JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730 print/ISSN 1822-3605 online
2012 Volume 18(1): 71–80
doi.org/10.3846/13923730.2011.652983

ARCHITECTURAL SOLUTIONS TO INCREASE THE ENERGY EFFICIENCY OF BUILDINGS

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Received 10 Jun. 2011; accepted 17 Oct. 2011

Abstract. While designing the volume of a building, architectural solutions can be employed to achieve greater energy efficiency for the entire lifecycle of the building. However, currently this possibility is not sufficiently utilised. The paper provides a comparative analysis of architectural solutions, presenting the ones that not only allow for a reduction in energy losses through the external envelope of a building considering the local climatic conditions; but also make it possible to increase the use of energy from renewable resources.

Keywords: A/S ratio, A/V ratio, building lifecycle, compactness, energy demand, energy efficiency, geometric efficiency, solar gains, sustainability.

1. Introduction

Efficient energy resource utilisation during the lifecycle of a building is in part determined by the use of rational architectural and layout measures at the time of planning the building volume. Givoni (1981) mentions that the ability of a building to save energy – aside from thermodynamic and heat retention qualities of materials – depends on its shape, orientation, layout of transparent envelopes, size, measures of protection from the sun, and the facade colour. Parasonis and Keizikas (2010) note that manipulation of the shape of the building alters its energy use value, even though the physical characteristics of the envelopes remain unchanged (assessed according to the building technical regulation STR 2.01.09:2005 (2005)). That means that this factor influences the energy demand of buildings.

Energy efficiency is one of the most essential aspects of the sustainability of buildings. The energy efficiency potential of buildings, which depends on the chosen architectural and layout solutions, can be assessed using various building energy efficiency methodologies, including national ones such as STR 2.01.09:2005 (2005) under EN 15217:2007 (2007); international ones such as the "passive" home certification system (Schnieders 2003); the LEED, DGNB, and BREEAM rating systems, and others (Ruckert *et al.* 2010a). According to the EBPD strategy, by the year 2020, their requirements will have to approach the nearly zero energy building standard (Directive 2010/31/EU 2010; Marszal *et al*. 2011). For this reason, the search for measures that allow for savings of materials, energy, and financial resources in the long-term outlook of the lifecycle of buildings is a relevant problem.

These goals are pursued by implementing the LONGLIFE energy efficient multiunit residential housing project for climatic conditions of the Baltic States according to the Baltic Sea Region Programme 2007–2013 (Ruckert *et al*. 2010b), with Vilnius Gediminas Technical University as one of the project partners representing Lithuania. During implementation of the project, most of the attention is devoted to saving natural energy resources and financial resources throughout all of the stages of the building lifecycle. It is planned that the annual energy demand of a LONGLIFE building will not exceed 40 kWh per unit of heated area, not including the energy used by domestic electric appliances. This type of multiunit building will draw 30% of its energy needs from renewable resources in 2012, nearly 100% excluding the energy used by domestic appliances by 2020, and all energy including that used by domestic appliances by 2050 (Ruckert *et al*. 2010a).

Within the framework of the aforementioned project, the paper presents the influence of the studied architectural and layout measures (compactness, building shape, and transparent and opaque external envelope combinations) on energy efficiency of a building. Besides, measures seeking to minimise energy loss, where applicable, as well as maximise its gains (based on the land lot and the conditions of the local environment) under Lithuanian climatic conditions are proposed.

2. The influence of architectural and layout solutions on the energy balance of a building

Compactness – an ability of a building volume to fit as much useful area into the external envelope (the totality of external walls, windows, roof and lower heated floor areas) as possible – is one of architectural and layout characteristics of a building.

During the construction and demolition stages, the utility of compactness is direct, as it determines quantitative needs of construction materials and thus the energy needs for their extraction, processing, transporting, construction, demolition, and recycling. Besides, buildings that have a smaller external envelope area but fit the same heated area will have less wasted energy, which is relevant during the operation stage.

