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A Comparative Case Study of the Impact of Square and Yurt-Shape Buildings on Energy Efficiency

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***Abstract*—**Regions with extreme climate conditions such as Astana city require energy saving measures to increase energy performance of buildings which are responsible for more than 40% of total energy consumption. Identification of optimal building geometry is one of key factors to be considered. Architectural form of a building has impact on space heating and cooling energy use, however the interrelationship between the geometry and resultant energy use is not always readily apparent. This paper presents a comparative case study of two prototypical buildings with compact building shape to assess its impact on energy performance.

***Keywords*—**Building geometry, energy efficiency, heat gain, heat loss.

I. Introduction

BUILDINGS represent the largest energy-consuming sector in the economy, with over 40% of all energy consumed there [1]. Energy-efficient buildings perform a set of architectural, design, and engineering solutions that best meets the requirements of minimizing energy consumption. A special challenge for developers is the regions with more than one contrasting season as it often requires conflicting design solutions [2]. This is especially true for continental climate zone characterized by significant annual variation in temperature, high precipitation and strong wind. The average range of the maximum high and low temperatures could reach from 32 C to -23 C. It means that the building in continental climate must be able to cope with significant variations in temperature, great snow and wind loads, intensive solar radiation, and other external pressures by adopting appropriate design solutions.

The impact of external climate on the heat balance of the building can be optimized through shape selection, space-planning and constructive solutions, efficient building materials technology on heating and ventilation systems regulation, internal heat, heat gain from solar radiation, the location of translucent structures such as windows and doors. The dependency between architectural shape solution of building and energy consumption related to the reference building has been thoroughly studied [3]-[6]. It has been identified that compact buildings account for minimum heat losses and therefore are most desirable to reduce energy need of buildings. In this regard, the aim of this paper is to conduct a comparative case study of two most compact architectural forms of buildings with the same characteristics such as floor area, height, type, schedule, occupancy, and location by differentiating only the building shapes.

The compactness of buildings is measured by its surface-area-to-volume ratio or so-called shape factor. Buildings with lower shape factor are more compact and therefore have a smaller surface area for a given volume. Among all possible geometric shapes the most compact form of building is a sphere because the volume of a sphere can be wrapped with the smallest envelope area. In practice spherical structures are mostly adopted for specialized uses such as auditoriums, observations, and storage facilities. In relation to residential construction it is more common to apply partial-spherical shapes well known as Fuller geodesic domes in Eastern countries. In Central Asia this shape has been widely used for centuries by nomads for design of its traditional collapsible shelter called 'Yurt' (Fig. 1).



Fig. 1 Nomads' potable dwelling Yurt

Although compactness of yurt-shape buildings provides high wind and earthquake resistance, and improved aerodynamic characteristics it is infrequently used in the modern architecture. It is evident that the geometry of the majority of buildings is predominantly rectangular. An American archaeologist Kent Flannery noticed that "rectangular structures replace circular ones through time in many archaeological areas around the world" [7]. The most compact shape with minimum number of corners and right angles is a cube with square shape floor.

Considering the above mentioned this study strives to compare two most compact geometries of buildings, which are square (Building A) and yurt shape (Building B), and its influence on energy performance. Both buildings are designed as one-storey residential houses for rural inhabitants in Astana city, the worlds' second coldest capital city. The climate of Astana is sharply continental with average temperature

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between -4°C and -19°C in January and between +19…+26°C in July. In winter temperature may decrease down to -45°C, and in summer rise up to +30. The heating season/operating period in the region is 216 days. The average temperature of internal and external air during the operating period is +23°C and -8°C respectively. The estimated temperature of external air in winter is -31°C. The average wind speed is 5,9 m/s. Floor plans are shown on Figs. 2 and 3.

