Table 3 shows that the external walls were taken a sandwich wall. Sandwich wall is the process of applying insulation between two bricks. Three different insulation materials were placed between the bricks of 0.085 m and 0.135 m thickness.

3 Results and discussion

At the 1st zone, energy savings (ES) are calculated between 1.235–5.133 ($/m^2), LCS 0.484–31.872 ($/m^2), LCT 20.935–69.096 ($/m^2) for different insulation materials and insulation thicknesses.

At the 2nd zone, energy savings (ES) are calculated between 1.819–7.534 ($/m^2), LCS 6.732–51.794 ($/m^2), LCT 25.971–71.032 ($/m^2) for different insulation materials and insulation thicknesses.

At the 3rd zone, energy savings (ES) are calculated between 2.356–9.790 ($/m^2), LCS 21.612–70.807 ($/m^2), LCT 29.912–79.107 ($/m^2) for different insulation materials and insulation thicknesses.

At the 4th zone, energy savings (ES) are calculated between 2.905–12.067 ($/m^2), LCS 26.814–90.645 ($/m^2), LCT 33.503–97.334 ($/m^2) for different insulation materials and insulation thicknesses.

At the 5th zone, energy savings (ES) are calculated between 3.593–14.932 ($/m^2), LCS 33.357–116.058 ($/m^2), LCT 37.559–120.261 ($/m^2) for different insulation materials and insulation thicknesses.

Optimum insulation thickness for different insulating materials was calculated between 0.044 to 0.122 m in the 1st region, between 0.058 to 0.081 m in the 2nd region, 0.069 to 0.096 m in the 3rd region, 0.079 to 0.110 m in the 4th region and 0.090 to 0.125 m in the 5th region.

Energy savings (ES) were calculated between 3.765 to 4.323 ($/m^2) for the 1st zone, LCS between 24.293 to 31.874 ($/m^2), LCT between 28.514 to 27.244 ($/m^2) for different insulation materials at the optimum insulation thickness.

Energy savings (ES) were calculated between 6.014 to 6.691 ($/m^2) for 2nd zone, LCS between 41.996 to 51.801 ($/m^2), LCT between 25.963 to 35.769 ($/m^2) for different insulation materials at the optimum insulation thickness.

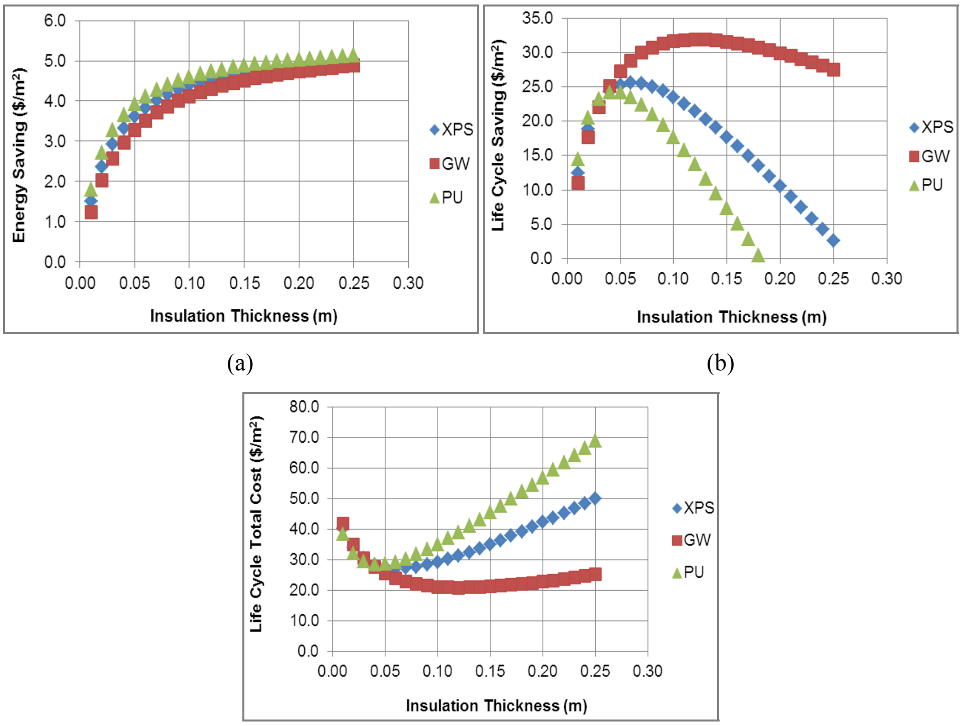
Energy savings (ES) were calculated between 8.135 to 8.900 ($/m^2) for 3rd zone, LCS between 59.258 to 70.809 ($/m^2), LCT between 29.911 to 41.462 ($/m^2) for different insulation materials at the optimum insulation thickness.