In scientific sources, compactness is assessed and its limit state (the most compact result of a building) is determined in various ways. To express compactness, Aksoy and Inalli (2006) use the Shape Factor (*SF*), which is equal to the proportion of a building's length to its width. Bostancioglu (2010) uses the ratio of external wall area to floor area (*EWA/FA*). Both *A/S ratio*, used by Gonzalo and Habermann (2002), and *A/V ratio*, applied by Hegger *et al.* (2008), determine the proportion of the area of a building envelope to its volume. This ratio is described by Depecker *et al.* (2001), who refers to it as the shape coefficient. Ourghi *et al.* (2007) and Tuhus-Dubrow and Krarti (2010) propose using the relative compactness (*RC*) coefficient, which reflects the ratio between the shape coefficient of a designed building (*A/V*) and the minimal shape coefficient of a rectangular building (reference building) with an equal volume $(A/V)_{ref}$ (where *A* represents the area of the external envelope and *V* represents the volume of a building) and shows the deviation of the shape of a building from the optimal compactness result:

$$RC = \frac{(A/V)_{building}}{(A/V)_{ref}} = \frac{A_{ref}}{A_{building}}. \quad (1)$$

However, buildings with identical shapes and volumes can differ in both their layout solutions and the number of storeys, thereby containing different useful (heated) areas. *RC* does not identify that within the same casing, a building with a greater number of square metres will be characterised by greater rationality and superior energy efficiency.

We propose several improvements to the Eq. (1): rather than using *A/V*, it would be much more appropriate to express compactness by the *A/S* ratio with the area of the external envelope of a building (*A*) and the useful (heated) area (*S*), showing how efficiently geometry of the building is utilised. We propose that the non-dimensional *A/S* ratio can be referred to as the concept of "geometric efficiency" (*GE*).

In comparison with *A/V* ratio, *GE* values in Fig. 1 demonstrate that the best results are achieved with more compact and larger volumes.

With a significantly larger area, non-compact buildings achieve *GE* values that are analogous to those of compact buildings. This means that both compact and non-compact buildings can have the same *GE* values. For this reason, when comparing buildings, we propose using the modified *RC* ratio, which is *RGE*:

$$RGE = \frac{(A/S)}{(A/S)_{ref}} = \frac{GE}{GE_{ref}}, \quad (2)$$

where: $GE_{ref} = (A/S)_{ref}$ is the limit (reference) expression of geometric efficiency that is the closest to a cubic building (reference building) that accommodates a given area; *RGE* shows how far *GE* of a designed building deviates from the GE_{ref} value of the reference building.

3. Limit states of proportions of a building

In this section, a method is proposed for determining the limit states of proportions of a building in search of the most energy efficient solution for the volume of a building, considering the local climatic conditions.

The benchmark GE_{ref} – which is the limit state of a building with the smallest external envelope area – is determined by solving the envelope surface area optimisation problem (Zilinskas 2005). In our case, we have the total heated area of the building *S* and the desired floor height *h* (multiplication of which would result in the volume *V*). For the purpose of calculations, the assumption was made that the design of the building is cube-shaped, as sides of equal length cover the smallest area. Fig. 2 presents a simplified reference building model.

Mathematically, the external envelope area minimisation problem is expressed as follows:

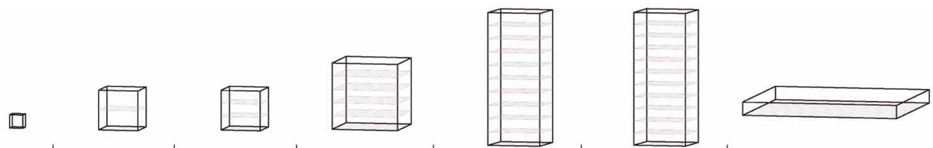
$$\min_X A(X),\ X = \{x_i,\ i = 1, 2, 3\},\ x_i > 0. \quad (3)$$

