RESEARCH

SIMPLE NONLINEAR OPTIMIZATION-BASED SELECTION OF INSULATION MATERIAL AND WINDOW TYPE IN TURKEY: EFFECT OF HEATING AND COOLING BASE TEMPERATURES

Fehmi Görkem Üçtuğ[1] and Semra Ağralı*[2]

ABSTRACT

The energy-savings of four hypothetical households in different climatic regions of Turkey were calculated via a nonlinear mixed integer optimization model. The ideal insulation material, its optimum thickness, and the ideal window type were determined. The standard degree days method was used with five different base temperatures for heating and five different base temperatures for cooling. The climatic conditions of the region, the properties of the insulation options, the unit price of fuel and electricity and the base temperature are used as model inputs, whereas the combination of selected insulation material with its optimum thickness and window type are given as model outputs. Stone Wool was found to be the ideal wall insulation material in all scenarios. The optimum window type was found to depend on the heating or cooling requirements of the house, as well as the lifetime of insulation. The region where the energy saving actions are deemed most feasible has been identified as Erzurum (Region 4), followed by Antalya (Region 1). Finally, the effect of changing the base temperature on energy savings was investigated and the results showed that an approximate average increase of $15/°C in annual savings is possible. Our model can be used by any prospective home-owner who would like to maximize their energy savings.

KEYWORDS:

Base temperature, Degree days method, HVAC systems, Insulation thickness, Nonlinear mixed-integer programming, Optimization

1. INTRODUCTION

Current statistics point out that buildings are responsible for more than 40% of global energy consumption, and the annual energy consumption associated with buildings keeps increasing at an average rate of 1.8% (Nejat et al., 2015). Furthermore, more than 30% of global energy-related greenhouse gas emissions are caused by buildings (Robert and Kummert, 2012; Zheng et al., 2011). Therefore, it is important to decrease energy consumption in buildings from

1. School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester, UK, M13 9PL {gorkem.uctug@manchester.ac.uk}

2. Department of Industrial Engineering, MEF University, 34396, Sarıyer, İstanbul, Turkey {agralis@mef.edu.tr}

* Corresponging Author

economical as well as environmental perspectives (Hester et al., 2012; Hou et al., 2012). In order to decrease energy consumption in buildings, conservation measures such as switching to more energy-efficient appliances or changing lifestyle habits may be applied; however, depending on climate, the bulk of energy can be saved from thermal insulation (Mills and Schleich, 2012; Dikmen, 2011).

While in piping systems applying insulation initially increases the undesired heat loss (or gain) due to an increase in the heat transfer area, buildings savings continuously increase as the insulation thickness increases. There is a non-linear relationship between the wall-insulation thickness and consequent energy savings as a result of the structure of the fundamental heat transfer equations explained in the following sections. Moreover, depending on the type of the insulation material, the savings obtained from the insulation and the cost of the insulation material changes.

Depending on the desired thickness of the wall, the width of the insulation material generally is subject to some limitations. Thus, finding the optimum insulation thickness becomes a non-linear optimization problem, in which the long-term net benefits obtained throughout the lifetime of insulation is maximized. The factors that affect the optimum insulation thickness are numerous; however, the most significant ones are the regional climatic conditions, the cost of insulation materials in the studied region, characteristics of the building, the cost of fuel and electricity in the studied region, the type of insulation materials chosen, and, most importantly, occupant lifestyle effects such as the interior temperature setpoint (Bolattürk, 2008; Yu et al., 2009; Bolattürk, 2006; Özkan and Onan, 2011; Çomaklı and Yuksel, 2003; Al-Khawaja, 2004; Ucar and Balo, 2010; Ozel, 2011a; Al-Sanea and Zedan, 2011; Al-Sanea et al., 2005; Dombaycı et al., 2006; Ozel, 2011b; Mahlia et al., 2007; Aktacir, 2012).