Energy savings (ES) were calculated between 10.332 to 11.180 ($/m^2) for 4th zone, LCS between 77.513 to 90.650 ($/m^2), LCT between 33.497 to 46.635 ($/m^2) for different insulation materials at the optimum insulation thickness.

Energy savings (ES) were calculated between 13.122 to 14.071 ($/m^2) for 5th zone, LCS between 101.128 to 116.061 ($/m^2), LCT between 37.557 to 52.490 ($/m^2) for different insulation materials at the optimum insulation thickness.

Figure 1(a) of the minimum insulation thickness, Figure 1(b) life cycle cost saving (LCS), and Figure 1(c) LCT was given depending on the insulation thicknesses for the 1st zone. Figure 2(a) of the minimum insulation thickness, Figure 2(b) life cycle cost saving (LCS), and Figure 2(c) LCT was given depending on the insulation thicknesses for the 2nd zone. Figure 3(a) shows that of the optimum insulation thickness, Figure 3(b) life cycle cost saving (LCS), and Figure 3(c) LCT according to insulation thicknesses for the 3rd zone. Figure 4(a) shows that of the optimum insulation thickness, Figure 4(b) life cycle cost saving (LCS), and Figure 4(c) LCT according to insulation thicknesses for the 4th zone. Figure 5(a) of the minimum insulation thickness, Figure 5(b) life cycle cost saving (LCS), and Figure 5(c) LCT was given depending on the insulation thicknesses for the 5th zone. The optimum insulation thickness, energy saving (ES), LCS and LCT for the insulation types and climate zones are shown in Table 4.

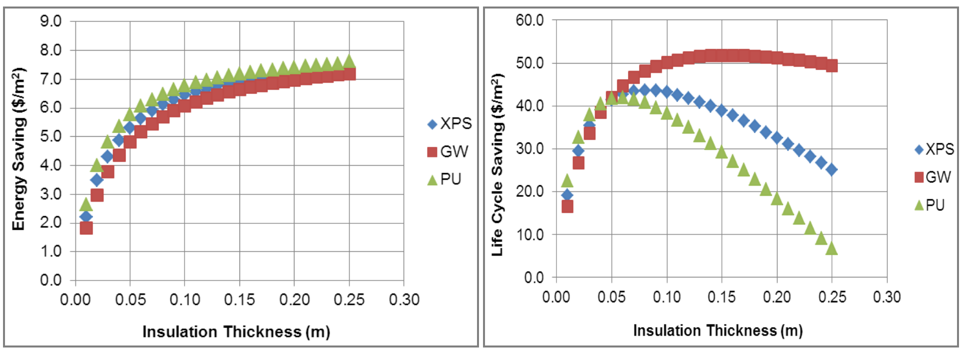
Figure 1 Zone 1 according to the insulation thicknesses, (a) energy saving cart (b) LCS cart (c) LCT cart (see online version for colours)



(a) (b)

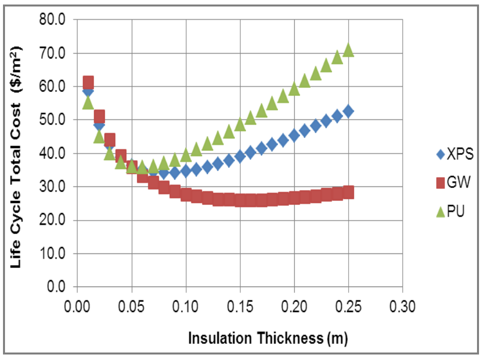
(c)

Figure 2 Zone 2 according to the insulation thicknesses, (a) energy saving cart (b) LCS cart (c) LCT cart (see online version for colours)



