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Residential Building Envelope Alternatives with Equivalent Cost

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ABSTRACT

Selecting the optimum envelope alternative in buildings is one of the most important factors in ensuring thermal comfort. This study calculated the heating costs, construction and lifecycle costs for a residential building in Istanbul with different envelope alternatives created by changing the type and thickness of the body and insulation materials used in the walls and roof, which are the structural components forming the building envelope. Envelope alternatives with equivalent costs were determined and evaluated. Hence, materials with varying properties and thicknesses were able to yield the same performance in terms of lifecycle and heating costs.

Key Words: *energy efficiency, envelope design, envelope alternatives with equivalent cost, life cycle cost, heating cost***.**

1. INTRODUCTION

Apart from addressing the sheltering needs of people, residential buildings should also offer comfortable conditions to their occupants within their lifecycle. In connection with the increase in energy consumed by artificial subsystems, the provision of comfortable conditions has become an issue with respect to the decline in available energy resources, dependence on foreign countries for these resources, hazardous effects of gases emitted by energy consumption on human health, increases in air pollution, and global warming. In light of this information, it is necessary to construct and operate buildings that meet the required comfort conditions and consume the minimum possible amount of energy.

Energy use, which causes important environmental problems, is also an indicator of the level of development of countries. Intense and efficient use of energy is as significant as the amount of energy consumed per capita. Turkey, which has not reached an adequate level of development in terms of energy consumed per capita, is also behind developed countries in terms of energy intensity. While the average energy intensity in the world was 0.29 TOE/thousand $ in 2001, in Turkey it was 0.38 TOE/thousand $ [1] The sixth EU Environment Action Programme, which aims to improve the quality of life and the environment in EU (European Union) countries, emphasised in its report called “Our future, our choice” that environmentally-friendly measures including saving energy should be taken into account when designing buildings [2].

In many countries, the energy required for space heating in buildings makes up the highest share of energy use, and represents about 40% of the total energy consumed in the residential sector (Table 1) [3].

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Table 1. Distrubution of energy consumption in buildings, in %.

	Space Heating	Water Heating	Air condition ventilation	Lighting illumination	Cooling freezing	Other
Houses	40	17	7	7	12	17
Commercial	32	5	22	25	-	16

Choosing the optimum heat insulation thickness in buildings is one of the most important factors in ensuring thermal comfort. Insulation creates energy savings by reducing heat gains and losses, enables protection of the environment, ensures thermal comfort and noise control, prevents condensation in structural elements and surfaces, and protects structural elements from external impacts [4].

Bolatturk comparatively determined the optimum insulation thickness on external walls of buildings based on annual heating and cooling loads [5]. Kaynakli determined the optimum insulation thicknesses on a prototype building in Bursa for different fuel types, namely natural gas, coal, fuel oil, LPG (liquefied petroleum gas) and electricity [6]. Kaynakli and Yamankaradeniz have identified insulation thicknesses for two different wall types based on annual fuel costs for natural gas fuel in various climatic regions of Turkey [7], [8]. Aksoy and Kelesoglu investigated the energy losses from opaque parts of a building envelope according to surface area, building orientation and insulation thickness for Elazig, one of the coldest cities in Turkey [9]. Sisman, Kahya, Aras and Aras determined the optimum insulation thicknesses for different degree-day(DD) regions of Turkey, namely Izmir (DD: 1450), Bursa (DD: 2203), Eskişehir (DD: 3215) and Erzurum (DD: 4856) over a lifetime of 10 years, maximising the present worth value of annual energy savings for insulated external walls [10]. Bolatturk calculated the optimum insulation thickness, the amount of energy saved and payback period for five different fuel types (coal, natural gas, fuel oil, LPG and electricity) using life cycle cost (LCC) analysis [11]. Aytac and Aksoy calculated the optimum insulation thickness of the external wall for different energy sources (coal, natural gas, LPG, fuel oil, electricity) and two different insulation materials (expanded polystyrene and rock wool) for Elazığ [12].