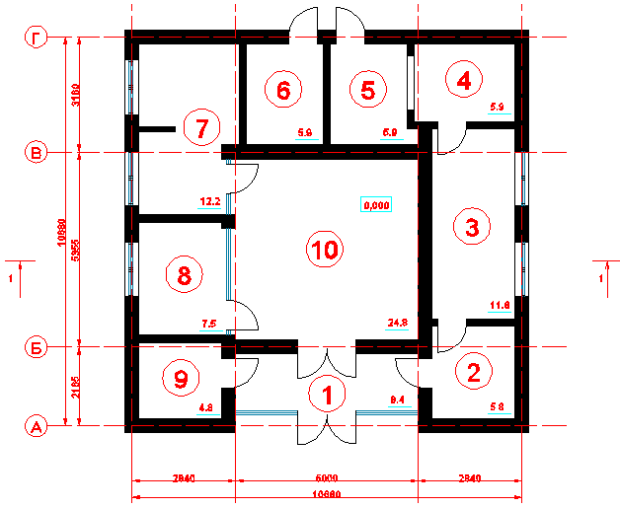


Fig. 2 Floor plan of Building A

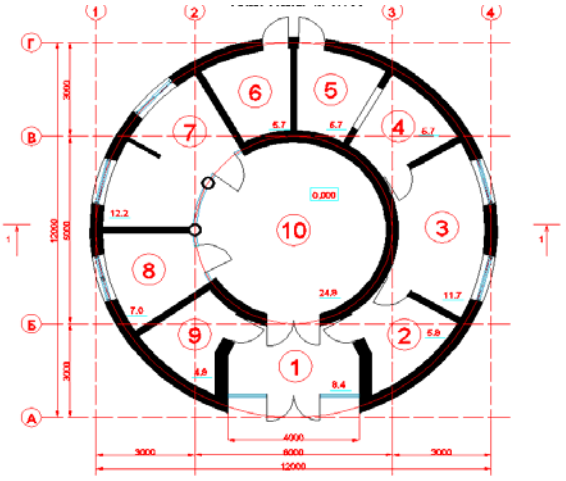


Fig. 3 Floor plan of Building B

This study presents two different approaches to evaluate energy efficiency of the buildings by adopting local building codes and internationally recognized standard. Thus, in the first scenario building materials for the envelope of both buildings satisfy the minimum requirements of building code of Kazakhstan - SN RK 2.04.01-2004 "Thermal Performance of The Buildings" and are based on estimation of thermo-physical properties of building materials; while in the second scenario the building materials meet the requirements of passive house standard.

Passive design is the design of the building's heating, cooling, lighting, and ventilation systems, relying on sunlight, wind, vegetation, and other naturally occurring resources on the building site (Fig. 4). Passive design includes the use of all possible measures to reduce energy consumption prior to the consideration of any external energy sources other than the sun and wind. Randy Croxton, one of the pioneers of contemporary ecological design, describes a good passive design as one tan allows a building to "default to nature". A building that has been designed in a passive sense could be disconnected from its active energy sources and still be reasonably functional due to daylighting, adequate passive heating and cooling, and ventilation being provided by the chimney effect, cross-ventilation, operable windows, and the prevailing winds [8].

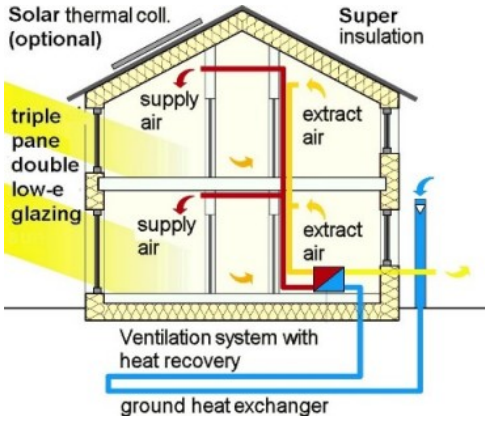


Fig. 4 Passive house

In 1988, Drs. Bo Adamson and Wolfgang Feist published their work showing energy modeling for a new type of energy-efficient building known as passive house, given its name for its "passive method" of heat gain. Following this, the first passive house was built in 1991 by architects Bott, Ridder and Westermeyer in Darmstadt Kranichstein in Germany. A single structure divided into four separate row homes accounting for 1.679 square feet each [9].

Nowadays, passive house is the world leading standard in energy-efficient construction: it requires as little as 10 percent of the energy used by typical central European buildings – meaning an energy savings of up to 90 percent. Owners of passive houses are barely concerned with increasing energy prices. The technical definition of a passive house according to the Darmstadt criteria encompasses the following central properties:

- Annual heat demand not more than 15 kWh/m^2 with peak heat load not more than 10 W/m^2
- Cooling demand not more than 15 kWh/ m^2 with Peak cooling load not more than 8 W/m^2
- Primary energy demand not more than 120 kWh/m^2

Considering the information mentioned above input data of both buildings are given in Table I.

