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The Relationship Between Building Shape and Energy Cost

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Abstract

In the design phase, decisions regarding building shape have a considerable effect on building energy cost. Therefore, this study will analyze the extent to which changes in building shape affect energy cost, and thereby provide pre-design information for future reference for residential buildings with less energy consumption and less environmental pollution. This study investigates the relationship between building shape and energy cost by taking into account thermophysical properties and orientations of external wall alternatives. Building shape is evaluated with external envelope area to the building's gross volume (A/V) ratio and external wall area/floor area (EWA/FA) ratio. 4 building shapes with different external wall area are selected for this study. The maximum and minimum energy costs of each building shapes are calculated on the basis of 14 different envelope and 4 different orientation alternatives taking into consideration the solar gain. The relationship between external wall area/floor area ratio, A/V ratio and building energy cost are determined for separately maximum and minimum energy costs. The increase in energy cost due to changes in building shape reaches up to 24.40%. EWA/FA and A/V ratio of buildings have significant impact on the energy cost.

Keywords

Building shape, Energy cost, Envelope design, Energy efficiency

1. Introduction

Control and management of energy consumption is becoming more and more important due to the rapid depletion of fossil energy resources and the increased environmental problems caused by them. In line with the targets identified under the Kyoto protocol, studies are being undertaken for 20% less energy consumption, 20% less carbon emission and to ensure that 20% of the total energy production is from renewable energy resources by the year of 2020 compared to figures from 1990 (Calis v.d., 2009). The sixth EU Environment Action Programme (Environment, 2010), which aims to improve the quality of life and the environment in European Union (EU) countries, emphasized in its report called 'Our future, our choice' that environmentally friendly measures, including saving energy, should be taken into account when designing buildings (http://ec.europa.eu/environment/air/pdf/6eapbooklet_en.pdf)

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 (Cengel, 1998). Heating accounts for the largest share of energy consumption in the residential and tertiary sectors in Greece (60.9 and 52.5%, respectively) and for an average of 57% of consumption in the EU (Bakos, 2000; Chwieduk, 2003). Therefore, this study will focus only on heating energy costs included within the operating costs of residential buildings.

The design parameters affecting the conservation of energy are location, orientation, building shape, thermophysical and optical features of the building envelope, size, accommodation type, distance between buildings and natural ventilation arrangement (Berkoz et al., 1995). The optical properties of the building envelope are coefficients of absorption, permeability and reflectivity of solar radiation. The thermophysical properties of the building envelope, on the other hand, are total heat permeability coefficient (U(k)) and transparency rate. These properties are determinants of the heat gain and loss from the building envelope unit of area, due to exterior temperature and solar radiation. Therefore, this study investigates the relationship between building shape and energy cost by taking into account thermophysical properties and orientations of external wall alternatives.

2. Relevant Studies

Aksoy and Inalli (2006), for checking the impact of shape on heating demand, express the compactness via the SF shape factor, corresponding to the ratio of the length to the depth of one typical storey of a building, while Bostancioglu (2010), who examines the effect of shape on construction, energy and lifecycle costs by comparing rectangular, H- and star-shaped buildings of the same size, places the emphasis on the ratio of the external wall area (facades) to floor area EWA/FA. However, the A/S ratio of Gonzalo and Habermann(2006) or the A/V ratio of Hegger et al. (2008) are the most widely used relative values for compactness evaluation, implying that, in both cases, it is the ratio of the area of a building's external envelope to its hosted inner volume. This value is described in the paper by Depecker, Menezo, Virgone, and Lepers (2001), where it is referred to as the shape coefficient, while characterizing the relation between the energy consumption and the shape of a building. Ourghi, AlAnzi, and Krarti (2007) provide a simplified analysis method to predict the impact of the shape of an office building on its annual cooling and total energy use. They modified the shape coefficient to express relative compactness (RC), which indicates the relationship between the designed building's shape factor $(A/V)_{building}$ and the minimum shape factor of the rectangular (reference) building of the same volume $(A/V)_{ref}$. Tuhus-Dubrow and Krarti (2010), who present a tool for optimizing a building shape and its envelope features, simplified relative compactness (RC) in the final expression. In both cases, RC shows the deviation of the building's shape from the best (reference) result. ($RC= (A/V)_{building} /(A/V)_{ref}= A_{ref} / A_{building}$).