Golcu, Dombayci and Abali calculated the optimum insulation thickness, energy savings and payback period for two different energy sources (coal and fuel oil) for the buildings in Denizli [13]. Dombayci, Golcu and Pancar calculated the optimum insulation thickness of the external wall for five different energy sources (coal, natural gas, LPG, fuel oil and electricity) and two different insulation materials (expanded polystyrene, rock wool) for Denizli [14]. Ozel and Pihtili investigated the variation of heat flux for different applications of insulation to building walls under summer and winter climate conditions, and obtained the optimum insulation for minimising heat gain in summer and heat loss in winter [15]. Comakli and Yuksel investigated the optimum insulation thickness for the coldest cities in Turkey, like Erzurum, Kars and Erzincan [16]. Al-Sanea evaluated and compared the thermal performance of building roof elements subject to periodic changes in ambient temperature, solar radiation and nonlinear radiation exchange for six variants of a typical roof structure used in the construction of buildings in Saudi Arabia [17]. Hasan developed a systematic approach for optimising material thickness and then applied the method in Palestine [18].

In buildings, most of the heat loss is from the roof and walls, the two structural elements that are exposed to the outdoor environment. A large majority of the currently available studies have investigated heat loss from external walls. In all of the studies carried out in Turkey, brick is considered the favourite wall material. There are no external wall alternatives using different wall body materials. However, materials other than brick are widely used as wall body materials in Turkey, especially in reinforced concrete structures. This study aims to identify the characteristics of envelopes with equivalent costs from alternatives derived by changing the building envelope characteristics that affect both the construction cost and the operational costs of the building. To this end, the heating costs, construction costs and lifecycle costs of a residential building in Istanbul were identified and assessed for different envelope alternatives derived by changing the type and thickness of the body and insulation materials used on the walls and roof.

2. METHODS AND ASSUMPTIONS

2.1. Determining the Building Envelope Alternatives

Most heat loss in residential buildings occurs through construction elements such as the walls, floor, roof, windows and heat bridges. The rate of heat loss from these locations varies depending on the architecture and position of the building, the level of thermal insulation, and the properties of the construction material used [19].

With current technology, we can refer to a wall both as a one-layer structure and as a construction element of multiple layers that contains insulating material. In Turkey, the most frequently used thermal insulating materials seem to be fibre and foam materials. Fibre materials should be mineral wools, such as rock wool and glass wool, and wood wool. Also, foam materials should be polystyrene foams and polyurethane foams, such as expanded polystyrene foam (EPS) and extruded polystyrene foam (XPS). The insulating materials to be used on the exterior walls should not negatively affect the structure of the building, and its insulating features should not change in humid conditions.

Today in Turkey, exterior walls are insulated with four different systems that differ in the location of the thermal insulating materials:

- Thermal insulation on the exterior side of the walls (exterior thermal sheathing),

- Thermal insulation on the interior side of the walls,
- Thermal insulation between two walls (sandwich walls), or
- Exterior walls with ventilation (curtain walling system).

The exterior insulation system, used commonly in Europe and America, has also been used more frequently in Turkey in recent years. With this system, the insulation surrounds the building like a jacket, and no heat bridges are formed. Thus, stress and cracks due to heat change are avoided, and the ventilation helps to keep the construction dry at all times. Although the cost of exterior insulation is higher than other systems, it is the most appropriate method for buildings used over a long period of time, such as housing [4].

This study considers building envelope properties, which must have efficient design parameters for an energy efficient environment and for conservation of heating energy in buildings. The building components forming a building envelope are the walls, roof and ground flooring. Different body and insulation materials used in the walls, roof and flooring and different thicknesses will result in different construction, operating and life cycle costs of a building. The materials that can be used in walls, floors and roofs as specified in the unit prices of the Ministry of Public Works [20],[21] and TS 825 (TS 825) [22] were first identified. A fixed wooden roof is approved. Extruded polystyrene foam with a thickness of 4 cm has been deemed appropriate for use as an insulation material in ground flooring, and 6, 8, or 10 cm thick glass wool has been found appropriate for use in roofs. It is assumed that brick, gasbeton in different thicknesses, bimsbeton and beton briquet will be used as wall body materials. Different alternatives include the use of extruded polystyrene foam and rock wool in different thicknesses as wall insulation materials. Since it is a more convenient system in buildings that are used for a prolonged period, such as housing, and there is a reduced risk of condensation as a result of steam diffusion, it is assumed that insulation is applied externally on the walls.