Vector $X = \{x_i, i = 1, 2, 3\}$ represents dimensions of the building: width, length, and height. The objective function (envelope area) of the problem looks like this:

$$A(X) = 2x_1 + 2x_1x_2 + 2x_2x_3, \quad (4)$$

while the permissible range *V* (the building volume, known size) is expressed in the following way:

$$V = \{\prod_{i=1}^{3} x_i,\ x_i > 0, x_3 = hn,\ n \in N\}. \quad (5)$$



Dimensions: length / width / height, m	3 / 3 / 3	9 / 9 / 9	9 / 9 / 9	15 / 15 / 15	12 / 12 / 30	12 / 12 / 30	33.54 / 33.54 / 3
Number of levels (n)	1	2	3	5	10	11	1
External envelope area (A), m²	54	486	486	1350	1728	1728	2652.5
Internal (heated) area (S), m²	9	162	243	1125	1440	1584	1125
Internal volume (V), m³	27	729	729	3375	4320	4320	3374.8
A/V ratio, 1/m	2	0.667	0.667	0.4	0.4	0.4	0.786
Geometric efficiency (GE=A/S)	6	3	2	1.2	1.2	1.09	2.36

Fig. 1. *A/V* ratio and *GE* values of various orthogonal volumes of different sizes, shapes and number of levels

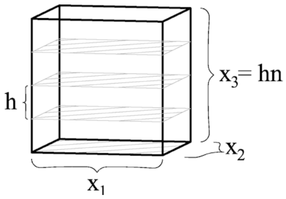


Fig. 2. Simplified model of internal volume of a building: x_1 – length; x_2 – width; x_3 – height; h – storey height; n – number of storeys

The minimisation of the external envelope area can be applied to volumes of various shapes, for example a cylinder or regular polygons. According to Tuhus-Dubrow and Krarti (2010), compact rectangular and regular polygon-shaped building volumes have optimal solutions under all climatic conditions. Their geometric efficiency value can be greater than that of a cube, but volumes of non-rectangular and curvilinear surface buildings have drawbacks in practical application. Thus, as a basis for the establishment of geometric efficiency, a limitary cubic volume is accepted as a reference shape.

Compactness is not the only volume/layout measure influencing energy needs. AlAnzi *et al*. (2009) indicates that the influence of a shape is important in the relationship between the area of windows and their solar transmittance abilities. This proposition is supported by Wang *et al*. (2006), Jedrzejuk and Marks (2002), Caldas and Norford (2002), which present algorithms for finding the optimal polygon shape of a building based on criteria of losses, gains, transparent and opaque external envelope area combinations, orientation, and climatic conditions. This proposition can be tested by determining the limitary building volume solution that retains the most gains and comparing it to the limit state of the reference building, given a fixed ratio of window and wall areas within the facades.

During the heating season, the flow of energy in opaque envelope elements moves from the facility to the exterior, while their function is to minimise this flow. Meanwhile, in transparent envelopes, the energy exchange process is bidirectional: windows both lose heat due to conduction and provide a possibility of reclaiming solar energy from the environment. When window energy gains begin exceeding heat transmittance losses, a greater window area provides the potential to reclaim more solar energy and decrease heating energy demand.

To maximise gains, the opposite problem is to be solved – the maximisation of the external envelope through which the greatest quantity of solar energy is reclaimed. Here, the facade orientation, gains, quantity, and thermal properties of transparent and opaque envelopes are expressed through the facade influence coefficient EF_i, which is introduced into the envelope maximisation problem. The general expression of the problem looks like this:

$$\max_X AF(X),\ X = \{x_i,\ i = 1,\ 2,\ 3\},\ x_i > 0. \quad (6)$$

Vector $X = \{x_i,\ i = 1, 2, 3\}$ represents dimensions of the building: width, length and height. The objective function of the task AF (the facade area) looks like this:

$$AF(X) = 2x_1x_3(EF_1 + EF_3) + 2x_2x_3(EF_2 + EF_4), \quad (7)$$

where: EF_1 and EF_3 as well as EF_2 and EF_4 are the influence coefficients of the opposite facades of a rectangular building, reflecting the maximum values of their gains according to their orientation.

The permissible range of the problem V (volume) remains analogous to the one expressed in Eq. (5).