The literature includes many studies that calculate the optimum insulation thickness. Fokaides and Papadopoulos (2014) evaluated the results of previous studies on insulation thickness optimization and compared these studies in terms of their strengths and weaknesses. They reviewed a total of 14 studies in terms of the analyzed country and proposed method; financial projection assumptions; energy costs; and type of construction and insulation materials. Ozel (2014) studied the effect of insulation location on the heat transfer characteristics of building walls and optimization of insulation thickness has been studied numerically using an implicit finite difference method under steady periodic conditions. Arslan and Kose (2006) calculated the optimum insulation thickness by taking the presence of condensed vapor in existing buildings into account. They repeated the same analysis method for different indoor temperatures of 18, 20, and 22°C. Cuce et al. (2014) investigated the optimum thermal insulation thickness of aerogel and its environmental impacts for the climatic conditions of Nottingham, UK. Insulation thickness dependencies of annual energy cost and energy saving were determined for different energy sources. Effects of the degree-day and present worth factor on optimum aerogel thickness were also investigated. Çomaklı and Yuksel (2003) calculated the optimum insulation thickness for three eastern cities in Turkey, with similar climatic conditions, characterized by extreme winters and cool summers, where coal was taken as the main source of fuel and expandable polystyrene was chosen as the insulation material. Dombaycı et al. (2006) calculated the optimum insulation thickness for two different insulation materials, stone wool and polystyrene, in the city of Denizli. They studied five scenarios by choosing different heat sources such as coal, natural gas, LPG, fuel oil, and electricity. Coal was found to be the most economical fuel source, followed by natural gas if environmental costs are ignored. Nyers et al. (2015) analyzed the optimum energy-economic thickness of a thermal insulation layer for an external wall for the climatic conditions in Serbia. They concluded that the optimum thickness of polystyrene as insulation material is 6.89 cm, with a specific R value of 3.088W/(m^2K), and the payback period is 1.22 years. Bektas Ekici et al. (2012) calculated the optimum insulation thickness of four different insulation materials (fiberglass, XPS, EPS polyurethane) in four different climatic regions of Turkey (Antalya-1st zone; Istanbul-2nd zone; Elazig-3rd zone; Kayseri-4th zone) for five different primary heat sources (natural gas, coal, electricity, fuel oil, and LPG). Kayfeci and Kecebas et al. (2013) calculated the optimum insulation thicknesses, insulation-energy costs, and savings resulting from the use of insulation in cities selected from four different climate zones in Turkey for four various insulation materials such as foamboard, extruded polystyrene (XPS), rock wool, and expanded polystyrene (EPS) in cold storage applications. Their calculations showed that rock wool is the most cost-effective insulation.

Recently, Üçtuğ et al. (2015) developed a nonlinear mixed-integer optimization model that decides on the optimal insulation material with its optimum thickness and optimal type of window that maximizes the net savings obtained by insulating walls and windows simultaneously. The model takes the monthly average temperatures, thermal conductivity of different insulation materials, inner structure of different window types, material costs, and fuel and electricity costs as inputs. They implemented the model with data obtained for four different regions of Turkey by using standard heat transfer equations and analyze the optimal insulation behaviour.

In this study, we use a standard degree-days (DD) method, which is very common in these types of studies. However, unlike the literature, the model implemented and results obtained are calculated by using different base temperatures. The major novelty of our method is the analysis of the effects of base temperature on the determination of the most effective energy-saving actions, optimum insulation thickness, and consequent energy savings. As indicated above, we used the common method of degree-days in order to calculate the economic gains as a result of applying energy saving measures. Degree-days depend on the extremity and duration of ambient temperature. They are essentially the summation of temperature differences between the ambient or outdoor air temperature and a reference temperature, which is also known as the base or balance point temperature (Mourshed, 2012). The base temperature, T_b, is referred to as the outdoor air temperature at which the heating or cooling systems do not need to run in order to maintain comfort conditions. In order to simplify the variables, T_b is assumed to be constant. In future work, the model can be modified to reflect the climate-based changes in the T_b. When the outdoor temperature is below (above) the base temperature, the heating (cooling) systems are required to operate, and therefore deviations result in increased energy requirements (Lee et al., 2014). Although they are two different concepts, thermal comfort of the residents in the building is also relevant to the base temperature (Chandel and Aggarwal, 2012; McGilligana et al., 2011). In degree-day theory, the reference point temperature of a building is defined as a means of accounting for indoor thermal comfort, which means it is the outdoor temperature that separates times when a building requires heating or cooling from times when it does not (Shin and Do, 2016). Hence, different base temperature values generally correspond to different indoor thermal comfort levels. By calculating the optimum energy-saving actions for different base temperature values, alternatives to consumers based on their choice of acceptable thermal comfort temperature can be derived. Many papers focus on wall insulation, however windows have higher energy-saving potential, too. In fact, window retrofitting can actually decrease the energy consumption of a building by 18 to 30% (Ah et al., 2016). We aim to investigate these effects in Turkey.

2. PROBLEM DEFINITION AND METHODOLOGY

In this study, a prospective homeowner is considered who wants to insulate the walls and windows of an apartment flat before it is built. There is a selection of different insulation materials with different thermal conductivity and price to be placed in the wall, as well as different window types, such as single-glazed, double-glazed, or triple glazed, to insulate the windows. Moreover, based on the price of the insulation and savings that will be achieved with insulation, the homeowner may choose to use no insulation material and include only single-glazed windows. We calculate the savings based on the monetary value of the decreased electricity usage in summer that is consumed by the air conditioner, and the decreased fuel usage of the heater in winter.