Parasonis, Keizikas and Kalibatiene considers the effect of architectural volumetric design solutions on the demand for energy and material resources for a building. The size, compactness and geometric efficiency of a building as well as the criteria for their evaluation are considered while performing the comparative analysis of a building's shapes. The method of determining rational values by finding their deviation from the best result is applied. They express the dimensionless ratio A/S may be referred to as 'geometric efficiency', GE (GE=A/S), or the area of building envelope per unit of heated area (Parasonis et al., 2012). In the study of Bekkouche, Benouaz, Cherier, Hamdani, Yaiche and Benamrane, the result proves that proper use of compactness index and building geometry parameters will noticeably minimize building energy and improve the internal temperature of the building. The compactness of a building, indicated by the S/V ratio (S:area of building envelope surface, V: volume of the building) has a considerable influence on the heating energy demand of buildings, regardless of the level of fabric insulation. The compactness is better when the compactness index is lower. (Bekkouche et.al, 2013)

3. Methods and Assumptions

Building shape, properties of building envelope and orientation, which are parameters affecting the development of an energy-efficient environment and conservation of heating energy on building scale, are discussed in this study.

3.1. Determinig the Building Shape

In the studies that evaluated heating energy costs, building shapes were evaluated with A/V, A/S, S/V or EWA/FA ratios. In this study, building shape will be evaluated with A/V (external envelope area to the building's gross volume) ratio and external wall area/floor area (EWA/FA) ratio. 4 building shapes with different external wall area are selected. They have same characteristics and equal height, they are differentiated on the basis of their plan shapes. It is assumed that alternatives to these shapes can be square, rectangular, H- or star-shaped. Buildings and residential units have the approximately same floor area and same characteristics. Windows and doors have the approximately same area. Only the external wall area of the buildings are varied. The building properties are given in Table 1.

Table 1: Building Properties

	building shape (square)	building shape (rectangular)	building shape (star shaped)	building shape (H shaped)
number of stories	5	5	5	5
number of flats	20	20	20	20
storey height (m)	2.70	2.70	2.70	2.70
external wall area (m²) (EWA)	1,080.00	1,125.90	1,314.90	1,501.20
floor area (m^2) (FA)	400.00	400.50	418.90	416.32
external wall area/ floor area (EWA/FA)	2.700	2.811	3.139	3.606
total floor area (m^2)	2,000.00	2,002.50	2,094.50	2,081.60
envelope area (A) (m²)	1,880.00	1,926.90	2,152.70	2,333.84
volume (V) (m³)	5,400.00	5,406.75	5,655.15	5,620.32
A/V	0.348	0.356	0.381	0.415
external wall area 1 (m²) (wall body material)	553.10	573.38	702.83	836.50
window area (m²)	110.50	119.20	124.15	127.40
external door area (m²)	100.80	99.12	99.12	100.80

3.2. Determining the 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 (Karagoz, 2004).

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. The most frequently used thermal insulating materials seem to be fibre and foam materials. Fibre materials should be mineral wools, such as rock wool, glass wool and wood wool. Foam materials should be polystyrene foams and polyurethane foams, such as expanded polystyrene foam (EPS) and extruded polystyrene foam (XPS). Insulating materials to be used on external walls should not negatively affect the structure of the building, and the insulating features should not change in humid conditions. External walls are insulated with four different systems that differ in the location of the thermal insulating materials:
(1) thermal insulation on the external side of the walls (exterior thermal sheathing)
(2) thermal insulation on the internal side of the walls

(3) thermal insulation between two walls (sandwich walls) or
(4) external walls with ventilation (curtain walling system).

With external insulation system 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 in keeping the construction dry at all times. Although the cost of external insulation is higher than other systems, it is the most appropriate method for buildings used over a long period of time, such as housing (Sezer, 2005).

This study takes into consideration not only the building shape but also the building envelope characteristics for heating energy savings and energy-effective environments; however, residential buildings are evaluated only as per their building shape characteristics. 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 energy costs of a building. The materials that can be used in the walls, floors and roofs as specified in Turkish Standard (TS) 825 (TS 825, 2008) are identified. A fixed wooden roof is approved. XPS with a thickness of 4cm is deemed appropriate for use as an insulation material in ground flooring, and 10cm thick glass wool is found appropriate for use in roofs. It is assumed that brick and gasbeton can be used as wall body materials. Different alternatives include the use of XPS, EPS 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. Envelope alternatives of buildings generate by differentiating body and insulation materials in construction compounds are displayed in Table 2. In building alternatives, double-glazed windows with wood casing are used as the transparent component type.