2.2. Calculating the Building's Construction, Annual Heating and Lifecycle Costs

Building costs emerge in different phases of the building construction process. The lifecycle costs of buildings are as important as their construction costs, as buildings will also incur costs during their utilisation. Maintenance, repair and operating costs arising within the utility period amount to a significant portion of the budget of home owners. In terms of energy efficiency, an assessment of lifecycle costs conducted during the design, implementation, utilisation or renovation phases of a building's use will contribute to making the right decisions about its design [23], [24].

The LCC analysis is an economic evaluation technique that calculates the cost of a system or a component over its lifetime. The LCC equation involves the following three variables: the pertinent costs of ownership, the period of time over which these costs are incurred, and the discount rate that is applied to future costs to equate them with present day costs. In this study, the total heating cost over a lifetime of LT years is converted to present value by multiplying it by the present worth factor (PWF). The PWF, which includes the interest rate (i) and inflation rate (g), is adjusted for inflation.

The interest rate adjusted for inflation (i*) is given by the following equations:

i*= (i-g)/ (1+g), for (i>g),

i*= (g-i)/ (1+i), for (i<g),

$$PWF = \frac{(1+i^*)^{LT} - 1}{i^* \cdot (1+i^*)^{LT}} \quad (1)$$

where LT= Lifetime [25].

In this study, the construction costs were first calculated for a two-story, 148 m^2 residential building, detached on all four sides, to be constructed with a reinforced concrete system. The window area/external wall area ratio for this building is 9%. The Ministry of Public Works unit price rates, a measurement standard adopted and used in Turkey, were used in the calculation of construction costs [20]. Unit Price Analysis has been conducted for the wall insulation materials with different thickness ratios, which are not covered by the Ministry of Public Works unit price list. The calculated construction costs also include the costs relating to civil works.

It is important that buildings also provide the required climatic comfort conditions for their users. In TS 825, Turkey is divided into four climatic regions by provincial centres. Region 1 represents the areas that require the least energy for heating, and Region 4 represents the areas that require the most energy for heating. Therefore, this study investigated whether the envelope designs in all of the evaluated projects conformed to the specifications of TS 825 in Region 2. Also, the wall alternatives were checked for the presence of condensation. All project alternatives evaluated in Tables 2 and 3 provide the required thermal comfort as per TS 825, and no condensation was found in these wall alternatives. Determination of the operating costs of the project alternatives was based on annual heating cost calculations. In order to calculate annual heating costs, the "TS 825 Heat Requirement Calculations" computer program was used. This calculation program, designed by Izoder, is based on the "TS 825 Heat Insulation Rules in Buildings" standard and Turkey's meteorological data for the last 20 years. Using this program, it is possible to calculate condensation values and the specific heat loss as defined in the "TS 825 Thermal Insulation Requirements for Buildings" standard, and compare the calculated values to the thresholds defined in the standard and hence evaluate the conformity of the designed building to national legislation on energy efficiency. The program operation is basically parallel to the TS 825 standard. First, data regarding the building subject to the standard are entered into the program, and then the building's annual heating energy demand and condensation values are calculated and checked against the criteria set forth in the standard. In the defined calculation method, annual heating energy demand is calculated by adding the monthly heating energy demand for the heating period. Hence it becomes possible to make a more realistic evaluation of the thermal performance of the building. In addition, the program enables the designer to evaluate the proposed design's capacity to take advantage of solar energy [26]. With this computer program, heat requirement values (Q_{year}) were calculated for all of the project alternatives. Annual heating expenditures of housing buildings are specified by the following equation:

$$B_y = \frac{Q_{year} \cdot 1,3}{2 \cdot H_u \cdot \eta_k} \quad (2)$$

B_y: Annual fuel quantity (m^3/year)