We use heating and cooling degree day (HDD and CDD) methods while calculating the heat loss (gain) from (to) our building. This is a standard method used in the literature, and we refer the reader to Bektas Ekici et al. (2012) for an explanation. In the literature HDD and CDD values are calculated for standard base temperatures as explained in Section 1. Thermal comfort of the residents in the building depend on the base temperature selected. Although different base temperature values correspond to different indoor thermal comfort levels, in the literature the base temperatures are taken as constant. Different base temperatures will change the HDD and CDD values, which in turn will affect the insulation material's thickness or window type that are used to insulate the house. For this reason, in this study, we analyze the effect of different base temperature values on the insulation behavior by calculating CDD and HDD values for different base temperature values. We use a similar optimization model that is developed by Üçtuğ et al. (2015), where average monthly temperatures are used in the heat transfer equations. However, in this study we use the degree day method in calculations. All parameter definitions used in the model along with their symbols and units can be found in Table 1.

TABLE 1. Nomenclature.

A^{wa}, A^{wi}:	*area of wall and window, respectively* (m^2)
Cal^f:	*calorific value of the fuel type f* ($kcal/m^3$)
COP^{ac}:	*COP value of the air conditioner*
h^{in}, h^{out}:	*heat transfer coefficient of air at inside and outside temperatures, respectively* (W/m^2K)
I:	*set of insulation materials, indexed by i*
J:	*set of windows types, indexed by j*
k^a, k^b, k^g, k^p:	*thermal conductivity of air, brick, glass and plaster respectively* (W/mK)
k_i:	*thermal conductivity of type i insulation material* (W/mK)
p^{elec}:	*price of electricity* ($\$/kWh$)
p^f:	*price of the fuel used for heaters* ($\$/m^3$)
p_i:	*price of type i insulation material* ($\$/m^2$)
pw_j:	*price of type j windows* ($\$/m^2$)
q^{wa}:	*heat transfer through uninsulated wall (Joule)*
q_i^{wa}:	*heat transfer through the insulated wall with type i insulation material (Joule)*

TABLE 1. Nomenclature *(Cont.)*

q_j^{wa}:	*heat transfer through window with j number of layers (Joule)*
$S_{i,j}^{HRD}$:	*the monetary value of the energy savings for heating required days (\$)*
$S_{i,j}^{CRD}$:	*the monetary value of the energy savings for cooling required days (\$)*
T:	*useful life of a house (number of years)*
T_b:	*base temperature for CDD (°C)*
T_c:	*base temperature for HDD (°C)*
W^p, W^a, W^b, W^g:	*width of plaster layer, air layer, brick layer and glass layer, respectively (m)*
W^{max}:	*maximum thickness of insulation (m)*
v^{hs}:	*efficiency of the heating system*

The decisions that the consumer needs to make are (*i*) the type of material used for insulation (X_i = 1, if type i insulation material is used; = 0, otherwise), (*ii*) the width of the insulation material chosen (W_i), and (*iii*) the window type used (Y_j = 1, if j-layer glass is used; = 0, otherwise). Then, for a given interest rate r and a useful lifetime of T, the optimization model for the system can be written as follows:

$$\text{Maximize} \quad z = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\frac{S_{i,j}^{HRD}X_iY_j + S_{i,j}^{CRD}X_iY_j}{(1+r)^t}\right) - \sum_{i=1}^{I} p_i A^{wi} W_i - \sum_{j=1}^{J} pw_j A^{wi} Y_j \tag{1}$$

$$\text{subject to} \quad W_i \le W^{max} X_i \quad \forall i \in I, \tag{2}$$

$$\sum_{i \in I} X_i \le 1, \tag{3}$$

$$\sum_{j \in J} Y_j = 1, \tag{4}$$

$$W_i \ge 0, \tag{5}$$

$$X_i, Y_j \in \{0,1\} \quad \forall i \in I, j \in J. \tag{6}$$

The objective function (1) maximizes the net present value of the savings obtained from insulating the walls and windows, less the insulation cost of walls and windows. The cost of insulation materials are calculated based on their usage in cubic meters, where p_i is the unit cost of type i insulation material and pw_j is the unit cost of type j window. Note that these price values include the installation cost of the insulation materials. The other costs of building a house, such as labor, material and land price, are independent of the insulation decisions; and if these prices are added to the model, they will be constant values in the objective function and will not affect the optimal decision. Constraint (2) limits the width of the insulation material put in the wall to an upperbound value of W^{max}, which is exogenously determined by the consumer depending on the type of wall used. Constraint (3) ensures that at most one type of insulation material is selected for insulation of the walls. Note that the model does not permit inclusion of the insulation material if it is optimal. In other words, if applying insulation has a higher cost than its benefit at all conditions, the model can return an optimum insulation thickness of zero, which would mean no insulation shall be applied at all. Constraint (4) ensures that exactly one type of window is selected. Constraints (5) and (6) are nonnegativity and binary constraints, respectively.