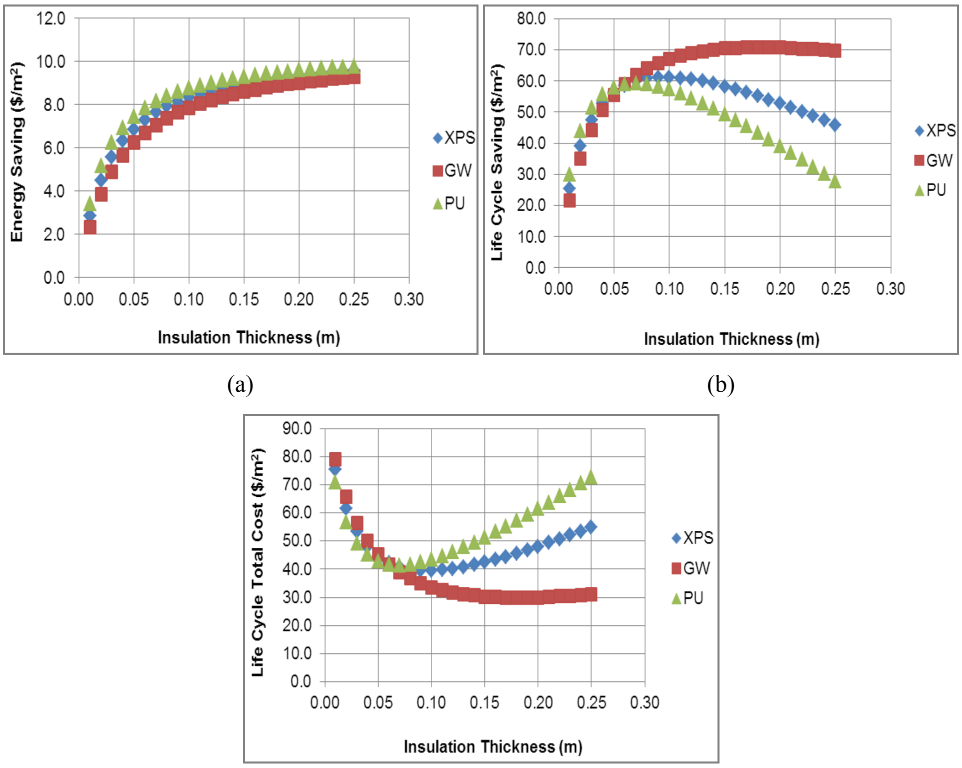
(a) (b)

Figure 2 Zone 2 according to the insulation thicknesses, (a) energy saving cart (b) LCS cart (c) LCT cart (continued) (see online version for colours)



(c)

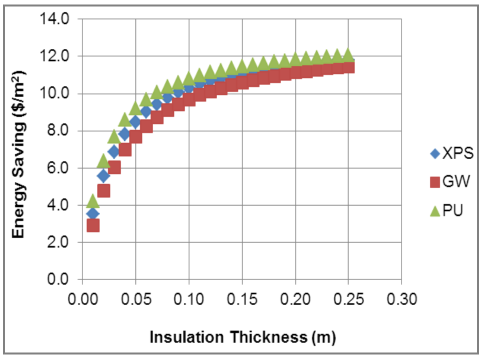
Figure 3 Zone 3 according to insulation thicknesses, (a) energy saving cart (b) LCS cart (c) LCT cart (see online version for colours)



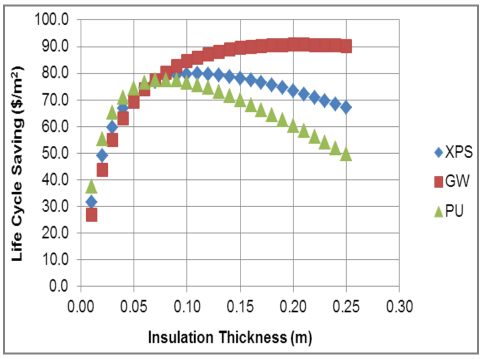
(a) (b)

(c)