II. Methodology

The energy performance analysis is based on the comparison of energy need for seasonal heating and cooling

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values of two prototypical buildings. Different analysis methods are used for predicting the impact of the shape on the total energy use. Ourghi et al. introduced a simplified tool that correlates the annual energy use to the relative compactness of buildings and is limited to rectangular and L-shape buildings [10]. AlAnzi et al. extended this methods to include T-shape, cross-shape, H-shape, U-shape, and cut-shape geometries, as well as window areas and glazing types [11]. Wang et al presented a methodology of floor plan shape optimization through genetic algorithm [12]. Peippo et al. developed a numerical multivariate optimization procedure to draft the optimum building design variables [13].

TABLE I
BUILDINGS' PARAMETERS

	Parameters	Building A	Building B
General parameters	total height	6,3 m	6,3 m
	floor height	3,0 m	3,0 m
	floors number	1	1
	floor area	87,0 m^2	87,0 m^2
	heated floor area	55 m^2	73,0 m^2
	heated volume	165 m^3	219,0 m^3
	estimated number of occupants	5	5
Geometrical parameters	external walls	100,0 m^2	78,0 m^2
	floor	113,0 m^2	113,0 m^2
	windows	11,0 m^2	11.0 m^2
	doors	12,0 m^2	12,0 m^2
Thermal resistance (R-value) local building codes	external walls	3,6 m^{2o}C/ W	3.6 m^{2o}C/ W
	floor	4,7 m^{2o}C/ W	5,34 m^{2o}C/ W
	windows	0,6 m^{2o}C/ W τ=0,8; k=0,68	0,62 m^{2o}C/ W τ=0,8; k=0,68
	doors	1,0 m^{2o}C/ W	0,97 m^{2o}C/ W
Thermal resistance (R-value) passive house standard	external walls	10,0 m^{2o}C/ W	10,0 m^{2o}C/ W
	floor	10,0 m^{2o}C/ W	10,0 m^{2o}C/ W
	windows	1,2 m^{2o}C/ W	1,2 m^{2o}C/ W
	doors	1,2 m^{2o}C/ W	1,2 m^{2o}C/ W

This study adopts the methodology presented in the manual on heat consumption calculation for existing residential building [14] adopted by CIS countries in 2007 which provides mathematical algorithms for energy use prediction and not limited to particular building shapes. According to 14 the total energy need Q_k^y is identified by:

$$Q_k^y = [Q_{tr}^y + Q_{inf}^y - (Q_{int}^y + Q_s^y)v\zeta\,]\beta_k, \quad (1)$$

where Q_{tr}^y - seasonal heat loss through the envelope (kWh), Q_{inf}^y - seasonal heat loss through air infiltration (kWh), Q_{int}^y - seasonal heat gain (kWh), Q_s^y – internal heat gain through windows and solar radiation (kWh), v - heat gain/heat loss factor (v = 0.8), ζ – automatic control systems efficiency factor, β_k – additional energy demand for heating factor associated with heat loss through heating systems and equipment.

Heat loss through the envelope is calculated by:

$$Q_{tr}^y = 0{,}024 D_d \sum_i \frac{1}{R_i} A_k n, \quad (2)$$

where D_d–heating degree days (°C·day), R_i-thermal resistivity (m^2K/W), A_k = area of exposed surface (m^2), n - adjusting coefficient reflecting the dependence of the external surface of walling in relation to the outside air.

Heat loss via air infiltration is obtained by:

$$Q_{inf}^y = 6{,}7 * 10^{-3}(L_v K_v + L_{vo}) C_v P_a^{inf} D_d, \quad (3)$$

where L_v - air change rate (m^3/h), K_v –coefficient of additional air infiltration through the entrance hall, staircase and elevator, as well as infiltration, exceeding the regulatory air circulation in apartments with low tightness of windows (resistance to air permeability of less than 0.9 m^2 · h/kg where ΔP = 10 Pa), L_{vo} – air change rate for embedded units (m^3/h), C_v – specific heat capacity (kJ/kg °C), P_a^{inf} – density of infiltrated air (kg/m^3).

Internal heat gain is identified by:

$$Q_{int}^y = 0{,}024 q_{int} z_{int} A_r, \quad (4)$$

where q_{int}- internal heat gain (W/ m^2), A_r- area of living rooms (m^2).