The monetary value of the energy savings for heating required days, S^{HRD}, when the household uses a heater with an efficiency of ν^{hs} that consumes f type fuel with a calorific value of Cal^f and a unit cost of p^f is calculated as follows

$$S_{i,j}^{HRD} = \triangle q_{i,j}^{HRD} \left(\frac{p^f}{Cal^f * 4184 * \nu^{hs}} \right). \tag{7}$$

The monetary value of the energy savings for cooling required days, S^{CRD},when the consumer uses an air conditioner with a COP value of COP^{ac}, and the unit price of electricity p^{elec}, can be calculated as

$$S_{i,j}^{CRD} = \triangle q_{i,j}^{CRD} \left(\frac{p^{elec}}{COP^{ac} \times 3.6 \times 10^6} \right) \tag{8}$$

where 3.6×10^6 is a conversion factor between kWh and J. The heat loss (or gain) savings, Δq, that a consumer makes is calculated by subtracting the heat loss of the non-insulated wall with single layer glass windows from the insulated wall and windows as follows

$$\triangle q_{i,j} = q^{wa} + q_1^{wi} - q_i^{wa} - q_j^{wi}, \tag{9}$$

The heat transfer between the building and its environment, q, is calculated as follows

$$q = U \times A \times DD \times 86{,}400, \tag{10}$$

where 86,400 is the conversion factor between day and seconds, DD represents degree day, which will be replaced by CDD and HDD for calculations, and A will be replaced with the area of the wall or window depending on the type of transfer calculated.

The heat transfer from the walls is based on the plaster, brick blocks and insulation material's conductivity values. When the wall is insulated by using W_i meters of type i insulation material with k_i thermal conductivity, the U value, represented by U_i^{wa}, can be given as

$$U_i^{wa} = \frac{1}{\frac{1}{h^{in}} + \frac{1}{h^{out}} + \frac{2W^p}{k^p} + \frac{W^b}{k^b} + \frac{W_i}{k_i}} \tag{11}$$

If the wall is uninsulated, then the U value, represented by U_0^{wa}, will be the same formulation with the insulated wall where $W_i = 0$.

Windows are insulated by increasing the number of glass layers used and packing a gas that has a low heat conductivity coefficient (usually air) between these glasses. The U value for a window that has j layers of glasses, U_j^{wi}, is given as

$$U_j^{wi} = \frac{1}{\frac{1}{h^{in}} + \frac{1}{h^{out}} + \frac{jW^g}{k^g} + \frac{(j-1)W^a}{k^a}} \tag{12}$$

In the following section, we report our analysis for different base temperature values for heating and cooling required days.

3. RESULTS AND DISCUSSION

We applied the mathematical model provided in the previous section to hypothetical houses in four different climate regions of Turkey by using five different base temperature values for cooling and heating required days. The analysis of the model outputs is provided in this section.

3.1. Definitions and Related Data

In this study, we consider identical hypothetical houses located in four different climate regions of Turkey, as given in the Turkish Thermal Insulation Standard (TS 825) (Bulut et al., 2007). Antalya (region 1) is located in the south of Turkey and has a semi-humid climate, characterized by long and very hot summers, and warm, rainy winters. Istanbul (region 2) is located in the north-west of Turkey and also has a semi-arid climate; however, sustained sub-zero temperatures during winter is very unusual for Istanbul. Ankara (region 3) is located in the Central Anatolia region of Turkey and its climate is characterized by cold winters and hot summers, with weather usually being very dry. Finally, Erzurum (region 4) is located in the east of Turkey and has a semi-arid climate, characterized by long and very cold winters and cool summers. We provide the climate data (in terms of CDD and HDD) for all four cities analyzed in our study in Table 2. The HDD and CDD values at different base temperatures were obtained from "http://www.degreedays.net."

TABLE 2. HDD and CDD values for different cities (www.degreedays.net).

	T_b (°C)	Antalya	Istanbul	Ankara	Erzurum
HDD	15	527	1027	2196	3616
	16	659	1204	2435	3895
	17	811	1396	2690	4184
	18	982	1598	2956	4479
	19	1166	1811	3233	4784
CDD	25	391	148	118	78
	26	302	99	88	57
	27	231	61	62	39
	28	171	37	41	25
	29	126	20	26	15

We use the parameter set given in Üçtuğ et al. (2015) and provide them in Table 3. We include three insulation materials, stone wool, EPS, and XPS, in our analysis. We assume that the fuel used to heat the building is natural gas as most buildings in Turkey are heated using natural gas.

TABLE 3. Data Set for the Case Study.