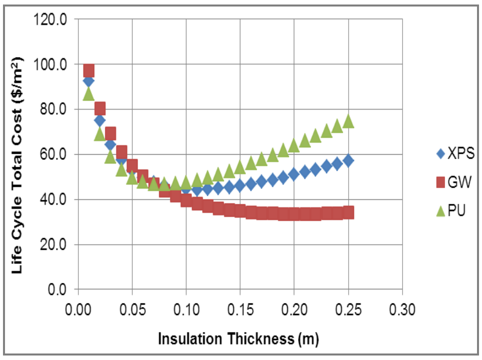
Figure 4 Zone 4 according to insulation thicknesses, (a) energy saving cart (b) LCS cart (c) LCT cart (see online version for colours)



(a)

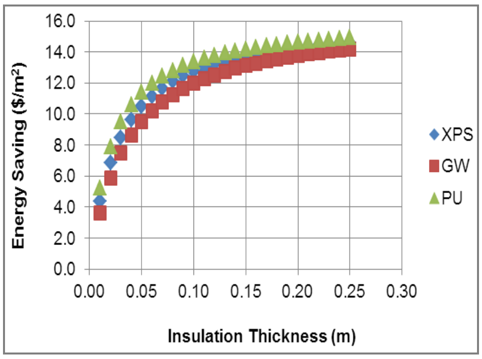


(b)

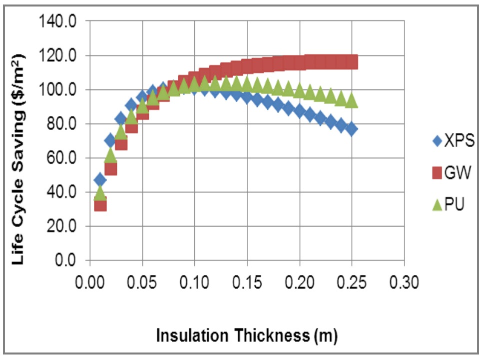


(c)

Figure 5 Zone 5 according to insulation thicknesses (a) energy saving cart (b) LCS cart (c) LCT cart (see online version for colours)

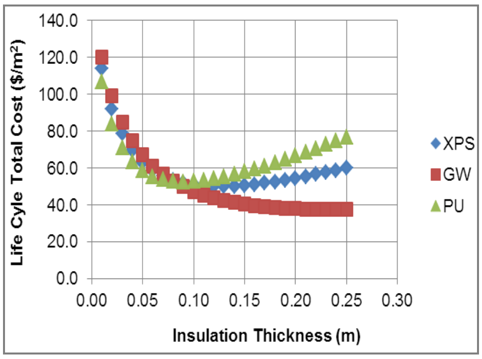


(a)



(b)

Figure 5 Zone 5 according to insulation thicknesses (a) energy saving cart (b) LCS cart (c) LCT cart (continued) (see online version for colours)



(c)

Table 4 The optimum insulation thickness, energy saving (ES), LCS and LCT for the insulation types and climate zones

Zone	*Extruded polystyrene (XPS)*	*Glass wool (GW)*	*Polyurathane (PU)*
Optimum insulation thickness (m)			
Zone 1	0.062	0.122	0.044
Zone 2	0.081	0.156	0.058
Zone 3	0.096	0.182	0.069
Zone 4	0.110	0.206	0.079
Zone 5	0.125	0.233	0.090
Energy saving (ES) ($/m^2)			
Zone 1	3.870	4.323	3.765
Zone 2	6.137	6.691	6.014
Zone 3	8.273	8.900	8.135
Zone 4	10.492	11.180	10.332
Zone 5	13.298	14.071	13.122
Life cycle saving (LCS) ($/m^2)			
Zone 1	25.562	31.874	24.293
Zone 2	43.659	51.801	41.996
Zone 3	61.231	70.809	59.258
Zone 4	79.767	90.650	77.513
Zone 5	103.701	116.061	101.128
Life cycle total cost (LCT) ($/m^2)			
Zone 1	27.244	20.933	28.514
Zone 2	34.105	25.963	35.769
Zone 3	39.489	29.911	41.462
Zone 4	44.380	33.497	46.635
Zone 5	49.917	37.557	52.490

4 Conclusions

In this study, the energy savings calculations of the airports which have a large area of use and structural envelope were made by insulating the external walls which have the highest heat transfer coefficient instead of dwellings. Economic studies based on interest and inflation rates have been made. These are based on LCS and LCT calculations for ten-year life. As the insulation thickness increases, the heat transfer from the external walls decreases. However, insulation costs are increasing. For this purpose, the thickness that makes sum of the insulation materials cost and electricity consumption cost minimum is the optimum insulation thickness. Optimum insulation thickness is determined as the most suitable insulation thickness considering the economic parameters.