Q_{year}: Annual heat requirement of the building (kWh)

H_u: Fuel heating value (kWh/m^3) = 10,38 kWh/m^3 (for natural gas)

η_k: Boiler efficiency = 0,85-0,92 (for natural gas) [27]

It is assumed that natural gas is consumed in all project alternatives, and the annual heating expenditures of the project alternatives are determined in accordance with natural gas prices in Istanbul in 2007.

However, construction costs, along with heating costs - which account for the largest share of costs incurred over a building's lifecycle - have been considered as operating costs in this study when identifying the lifecycle costs. Other costs have not been taken into account. When determining the lifecycle cost, the period that will be covered in the economic evaluation can be the estimated lifetime of the building, the lifetime of an element of one of the subsystems for which the calculation is being made, or any period foreseen in terms of investment by individuals or organisations that demand the evaluation, and hence is a parameter that is not bound by any rules. In order to economically evaluate the performance of the envelope options in terms of climatic comfort conditions, the global change in radiator fuel prices and the maximum duration estimated for such price changes were taken as bases. Since this study is based on the United States Department of Energy's estimated world oil prices for the next 20 years, a period of 20 years was used for the economic evaluation.

It is necessary to determine the ratio of the cost increase per each time slice within the period of the economic evaluation. This ratio is dependent on the specific conditions of the sector for which the evaluation is being made, as well as on inflation; also, results of studies by various statistical or estimation organisations can be used. The interest rate can be determined using the ratios calculated by various statistical and estimation organisations in order to transform into current values the parameters for which the future costs have been established. In consideration of the country and project risks, the interest rate of 15% applied to projects in Turkey by the International Finance Corporation (IFC) was taken as a basis. Turkey's bonds, issued in dollars, are traded at 13%, and a 2% risk margin is added [23].

The lifecycle costs of buildings with different envelope alternatives were calculated using the present worth value method based on a lifetime of 20 years and an interest rate of 15%. Construction, annual heating costs and life cycle costs that were calculated in TL were changed to dollars. The exchange rate to dollars was taken from data from the Central Bank of the Republic of Turkey. The 2007 exchange rate of $1 = 1,30 TL was used since all costs were calculated using 2007 prices [28].

3. RESULTS AND DISCUSSION

The construction, lifecycle and annual heating costs were calculated for a two-story residential building constructed with different envelope alternatives that provide thermal comfort in fulfilment of TS 825 with no condensation. Envelope alternatives with equivalent costs are evaluated in Tables 2, 3 and 4.

Table 2 compares annual heating costs for 166 different envelope alternatives, and shows that the envelope alternative with the lowest heating cost is one in which 25 cm gasbeton as the wall body material is mantled with 8 cm XPS, and 10 cm glass wool is used in the roof space. The alternative with the highest heating cost uses 25 cm gasbeton as the wall body material, 8 cm rock wool for mantling, only on the reinforced concrete surfaces, and 8 cm glass wool for the roof space. The following alternatives have equivalent annual heating costs:

- The alternative using 20 cm bimsbeton as the wall body material, mantled with 8 cm XPS and using 6 cm glass wool in the roof space has a fuel cost equivalent to that of the alternative using 20 cm bimsbeton as the wall body material, mantled with 8 cm rock wool, with 10 cm glass wool for the roof space;
- The alternative using 25 cm gasbeton as the wall body material, mantled with 8 cm rock wool and using 6 cm glass wool in the roof space, and the alternative using 20 cm beton briquet as the wall body material, mantled with 8 cm rock wool and using 10 cm glass wool for the roof space;
- The alternative using 22,5 cm gasbeton as the wall body material, mantled with 6 cm rock wool and using 10 cm glass wool in the roof space, and the alternative using 25 cm gasbeton as the wall body material, mantled with 6 cm XPS and using 6 cm glass wool for the roof space, etc.