Parameter	Unit	Value
k_1 (Stone wool)	W/mK	0.035
k_2 (XPS)	W/mK	0.031
k_3 (EPS)	W/mK	0.04
p_1 (Stone wool)	$\$/m^3$	85
p_2 (XPS)	$\$/m^3$	152
p_3 (EPS)	$\$/m^3$	75
k^p	W/mK	0.72
k^b	W/mK	0.72
k^g	W/mK	0.78
k^a	W/mK	0.0242
W^p	m	0.02
W^b	m	0.19
W^g	m	0.004
W^a	m	0.012
pw_1	$\$/m^2$	15
pw_2	$\$/m^2$	25
pw_3	$\$/m^2$	36
p^f	$\$/m^3$	0.4
Cal^f	$kcal/m^3$	8250
p^{elec}	$/kWh	0.12
v^{hs}	—	0.92
COP^{ac}	—	2.5
A^{wa}	m^2	110
A^{wi}	m^2	21
h^{in}	W/m^2K	2
h^{out}	W/m^2K	20
W^{max}	m	0.3

3.2. Sensitivity Analysis

Stone wool has been chosen by the model as the insulation material in all climatic regions, for all HDD, CDD, and lifespan values. These results are explained in Üçtuğ et al. (2015) as follows: Define an arbitrary insulation performance indicator function called ip_{in}, which would be calculated as the multiplication of thermal conductivity by the material cost. The model can be expected to choose the insulation material with the lowest ip_{in} score. When we calculated the ip_{in} values of the three insulation materials, we obtain the following values:

$$ip_{in}\ \text{(stone wool)} = 2.98\ \$/m^4K$$

$$ip_{in}\ \text{(EPS)} = 3.00\ \$/m^4K$$

$$ip_{in}\ \text{(XPS)} = 4.71\ \$W/m^4K$$

Hence, stone wool is chosen as the insulation material for all conditions as a result of having the lowest ip_{in} score. The optimum insulation thickness values for stone wool in different climatic regions are displayed in Figures 1–4. The full set of results are provided as supplementary material. Hence, the optimum insulation thickness data for five different base temperature values for CDD and HDD values for five different insulation lifespans (10, 20, 30, 40, 50 years) can be seen in the supplementary material. In Figures 1–4 we only provide the data corresponding to an average lifespan of 30 years.

When the data provided in Figures 1–4 is compared, we can see that the highest optimum insulation thickness values belong to Erzurum (Region 4), while the lowest optimum insulation thickness values are observed in the case of Istanbul (Region 2). Interestingly, Antalya (Region 1) requires more insulation than Istanbul (Region 2) despite the fact that the typical cumulative annual HDD value in Antalya is around 800 on the average while for Istanbul this figure is approximately 1500. This means that in warm and mild climates, energy-saving actions would also return significant economic saving as a result of decreased electricity consumption for air conditioning during the summer season.

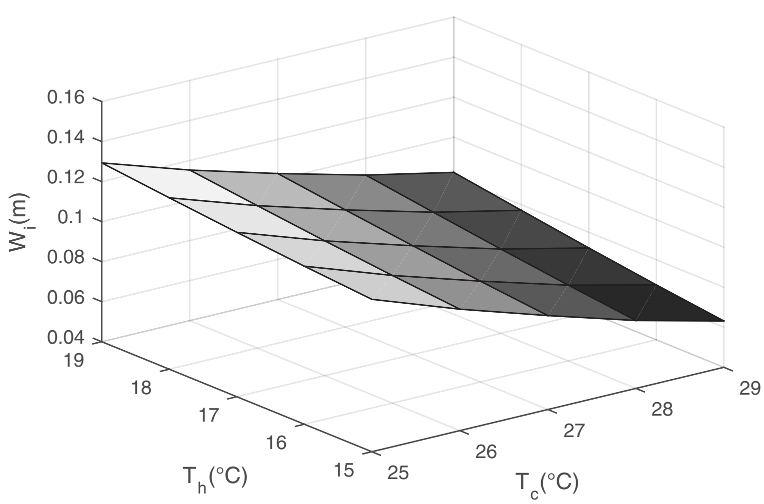


FIGURE 1. Region 1 (Antalya).

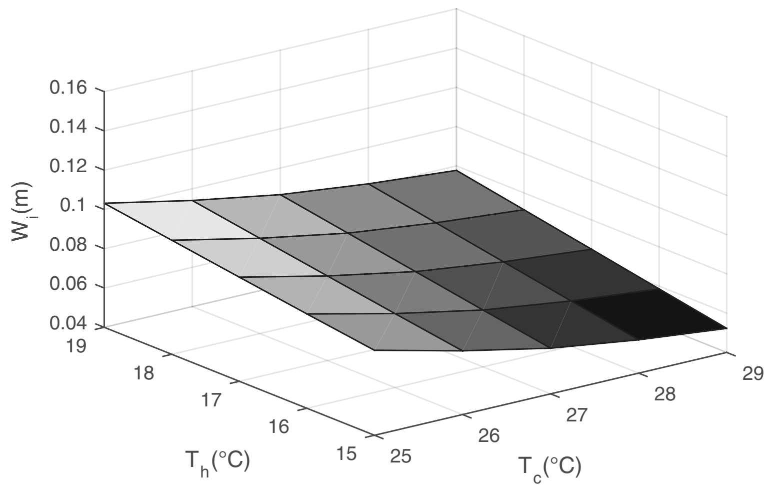


FIGURE 2. Region 2 (Istanbul).