As the climate zone changes from 1st to 5th and the insulation thickness increases, energy saving is increasing. The highest amount of energy saving is found in polyurethane insulation material. The lowest is glass wool. The polyurethane has the lowest thermal conductivity (0.024 W/m.K) and the highest insulation material price is 260 $\$/m^3$. Glass wool has the highest thermal conductivity (0.040 W/m.K) and the lowest insulation material price with 75 $\$/m^3$. XPS' thermal conductivity 0.031 W/m.K and insulation material price is 180 $\$/m^3$.

As the climate region changes from 1st to 5th, the LCT value increases. The LCT value is reduced to the optimum insulation thickness and then increased. The highest LCT value is found in polyurethane insulation material and the lowest in glass wool insulation material.

As the climate zone changes from 1st to 5th, the maximum value of the LCS, which increases up to the optimum insulation thickness then falls is found for glass wool insulation material and the lowest is polyurethane insulation material. Glass wool insulation material has the highest thermal conductivity and the lowest insulation material price.

Optimum insulation thickness is the lowest polyurethane insulation material in the highest glass wool insulation material. The optimum insulation thickness was calculated as between 0.062 to 0.125 m for XPS, between 0.122 to 0.233 m for Glass wool (GW) and between 0.044 to 0.090 m for polyurathane (PU) according to different climate zones. Energy saving (ES) at the optimum insulation thickness was calculated between 3,870 to13,298 $\$/m^2$ for XPS, between 4,323 to 14,071 $\$/m^2$ for glass wool (GW) and between 3,765 to 13,122 $\$/m^2$ for Polyurethane (PU). LCS at the optimum insulation thickness was calculated between 25.562 to103.701 $\$/m^2$ for XPS, between 31.874 to 116.061 $\$/m^2$ for glass wool (GW) and between 24.293 to 101.128 $\$/m^2$ for polyurethane (PU). LCT at the optimum insulation thickness was calculated between 27.244 to 49.917 $\$/m^2$ for XPS, between 20.933 to 37.557 $\$/m^2$ for glass wool (GW) and between 28.514 to 52.490 $\$/m^2$ for polyurethane (PU). In the same insulation materials, it was observed that the optimum insulation thickness was two times different between the 1st zone and the 5th zone. Energy saving (ES) value is between 1st and 5th regions; 3.5 times different, LCS value is 4.2 times different, LCT value is calculated as 1.8 times different. Energy saving, LCS and LCT values have the highest difference between 1st to 5th regions for polyurethane insulation material. The lowest difference was found in the glass wool insulation material.

References

Akyüz, M.K., Altuntaş, Ö. and Söğüt, M.Z. (2017) 'Economic and environmental optimization of an airport terminal building's wall and roof insulation', *Sustainability*, Vol. 9, p.1849, https://doi.org/10.3390/su9101849.

Alghoul, S.K., Gwesha, A.O. and Naas, A.M. (2016) 'The effect of electricity price on saving energy transmitted from external building walls', *Energy Research Journal*, Vol. 7, No. 1, pp.1–9.

Al-Khawaja, M. (2004) 'Determination and selecting the optimum thickness of insulation for buildings in hot countries by accounting for solar radiation', *Applied Thermal Engineering*, Vol. 24, Nos. 17–18, pp.2601–2610.

Arslanoglu, N. and Yigit, A. (2017) 'Investigation of efficient parameters on optimum ınsulation thickness based on theoretical-taguchi combined method', *Environmental Progress & Sustainable Energy*, Vol. 36, No. 6, pp.1824–1831.

Aydın, Ö. (2011) *Investigation of Relationship between Energy Efficiency and Insulate Applications on Vertical Outer Shell of Building*, in Turkish, PhD thesis, Karadeniz Technical Universty, Institute of Science, Department of Architecture, Trabzon.

Bolattürk, A. (2006) 'Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey', *Applied Thermal Engineering*, Vol. 26, Nos. 11–12, pp.1301–1309.