  Table 3 compares lifecycle costs for 166 different envelope alternatives, demonstrating that the envelope alternative with the lowest lifecycle cost is the one in which 19 cm brick is used as the wall body material, mantled with 5 cm XPS, and 8 cm glass wool is used in the roof space. The alternative with the highest lifecycle cost is the one that uses 25 cm gasbeton as the wall body material, mantled with 8 cm rock wool, with 10 cm glass wool for the roof space. Alternatives with equivalent lifecycle costs are:

- The alternative using 20 cm beton briquet as the wall body material, mantled with 6 cm XPS and using 8 cm glass wool in the roof space, and the alternative using 19 cm brick as the wall body material, mantled with 8 cm XPS and using 8 cm glass wool for the roof space;

Table 2. Envelope alternatives with equivalent annual heating energy costs ($).

	wall body material- 19 cm brick			wall body material- 20 cm bimsbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
4 cm XPS						397.00
5 cm XPS		393.20	384.97	395.97	383.43	375.43
6 cm XPS	386.78	374.78	367.06	379.29	367.16	358.68
8 cm XPS	361.08	348.81	341.56	356.26	344.40	336.20
5 cm rock wool						400.28
6 cm rock wool		401.20	392.93	402.74	389.92	381.96
7 cm rock wool	397.34	384.76	376.76	387.97	375.94	368.22
8 cm rock wool	383.91	371.84	363.64	376.59	364.25	356.26

	wall body material- 19 cm gasbeton			wall body material- 20 cm gasbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
3 cm XPS			400.79			398.64
4 cm XPS	397.51	384.90	376.93	395.49	382.95	374.99
5 cm XPS	380.08	368.01	359.47	378.40	366.30	357.97
6 cm XPS	366.71	354.24	346.72	365.55	353.01	345.73
8 cm XPS	347.17	335.34	327.38	346.69	334.32	326.66
4 cm rock wool			398.19			395.70
5 cm rock wool	400.00	387.15	379.50	398.26	385.48	377.51
6 cm rock wool	385.34	373.28	365.25	383.91	371.77	363.54
7 cm rock wool	373.82	361.49	353.52	372.59	359.98	352.05
8 cm rock wool	364.32	352.02	344.50	363.09	350.82	343.27

	wall body material- 22.5 cm gasbeton			wall body material- 25 cm gasbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
*7 cm rock wool						400.28
*8 cm rock wool					403.73	395.49
2.5 cm XPS						402.63
3 cm XPS		401.20	392.96		396.62	388.08
4 cm XPS	391.68	378.81	371.29	387.15	375.12	367.36
5 cm XPS	374.88	362.58	354.62	371.91	359.37	351.68
6 cm XPS	362.58	350.31	342.79	359.61	347.34	340.09
8 cm XPS	345.01	332.16	324.47	342.96	330.18	322.49
4 cm rock wool		398.88	390.30		394.16	385.96
5 cm rock wool	393.89	381.27	373.52	389.68	377.38	369.96
6 cm rock wool	380.25	368.12	359.61	377.04	364.70	356.46
7 cm rock wool	369.69	356.80	348.84	366.71	354.17	346.65
8 cm rock wool	360.12	347.85	340.64	357.69	346.14	337.90

	wall body material- 20 cm beton briquet		
	roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool
4 cm XPS			399.90
5 cm XPS	398.19	385.34	377.38
6 cm XPS	380.97	369.18	360.63
8 cm XPS	357.15	345.66	337.39
6 cm rock wool		392.59	384.66
7 cm rock wool	389.92	377.69	370.17
8 cm rock wool	378.03	366.00	357.69

(dark grey)	difference between 0.00$- 0.05$
(light grey)	difference between 0.06$- 0.10$

*Heat insulation materials are used only on the external surfaces of reinforced concrete. No heat insulation materials were used on the external surfaces of the wall body material.