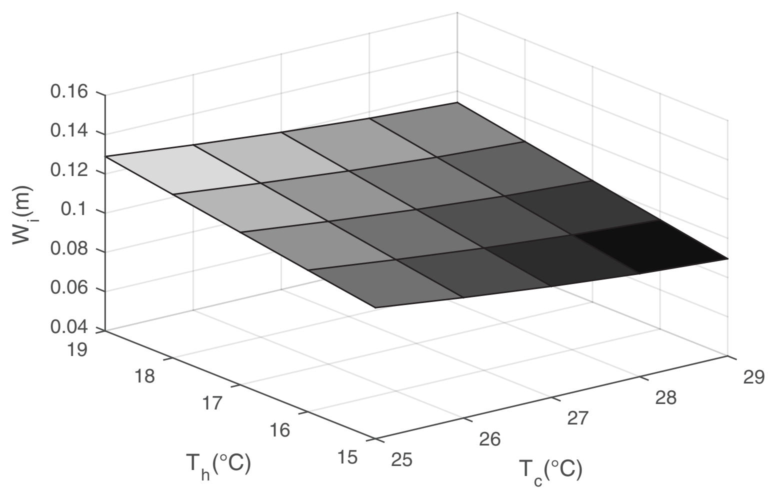


FIGURE 3. Region 3 (Ankara).

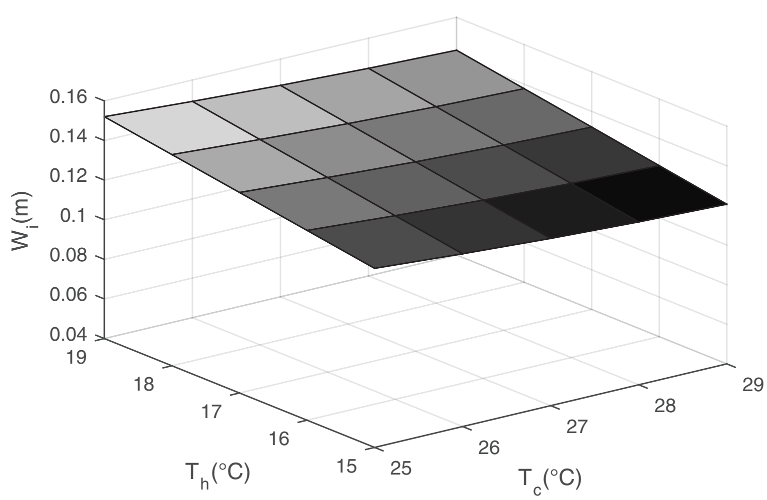


FIGURE 4. Region 4 (Erzurum).

Unlike wall insulation, where the same material has been chosen by the model in all scenarios, selected window type was found to vary with HDD, CDD, and lifespan values. For low values of T_h or high values of T_c, the model opts to choose single glass windows in Antalya and Istanbul, cities in which CDD values exceed HDD values. Again, in these two cities, double glazed windows remain preferable if T_c values are kept high. Only when T_c values are decreased and T_h values are increased, does the model select triple glazed windows in Antalya and Istanbul. On the other hand, Ankara and Erzurum, where HDD values are more dominating than CDD values, single glass windows are not selected at all, and double glazed windows are feasible for only high T_c and low T_h values. For most scenarios, triple glazed windows are the optimum choice in colder climates.

Next, we would like to focus on the economic implications of the energy-saving actions for the end user. Naturally, total savings increase continuously with increasing lifespan. However for Antalya, Istanbul, and Ankara, the highest average annual savings were calculated for a lifespan of 20 years whereas for Erzurum, the highest average annual savings correspond to a lifespan of 10 years.

FIGURE 5. Maximum average annual savings for each climatic region (T_h = 15°C, T_c = 29°C) majority of the scenarios. In Figure 5, the highest possible average annual savings for each city are provided. As one would expect, these maximum savings were all calculated for a combination of the minimum possible T_h and maximum possible T_c values, which are 15°C and 29°C, respectively.