Dağıdır, C. and Bolattürk, A. (2011) 'Sıcak iklim bölgelerindeki binalarda ısıtma ve soğutma yüküne göre tespit edilen optimum yalıtım kalınlıklarının karşılaştırılması', *Ulusal Tesisat Mühendisliği Kongresi*, in Turkish, Vol. 10, pp.253–270, İzmir.

Değirmenci, A.İ. (2010) *Insulation Techniques Applied Research in Turkey used Effectively to the Thermal Camera*, in Turkish, MSc thesis, Sakarya Universty, Institute of Science, Department of Building Training.

Dombaycı, Ö.A., Gölcü, M. and Pancar, Y. (2006) 'Optimization of insulation thickness for external walls using different energy-sources', *Applied Energy*, Vol. 83, No. 9, pp.921–928.

Gölcü, M., Dombaycı, A. and Abalı, S. (2006) 'Denizli için optimum yalıtım kalınlığının enerji tasarrufuna etkisi ve sonuçları', *Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, Vol. 21, No. 4, pp.639–644.

Gültekin, M.L. and Kadıoğlu, M. (1996) 'Marmara bölgesinde ısıtma soğutma derece-günlerinin dağılımı', *Tesisat Mühendisliği Dergisi*, Vol. 3, No. 31, pp.33–41.

Jraida, K., Farchi, A., Mounir, B. and Mounir, İ. (2017) 'A study on the optimum insulation thickness of building walls with respect to different zones in Morocco', *İnternational Jounal of Ambient Energy*, Vol. 38, No. 6, pp.550–555.

Kaynakli, Ö. (2011) 'Parametric investigation of optimum thermal insulation thickness for external walls', *Energies*, Vol. 4, No. 6, pp.913–927.

Kon, O. (2014). *Determining Theoretically and Practically the Optimum Insulation Thickness of Buildings used for Different Purposes According to Heating and Cooling Loads*, PhD thesis, Balikesir University, Institute of Science, Department of Mechanical Engineering, Balikesir.

Kurekçi, N.A. (2016) 'Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers', *Energy and Buildings*, Vol. 118, pp.197–213, https://doi.org/10.1016/j.enbuild.2016.03.004.

Mahlia, T.M.I., Taufiq, B.N., Ismail, B.N. and Masjuki, H.H. (2007) 'Correlation between thermal conductivity and the thickness of selected insulation materials for building wall', *Energy and Buildings*, Vol. 39, No. 2, pp.182–187.

Turkish Standard (TS 825) (2013) *Thermal Insulation Requirements for Buildings*, December.

Uçar, A. and Balo, F. (2009) 'Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic of Turkey', *Applied Energy*, Vol. 86, No. 5, pp.730–736.

Ulaş, A. (2010) *Basen on TS 825 Directive, Analysis of Heat Loss, Fuel Consumption, Carbon Dioxide Emission and Cost for Buildings*, MSc thesis, Gazi University Institute of Science and Technology, Department of Mechanical Engineering, Ankara.

Uludağ Electricity Distribution Corporation (2017) *Data*.

Yu, J., Yang, C., Tian, L. and Liao, D. (2009) 'A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China', *Applied Energy*, Vol. 86, No. 11, pp.2520–2529.

References

http://www.turgutlutuglasi.org/ (accessed 27 November 2017)

Nomenclature

HDD	Heating degree-day
CDD	Cooling degree-day
DD	Degree-day
x	Insulation thickness (m)
k	Insulation material heat conduction coefficient (W/m.K)
η	Heating system efficiency
C	Cost ($)
COP	Performance coefficient of cooling
ES	Energy saving ($\$/m^2$)
LCS	Life cycle saving ($\$/m^2$)
LCT	Life cycle total cost ($\$/m^2$)
XPS	Extruded polystyrene
GW	Glass wool
PU	Polyurethane
q	Total transmission rate through unit area (W/m^2)
PWF	Present worth factor
i	Interest rate
g	Inflation rate
R	Thermal resistance ($m^2.K/W$)
U	Heat transfer coefficient ($W/m^2.K$)

N	Life (year)
E	Annual energy load (kWh/m^2)
r	Interest rate
T	Temperature (°C)

Index

opt	Optimum
e	Electricity
ins	Insulation
C	Cool
H	Heat
t, w	Uninsulated wall
i	Internal
0	External
Δ	Difference