Heat gain through windows and solar radiation is calculated by:

$$Q_s^y = T_F K_F \sum_{K-1}^{8} A_{F.K}\, I_K, \quad (5)$$

where T_F - relative penetration of solar radiation through the light-transmitting windows factor, K_F – shading factor, $A_{F.K}$ – area of windows (m^2), I_K - average intensity of solar radiation on a vertical surface during the heating period (kWh/ m^2).

Energy consumption per square meter is defined by:

$$q_k^y = \frac{Q_k^y}{A_k} \quad (6)$$

III. KEY FINDINGS

Based on the methodology described above, energy loss and gain values of both prototypical buildings have been identified. The summarized results are shown in the Tables II and III.

TABLE II
HEAT LOSS AND GAIN RESULTS FOR LOCAL BUILDING CODES

Parameters	Building A	Building B
Heat loss through the envelope, Q_{tr}^y	16 650 kWh	14 352 kWh
Heat loss via air infiltration, Q_{inf}^y	22 918 kWh	21 319 kWh
Internal heat gain, Q_{int}^y	6 433 kWh	6 433 kWh
Heat gain through windows and solar radiation, Q_s^y	5 812 kWh	5 812 kWh
Total energy need Q_k^y	30 328 kWh	23 425 kWh
Energy consumption per square meter, q_k^y	350 kWh/m^2	270 kWh/m^2

According to Table II, Building A loses 13,8% more heat through envelope and 7% through air infiltration than Building B. This is caused by geometrical thermal bridges which usually arise at the junction of two planes such as corners of the walls and cannot be avoided in rectangular shape building which have at least four corners. Building B has no corners;

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however heat leaking still takes place because in both cases most heat loss occurs through discontinuities and gaps in the insulation material which admits accidental introduction of outside air into the building - infiltration. The similar trend is observed in Table III with 11,7% and 6,5% less energy loss through the envelope and through infiltration respectfully; however the total amount of heat loss is more than twice less. Passive house standard has stricter requirements for thermal insulation than building codes in Kazakhstan. As seen in Table I, thermal resistance of building elements are 2-2,5 times higher in passive house standard.

TABLE III
HEAT LOSS AND GAIN RESULTS FOR PASSIVE HOUSE STANDARD

Parameters	Building A	Building B
Heat loss through the envelope, Q_{tr}^{y}	8 530 kWh	7 526 kWh
Heat loss via air infiltration, Q_{inf}^{y}	9 109 kWh	8 514 kWh
Internal heat gain, Q_{int}^{y}	6 433 kWh	6 433 kWh
Heat gain through windows and solar radiation, Q_{s}^{y}	3 270 kWh	3 270 kWh
Total energy need Q_{k}^{y}	8 809 kWh	6 377 kWh
Energy consumption per square meter, q_{k}^{y}	100 kWh/m^2	73 kWh/m^2

Since the identical input parameters have been used for Building A and Building B with the same number of occupants, lighting, electric appliances, and windows and doors characteristics, and its orientation, the resulted values of internal heat gain as well as heat gain through window and solar radiation came out similar for both buildings. The only difference is noticed when comparing solar radiation through windows for local codes and passive house standard, when light transmission of passive windows is twice higher than conventional window. According to the requirements of passive house standard glazing should have a high total solar transmittance (g-value) of at least 50% making a net heat gain possible during the winter. The windows must be airtight and the spacers in the glass seal edge must be thermally separated.

As for the total energy need in both scenarios Building B saves 23-27% more energy for heating and cooling than Building A; wherein both buildings show significant improvement of energy efficiency when adopting passive house standard with 3,5 times less total energy required. It should be noted that both buildings have met the requirements set by passive house standard on the primary energy demand when the total energy to be used for all domestic applications including heating, hot water and domestic electricity must not exceed 120 kWh per square meter of treated floor area per year.

IV. CONCLUSION

This article sets out a study on the link between the building shape and their energy consumption. The study has determined that:

1. A yurt-shape building is more energy efficient as it requires 23-27% less total energy for heating and cooling than rectangular shape building;
2. Internal heat gain and amount of solar radiation through transparent elements are not affected by the building shape;
3. Adoption of passive house standard for the buildings regardless the geometry improve energy performance in 3,5 times compared to local building codes.

To extend this research the next step is to carry out an in-depth analysis of energy performance of buildings using computer simulation tools such as TAS Engineering or IES VE to assess the link between the building geometry and energy need in different orientations, applying different building materials, and engineering systems. More standards could be used in addition to local building codes and passive house standard, such as American LEED, British BREEAM or German DGNB rating systems for green building design.

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