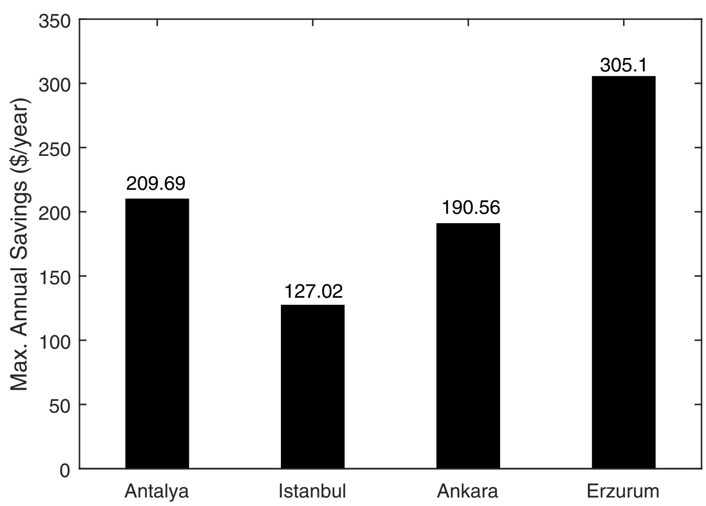


Figure 5 shows that the saving potential in extreme climates (Antalya-region 1: very hot, Erzurum-region 4: very cold) is higher than milder climates. This was especially interesting because Ankara, although not having a climate that is as cold as that of Erzurum, still experiences very long and cold winters during which sustained subzero temperatures for days or even weeks is very common. Yet, the economic savings potential of Antalya was found to be greater than that of Ankara. The mathematical explanation of this finding is that due to the relatively high cost of electricity, removing one unit of energy from the building (cooling) is more expensive than providing one unit of energy to the building (heating). The mathematical explanation of this finding is that due to the relatively high cost of electricity, removing one unit of energy from the building (cooling) is more expensive than providing one unit of energy to the building (heating). By using the data given in Table 3, the unit cost of heating ($P_{u,heat}$) and the unit cost of cooling ($P_{u,cool}$) can be calculated as follows:

$$P_{u,heat} = 1\,J \times \frac{1\,kcal}{4184\,J} \times \frac{1\,m^3\,NG}{8250\,kcal} \times \frac{\$0.4}{1\,m^3\,NG} \\ = \$1.16 \times 10^{-8} \tag{13}$$

$$P_{u,cool} = 1\,J \times \frac{1\,J\,(electricity)}{0.94\,J\,(heat)} \times \frac{1\,kWh}{3.6 \times 10^6 J} \times \frac{\$0.31}{1\,kWh} \\ = \$9.16 \times 10^{-8} \tag{14}$$

As the calculations above indicate, the unit cost of cooling is approximately 8 times higher than the unit cost of heating. Consequently, an energy-saving investment in warmer climates with high CDD values turns out to be more profitable than energy-saving investments in colder climates with high HDD values.

Last but not least, we analyze the effect of changing the base temperature on the annual savings, which was the main discussion point of this particular study. In Table 4, the annual savings for each region with respect to several heating and cooling base temperatures are presented. Due to an abundance of results data, only the savings corresponding to an insulation material lifetime of 20 years were considered, and the reason for this choice is that in many regions the highest annual savings were observed when lifetime was taken as 20 years.

TABLE 4. Effect of Heating and Cooling Base Temperatures on Annual Savings.

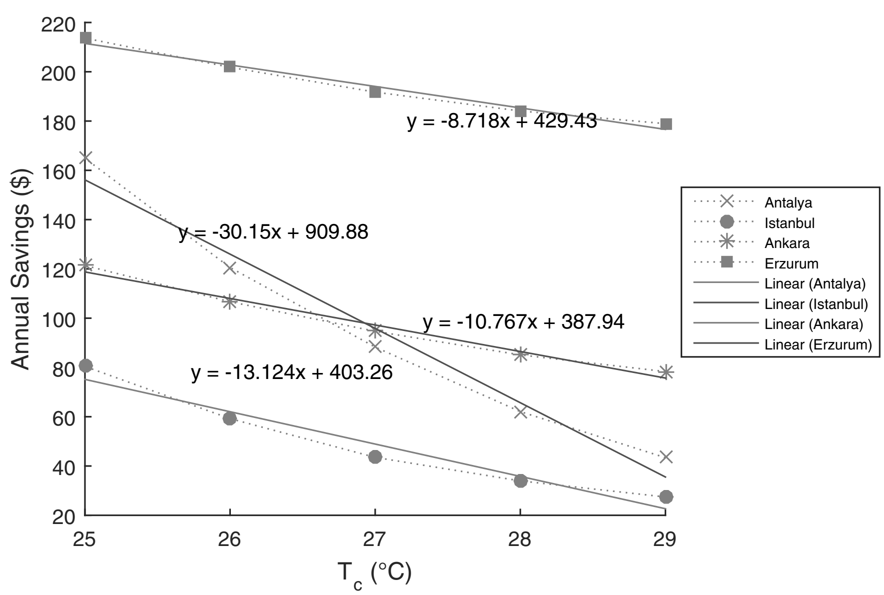
Annual Savings ($) *(r = 5%, lifetime = 20 years, T_c = 29°C, T_h = 15°C)*				
T_h (°C)	Antalya	Istanbul	Ankara	Erzurum
15	43.38	27.43	78.33	178.94
16	50.43	36.36	92.49	197.74
17	58.73	46.43	107.71	217.38
18	68.26	57.38	125.02	237.59
19	78.72	69.25	143.27	258.64
T_c (°C)	Antalya	Istanbul	Ankara	Erzurum
25	164.89	80.41	121.38	213.66
26	120.56	59.24	106.67	201.82
27	88.26	43.51	94.68	191.74
28	62.08	33.96	85.1	184.08
29	43.38	27.43	78.33	178.94