Table 3. Envelope alternatives with equivalent life cycle costs ($)

	wall body material- 19 cm brick			wall body material- 20 cm bimsbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
4 cm XPS						51,006.37
5 cm XPS		50,830.83	50,879.99	51,173.42	51,272.27	51,322.92
6 cm XPS	51,063.35	51,165.61	51,217.99	51,519.13	51,620.54	51,668.20
8 cm XPS	51,804.12	51,904.67	51,960.03	52,276.58	52,379.70	52,429.07
5 cm rock wool						52,401.72
6 cm rock wool		52,297.53	52,346.48	52,632.43	52,729.56	52,780.44
7 cm rock wool	52,567.74	52,666.37	52,717.03	53,011.75	53,113.80	53,166.17
8 cm rock wool	53,043.40	53,145.24	53,194.62	53,500.25	53,600.37	53,651.04
	wall body material- 19 cm gasbeton			wall body material- 20 cm gasbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
3 cm XPS			52,216.16			52,375.75
4 cm XPS	52,367.66	52,466.07	52,516.94	52,528.10	52,626.94	52,677.81
5 cm XPS	52,710.09	52,811.93	52,859.17	52,872.67	52,974.30	53,022.82
6 cm XPS	53,076.54	53,175.82	53,229.47	53,242.33	53,341.18	53,396.33
8 cm XPS	53,855.82	53,959.15	54,010.03	54,025.88	54,125.80	54,178.60
4 cm rock wool			53,495.37			53,652.83
5 cm rock wool	53,758.08	53,855.00	53,907.80	53,920.24	54,017.58	54,068.46
6 cm rock wool	54,159.68	54,261.52	54,311.97	54,323.76	54,425.17	54,474.33
7 cm rock wool	54,559.33	54,659.45	54,710.33	54,724.69	54,823.11	54,874.19
8 cm rock wool	55,059.59	55,159.93	55,213.59	55,224.95	55,325.51	55,378.95
	wall body material- 22.5 cm gasbeton			wall body material- 25 cm gasbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
*7 cm rock wool						51,936.58
*8 cm rock wool					52,031.29	52,080.45
2.5 cm XPS						52,996.29
3 cm XPS		52,700.86	52,750.02		53,082.97	53,130.21
4 cm XPS	52,910.28	53,010.83	53,064.49	53,296.45	53,398.51	53,450.67
5 cm XPS	53,260.42	53,360.76	53,411.64	53,652.58	53,751.43	53,804.02
6 cm XPS	53,336.10	53,734.06	53,787.71	54,025.67	54,126.23	54,181.59
8 cm XPS	54,127.78	54,522.10	54,574.69	54,823.12	54,920.47	54,973.06
4 cm rock wool		53,981.78	54,028.80		54,363.04	54,412.41
5 cm rock wool	54,302.63	54,401.05	54,453.21	54,687.10	54,787.44	54,841.74
6 cm rock wool	54,710.66	54,812.07	54,859.52	55,101.32	55,201.45	55,250.61
7 cm rock wool	55,116.29	55,212.99	55,263.87	55,508.45	55,607.30	55,660.96
8 cm rock wool	55,616.13	55,716.58	55,772.26	56,011.71	56,116.76	56,165.92
	wall body material- 20 cm beton briquet					
	roof insulation					
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool			
4 cm XPS			51,295.89		difference between 0 $- 5 $	
5 cm XPS	51,458.66	51,555.58	51,606.45		difference between 5.1 $- 9.9 $	
6 cm XPS	51,800.94	51,904.48	51,951.73			
8 cm XPS	52,553.47	52,658.94	52,707.89	*Heat insulation materials are used only on		
6 cm rock wool		53,017.58	53,068.67	external surfaces of reinforced concrete		
7 cm rock wool	53,295.27	53,396.04	53,449.70	No heat insulation materials were used on		
8 cm rock wool	53,780.57	53,882.61	53,931.35	external surfaces of the wall body material.		