Table 2: Envelope Alternatives

envelope alternative	wall body material	wall insulation material	roof insulation material	ground floor insulation material
t	19 cm brick		10 cm glasswool	4 cm XPS
t10c	19 cm brick		10 cm glasswool	4 cm XPS
t3x10c	19 cm brick	3 cm XPS	10 cm glasswool	4 cm XPS
t4x10c	19 cm brick	4 cm XPS	10 cm glasswool	4 cm XPS
t5e10c	19 cm brick	5cm EPS	10 cm glasswool	4 cm XPS
t5t10c	19 cm brick	5 cm rockwool	10 cm glasswool	4 cm XPS
t5x10c	19 cm brick	5 cm XPS	10 cm glasswool	4 cm XPS
g	19 cm gasbeton			
g10c	19 cm gasbeton		10 cm glasswool	4 cm XPS
g3x10c	19 cm gasbeton	3 cm XPS	10 cm glasswool	4 cm XPS
g4x10c	19 cm gasbeton	4 cm XPS	10 cm glasswool	4 cm XPS
g5t10c	19 cm gasbeton	5 cm rockwool	10 cm glasswool	4 cm XPS
g5e10c	19 cm gasbeton	5cm EPS	10 cm glasswool	4 cm XPS
g5x10c	19 cm gasbeton	5 cm XPS	10 cm glasswool	4 cm XPS

3.3. Calculating the Energy Costs

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. The heating energy demand and annual fuel amounts for project alternatives are calculated for second climate zone, which is a temperate climate zone and which also covers Istanbul. Wall alternatives are checked for the presence of condensation and no condensation is found in these wall alternatives. In order to calculate heating energy costs, “TS 825 Heat Requirement Calculations” computer program is 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 (http://www.izoder.org.tr).

It is assumed that natural gas is consumed in all project alternatives. Calculation of heating energy costs are based on the gas prices applicable for the month of November 2014 in Istanbul (http://www.igdas.com.tr). Annual heating costs are calculated both based on different wall alternatives and also different orientations. Taking into consideration the solar gain of the buildings, annual heating costs are calculated based on each shape and envelope alternative with four different orientations. The window areas based on different directions, considering four different orientations of different shapes are given in Table 3. Heating energy costs that are calculated in TL are changed to $. The exchange rate of $ is taken from Central Bank of the Republic of Turkey (http://www.tcmb.gov.tr).

Table 3: Window Areas Based on Different Directions

	window area (m^2)							
	square	rectangular	star shaped	H shaped	square	rectangular	star shaped	H shaped
	direction 1				direction 2			
north	36.40	53.30	31.20	32.50	35.10	53.30	31.20	37.70
south	35.10	53.30	31.20	37.70	36.40	53.30	31.20	32.50
west	19.50	6.50	30.55	28.60	19.50	6.10	31.20	28.60
east	19.50	6.10	31.20	28.60	19.50	6.50	30.55	28.60
	direction 3				direction 4			
north	19.50	6.10	31.20	28.60	19.50	6.50	30.55	28.60
south	19.50	6.50	30.55	28.60	19.50	6.10	31.20	28.60
west	36.40	53.30	31.20	32.50	35.10	53.30	31.20	37.70
east	35.10	53.30	31.20	37.70	36.40	53.30	31.20	32.50

4. Results and Discussion

The annual energy costs per m^2 of buildings with 4 different building shapes (have different EWA/FA ratio and A/V ratio) are calculated on the basis of 14 different envelope and 4 different orientation alternatives. In Table 4 and Figure 1, buildings with different building shapes (EWA/FA and A/V ratio) and envelope alternatives are compared in terms of minimum annual energy costs per m^2 considering 4 different orientation alternatives. The minimum annual energy costs per m^2 of rectangular (EWA/FA=2.811 and A/V=0.356) with different envelope alternatives are between 1.37% and 3.23 % more than that of the square buildings (EWA/FA=2.700 and A/V=0.348). The minimum annual energy costs per m^2 of star shaped (EWA/FA=3.139 and A/V=0.381) with different envelope alternatives are between 4.02% and 11.93% and the minimum annual energy costs per m^2 of H- shaped (EWA/FA=3.606 and A/V=0.415) with different envelope alternatives are between 8.84% and 24.14% more than that of the square buildings (EWA/FA=2.700 and A/V=0.348).