Figures 6 and 7 show the variation in the annual savings as a function of changing base temperatures in a more explicit manner. The linear trendlines in Figures 6 and 7 for each curve are in the form of "*ax* + *b*." The coefficient "*a*" in these linear trendlines would be equal to the average change in the annual savings when the base temperature is changed by one degree. If we take the average of the "*a*" values in Figures 6 and 7, we obtain values of 15.69 $/°C and 13.87 $/°C, respectively. Hence, changing one's accepted thermal comfort temperature by one degree would lead to an approximate saving of $15 per year. However, it must be reminded that this $15 increase in savings is relative to the next best combination of energy saving actions, not to the case of no insulation.

4. CONCLUSION

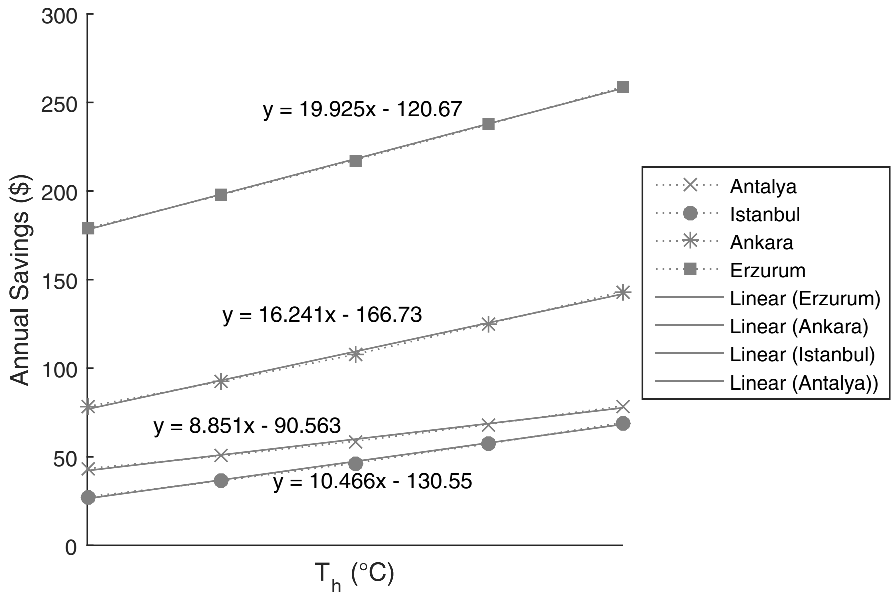
In this study, we applied a non-linear benefit-cost optimization method by using five different cooling and heating base temperatures for four identical houses located in different regions of Turkey.

FIGURE 6. Effect of T_c (T_h = 15°C).



Energy-saving actions were studied in two groups: choosing the insulation material with optimum insulation thickness, and choosing the number of window glazing layers x. For insulation materials, the three most common materials in the Turkish market are used, which are stone wool, EPS, and XPS. For windows, we studied three alternatives: single glass windows, double-glazed windows, and triple-glazed windows. We implemented the model using a General Algebraic Modeling System (GAMS) software and applied sensitivity analysis based on heating and cooling base temperatures.

FIGURE 7. Effect of T_h (T_c = 29°C).



Our results showed that stone wool is marginally the preferable insulation material in all regions for all base temperatures, due to the fact that its thermal conductivity times cost value is the smallest amongst all the alternatives. Since an ideal insulation material should have low thermal conductivity and low cost, the material with the lowest value of the multiplication of these two parameters would be chosen by the model. For low values of heating, base temperature or high values of cooling base temperature, meaning less energy expenditure, single glass windows may be preferable. When the energy needed to achieve thermal comfort is increased either by changing the base temperatures or by studying regions with more energy demand (regions 1 and 4, especially), double-glazed windows become preferable for low values of insulation lifetime. When the lifetime values exceed 30 years, triple-glazed windows become the ideal choice. The highest insulation thicknesses and the highest energy savings arising from applying insulation in walls and windows were observed in Erzurum (region 4), and then Antalya (region 1). The fact that applying-energy saving measures in Antalya, a city with long, hot summers and cool winters, would have a higher economic return than applying such actions in Istanbul and Ankara, cities in which winters are much colder and longer than Antalya, was attributed to unit cost of cooling being higher when compared to the unit cost of heating. Finally, when the effect of changing the base temperatures was studied, it was found that the average additional annual savings as a result of increasing the cooling base temperature or decreasing the heating base temperature by one celsius degree is approximately $15.

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