Table 4. Envelope alternatives with equivalent construction costs ($).

	wall body material- 19 cm brick			wall body material- 20 cm bimsbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
4 cm XPS						48,521.45
5 cm XPS		48,369.65	48,470.36	48,694.92	48,872.27	48,972.98
6 cm XPS	48,642.38	48,819.74	48,920.46	49,145.02	49,322.37	49,423.08
8 cm XPS	49,544.02	49,721.38	49,822.09	50,046.65	50,224.00	50,324.72
5 cm rock wool						49,896.26
6 cm rock wool		49,786.29	49,887.02	50,111.56	50,288.92	50,389.64
7 cm rock wool	50,080.68	50,258.03	50,358.75	50,583.30	50,760.65	50,861.37
8 cm rock wool	50,640.41	50,817.76	50,918.48	51,143.04	51,320.38	51,421.11
	wall body material- 19 cm gasbeton			wall body material- 20 cm gasbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
3 cm XPS			49,707.49			49,880.56
4 cm XPS	49,879.52	50,056.88	50,157.59	50,052.58	50,229.94	50,330.65
5 cm XPS	50,331.06	50,508.42	50,609.13	50,504.12	50,681.48	50,782.19
6 cm XPS	50,781.15	50,958.51	51,059.22	50,954.22	51,131.57	51,232.29
8 cm XPS	51,682.79	51,860.15	51,960.86	51,855.85	52,033.21	52,133.92
4 cm rock wool			51,002.96			51,176.03
5 cm rock wool	51,254.33	51,431.68	51,532.41	51,427.40	51,604.75	51,705.47
6 cm rock wool	51,747.71	51,925.06	52,025.78	51,920.77	52,098.12	52,198.84
7 cm rock wool	52,219.45	52,396.79	52,497.52	52,392.51	52,569.86	52,670.58
8 cm rock wool	52,779.18	52,956.53	53,057.25	52,952.24	53,129.59	53,230.32
	wall body material- 22.5 cm gasbeton			wall body material- 25 cm gasbeton		
	roof insulation			roof insulation		
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool	6 cm glass wool	8 cm glass wool	10 cm glass wool
*7 cm rock wool						49,431.12
*8 cm rock wool					49,504.22	49,604.94
2.5 cm XPS						50,476.07
3 cm XPS		50,189.62	50,290.34		50,600.40	50,701.12
4 cm XPS	50,462.36	50,639.72	50,740.44	50,873.14	51,050.49	51,151.22
5 cm XPS	50,913.91	51,091.25	51,191.98	51,324.68	51,502.03	51,602.75
6 cm XPS	51,066.59	51,541.85	51,642.07	51,774.78	51,952.13	52,052.85
8 cm XPS	51,968.23	52,442.98	52,543.71	52,676.41	52,853.76	52,954.48
4 cm rock wool		51,485.09	51,585.81		51,895.87	51,996.58
5 cm rock wool	51,837.18	52,014.53	52,115.25	52,247.95	52,425.31	52,526.02
6 cm rock wool	52,330.55	52,507.91	52,608.62	52,741.33	52,918.68	53,019.40
7 cm rock wool	52,802.28	52,979.64	53,080.36	53,213.06	53,390.42	53,491.14
8 cm rock wool	53,362.02	53,539.38	53,640.09	53,772.80	53,950.15	54,050.87
	wall body material- 20 cm beton briquet					
	roof insulation					
wall insulation	6 cm glass wool	8 cm glass wool	10 cm glass wool			
4 cm XPS			48,792.78		difference between 0 $- 4 $	
5 cm XPS	48,966.25	49,143.60	49,244.32		difference between 4.1 $- 7.9 $	
6 cm XPS	49,416.35	49,593.69	49,694.42			
8 cm XPS	50,317.98	50,495.33	50,596.05	*Heat insulation materials are used only on the		
6 cm rock wool		50,560.25	50,660.97	external surfaces of reinforced concrete surfaces		
7 cm rock wool	50,854.63	51,031.98	51,132.70	No heat insulation materials were used on the		
8 cm rock wool	51,414.37	51,591.72	51,692.44	external surfaces of the wall body material.		