Table 4: Minimum Annual Energy Costs per m^2 with Different EWA/FA Ratio and A/V Ratio

EWA/ FA	2.700		2.811		3.139		3.606	
A/V	0.348		0.356		0.381		0.415	
	annual energy cost per m^2 ($\$/m^2$)	relative annual energy cost per m^2	annual energy cost per m^2 ($\$/m^2$)	relative annual energy cost per m^2	annual energy cost per m^2 ($\$/m^2$)	relative annual energy cost per m^2	annual energy cost per m^2 ($\$/m^2$)	relative annual energy cost per m^2
t	34.83	100.00	35.63	102.30	37.94	108.93	41.04	117.83
g	31.82	100.00	32.52	102.20	34.24	107.61	36.61	115.05
t10c	25.31	100.00	26.12	103.20	28.33	111.93	31.42	124.14
g10c	22.32	100.00	23.04	103.23	24.74	110.84	27.10	121.42
t3x10c	14.06	100.00	14.30	101.71	14.89	105.90	15.82	112.52
g3x10c	13.41	100.00	13.62	101.57	14.13	105.37	14.86	110.81
t4x10c	13.33	100.00	13.53	101.50	14.05	105.40	14.79	110.95
t5t10c	13.16	100.00	13.35	101.44	13.83	105.09	14.59	110.87
t5e10c	13.16	100.00	13.35	101.44	13.83	105.09	14.59	110.87
g4x10c	12.84	100.00	13.04	101.56	13.45	104.75	14.10	109.81
t5x10c	12.82	100.00	13.00	101.40	13.42	104.68	14.09	109.91
g5t10c	12.73	100.00	12.92	101.49	13.29	104.40	13.91	109.27
g5e10c	12.73	100.00	12.92	101.49	13.29	104.40	13.91	109.27
g5x10c	12.45	100.00	12.62	101.37	12.95	104.02	13.55	108.84

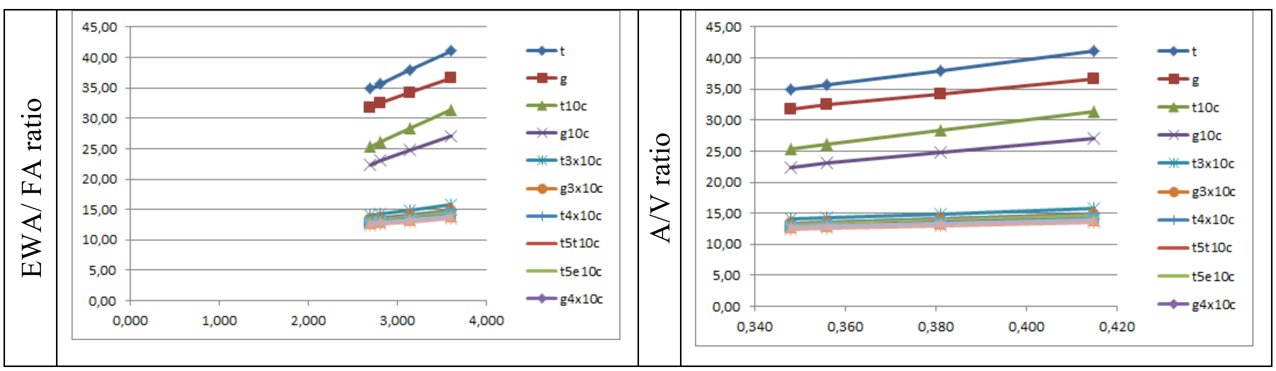

Figure 1: Minimum Annual Energy Costs per m^2 with Different EWA/FA Ratio and A/V Ratio

In Table 5 and Figure 2, buildings with different building shapes (EWA/FA and A/V ratio) and envelope alternatives are compared in terms of maximum annual energy costs per m^2 considering 4 different orientation alternatives. The maximum annual energy costs per m^2 of rectangular (EWA/FA=2.811 and A/V=0.356) with different envelope alternatives are between 1.67% and 3.31 % more than that of the square buildings (EWA/FA=2.700 and A/V=0.348). The maximum annual energy costs per m^2 of star shaped (EWA/FA=3.139 and A/V=0.381) with different envelope alternatives are between 4.01% and 11.88% and the maximum annual energy costs per m^2 of H- shaped (EWA/FA=3.606 and A/V=0.415) with different envelope alternatives are between 9.23% and 24.40% more than that of the square buildings (EWA/FA=2.700 and A/V=0.348).