- The alternative using 20 cm beton briquet as the wall body material, mantled with 7 cm rock wool and using 8 cm glass wool in the roof space, and the alternative using 20 cm gasbeton as the wall body material, mantled with 6 cm XPS and using 10 cm glass wool for the roof space;
- The alternative using 25 cm gasbeton as the wall body material, mantled with 5 cm XPS and using 6 cm glass wool in the roof space, and the alternative using 20 cm gasbeton as the wall body material, mantled with 4 cm rock wool and using 10 cm glass wool for the roof space, etc.

Table 4 compares construction costs for 166 different envelope alternatives. Envelope alternative with the lowest construction cost is that in which 19 cm brick is used as the wall body material, mantled with 5 cm XPS, and 8 cm glass wool is used in the roof space. The alternative with the highest construction cost is the one that uses 25 cm gasbeton as the wall body material, mantled with 8 cm rock wool, with 10 cm glass wool for the roof space. The alternatives with equivalent construction costs are:

- The alternative using 19 cm gasbeton as the wall body material, mantled with 4 cm XPS and using 6 cm glass wool in the roof space, and the alternative using 20 cm gasbeton as the wall body material, mantled with 3 cm XPS and using 10 cm glass wool for the roof space;
- The alternative using 20 cm gasbeton as the wall body material, mantled with 4 cm XPS and using 10 cm glass wool in the roof space, and the alternative using 19 cm gasbeton as the wall body material, mantled with 5 cm XPS and using 6 cm glass wool for the roof space;
- The alternative using 22,5 cm gasbeton as the wall body material, mantled with 4 cm XPS and using 8 cm glass wool in the roof space, and the alternative using 19 cm brick as the wall body material, mantled with 8 cm rock wool and using 6 cm glass wool for the roof space, etc.

4. CONCLUSION

Subsystems that provide comfort consume large amounts of energy, which has become a serious problem given the increasingly limited energy resources, the dependence on other countries for these resources, the harmful gases emitted by energy consumption, increasing air pollution and related global warming issues. In Turkey, heat losses from buildings are one of the primary sources of energy waste. Based on all the foregoing concerns, it is necessary to produce and operate residential buildings that provide the necessary thermal comfort while consuming the minimum amount of energy. One way of ensuring this balance is to use a sound building envelope design.

In this study, the materials used in the structural components forming the building envelope were changed and the envelope alternatives with equivalent costruction costs, lifecycle costs and annual heating costs were determined. This allowed for the identification of materials with different qualities and thicknesses that have the same performance in terms of construction cost, lifecycle cost and annual heating cost for the envelope. The results showed that increasing the thickness of the insulation is not necessary to achieve better performance; the same performance can be achieved using materials with smaller thicknesses.

In envelope alternatives providing the thermal comfort required pursuant to TS 825, the alternatives using minimum-thickness insulation materials are the most economic solution in terms of lifecycle costs. When determining lifecycle costs, heating expenses were taken as a basis for operational costs, as they make up the biggest share of operational expenses. However, when determining the lifecycle costs of the building, the lighting expenses and maintenance and repair costs that constitute a part of the operational costs of the building will reduce the share of lifetime costs accounted for by construction costs, causing discrepancies in the evaluation of lifecycle costs. As the thickness of the insulation material increases, the savings that are achieved in heating costs increase less compared to the increase in insulation material thickness. Looking at the wall body materials used in envelope alternatives providing the thermal comfort required by TS 825, minimum insulation thicknesses are achieved by using gasbeton wall body materials. Gasbeton as a wall body material provides the most effective savings in heating energy compared to other materials, whereas for wall insulation materials, extruded polystyrene foam provides more savings in heating energy compared to rock wool.

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