Table 5: Maximum Annual Energy Costs per m^2 with Different EWA/FA Ratio and A/V Ratio

EWA/ FA	2.700		2.811		3.139		3.606	
A/V	0.348		0.356		0.381		0.415	
	annual energy cost per m^2 (\$/m^2)	relative annual energy cost per m^2	annual energy cost per m^2 (\$/m^2)	relative annual energy cost per m^2	annual energy cost per m^2 (\$/m^2)	relative annual energy cost per m^2	annual energy cost per m^2 (\$/m^2)	relative annual energy cost per m^2
t	34.86	100.00	35.69	102.38	37.95	108.86	41.13	117.99
g	31.85	100.00	32.59	102.32	34.25	107.54	36.70	115.23
t10c	25.33	100.00	26.16	103.28	28.34	111.88	31.51	124.40
g10c	22.36	100.00	23.10	103.31	24.75	110.69	27.16	121.47
t3x10c	14.09	100.00	14.35	101.85	14.90	105.75	15.89	112.78
g3x10c	13.42	100.00	13.69	102.01	14.14	105.37	14.92	111.18
t4x10c	13.35	100.00	13.59	101.80	14.06	105.32	14.86	111.31
t5t10c	13.20	100.00	13.42	101.67	13.84	104.85	14.62	110.76
t5e10c	13.20	100.00	13.42	101.67	13.84	104.85	14.62	110.76
g4x10c	12.88	100.00	13.11	101.79	13.46	104.50	14.18	110.09
t5x10c	12.86	100.00	13.07	101.63	13.43	104.43	14.17	110.19
g5t10c	12.74	100.00	12.97	101.81	13.30	104.40	13.98	109.73
g5e10c	12.74	100.00	12.97	101.81	13.30	104.40	13.98	109.73
g5x10c	12.46	100.00	12.68	101.77	12.96	104.01	13.61	109.23

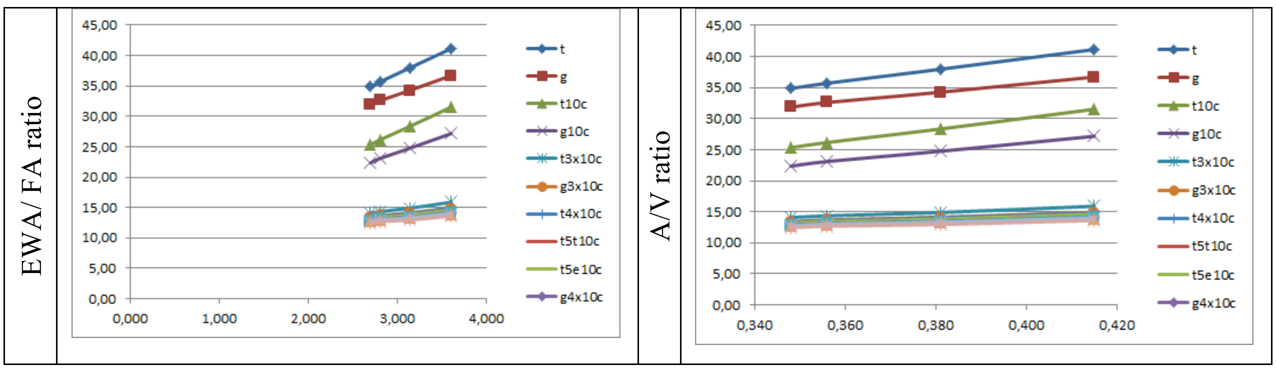

Figure 2: Maximum Annual Energy Costs per m^2 with Different EWA/FA Ratio and A/V Ratio

4. Conclusion

In this study, taking into consideration the building envelope alternative and the solar gain based on orientation; the impact of the decisions made regarding the building shape (EWA/FA and A/V ratio) during the design phase on energy costs are evaluated. The solar gain based on orientation also causes variations in energy cost. However, the cost variations caused by the solar gain is insignificant when compared with the cost variations caused by changes in building shape. The increase in energy cost due to changes in building shape reaches up to 24.40%.

As it can be seen in this study, the building shape has a significant impact on energy cost. The decisions made regarding the EWA/FA and A/V ratio of buildings during the design phase have a very significant impact on the energy cost. When EWA/FA and A/V ratio of buildings increase, energy cost also increases. Thus while decisions are taken it is vital to have the awareness for designing buildings that consume minimum energy and provide the necessary comfort.

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