The establishment of EF_i, where i indicates the orientation direction, relies on the energy balance maximisation of the facades according to their orientation *max* EF_i, where:

$$EF_i = Q_i^{wall} \times AC_i^{wall} + Q_i^{window} \times AC_i^{window},\ i = 1...8. \quad (8)$$

For equality, the following constraints are applied:

$$AC_i^{wall} \in [0;1];\ AC_i^{window} \in [0;1];\ AC_i^{wall} + AC_i^{window} = 1, \quad (9)$$

where: Q_i represents the energy balance of a facade element oriented towards direction i during the heating season; AC_i represents the area coefficient, indicating the part of the total facade covered with transparent or opaque elements.

For an accurate comparison of maximised and minimised volume limit states, identical EF coefficients must be applied to facades oriented towards a given direction. Calculated under these conditions, the energy efficiency of buildings will show the rationality of deviation of the volume from the reference proportions.

To save energy and material resources, it is useful to compare the external envelope minimisation with maximisation possibilities in the context of energy losses experienced during every stage of the lifecycle of a building. That would help avoiding inaccuracies related to the nature of energy losses predominant in various locations. For example, in northern regions energy resources are used to heat buildings, while in southern regions they are devoted to cooling. That is also reflected in the volumetric solutions of buildings. Ourghi *et al*. (2007) shows that a compact shape of a building (similar to the reference building) in southern regions is more efficient. The most suitable type for Lithuanian climatic conditions becomes clear after performing calculations according to the presented methodology.

4. Case study

4.1. Determination of the reference building

Based on climatic conditions predominant in Lithuania, a multiunit residential building with a planned heated area S of 900 m^2 (which includes the area occupied by internal walls but not the area occupied by external envelope elements) is being considered.

When the height of a storey h is equal to 3.2 m (from the floor of one storey to the floor of the next storey), the building volume V is equal to 2880 m^3. For this volume, the geometric efficiency GE_{ref} of the reference building $House_{ref}$ is calculated. To solve the optimisation task, the Microsoft Office Excel *what-if* analysis *Solver* tool (which finds the optimal value of a target cell by changing values in cells applied to calculate the target cell) is used. The given result is GE_{ref} = 1.353 and the optimal number of floors n of $House_{ref}$ is equal to 4.

Table 1. Climate. Mean monthly outside air temperature and daily solar radiation flux density for Kaunas, Noreikiskes (RSN 156-94 (1995))

			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.	Mean temperature, °C		–5.2	–4.3	–0.3	6	12.8	16.2	16.9	16.4	11.9	7.1	1.8	–2.3
Daily flux density, W/m^2:	2.	South	42.2	72.8	123.7	119.2	131.6	136.9	127.5	127.7	117.2	71.6	31.4	28.7
	3.	South-west	35.2	64.1	112	113.3	134.8	146.1	133	128.6	105.4	37	25.5	23.5
	4.	West	20.6	44.7	84.5	93.5	123.3	142.1	127.5	109.3	78.9	38	14.7	12.7
	5.	North-west	15.7	33.3	59.7	70.1	97.2	117.4	105.9	85.4	54.8	25.6	10.7	9.5
	6.	North	15.6	32.4	52.7	56.9	84.4	97.8	88.7	67.9	45.3	23.7	10.5	9.5
	7.	North-east	15.7	33.3	59.3	70.8	105.3	121.3	109.1	87.3	54.7	25.8	10.6	9.5
	8.	East	19.9	42.7	81.7	97.9	133.7	150	134	113.9	81.8	39.8	14.8	12.5
	9.	South-east	34	61.1	109.7	118.4	139	152.7	137.3	128.6	107.3	61.6	24.9	22.9

4.2. The climate data and characteristics of envelope elements

Comparing buildings of different compactness, it is necessary to analyse the potential of the transparent and opaque elements of the external envelope, which determine their efficiency, both admitting solar gains and limiting heat losses, depending on the local climatic conditions. In search for the most efficient internal solution, which is subject to the orientation of a building, this potential determines the proportion of rational quantities of walls and windows.

RSN 156-94 "Construction Climatology" (1995) provides the most data for the vicinity of Kaunas, which geographically corresponds to the centre of Lithuania. The climate data of this city are used in subsequent calculations and are presented in Table 1.

In this study, thermal characteristics of walls and windows are used, values of which range from the minimum requirements spelled out in Lithuanian regulations STR 2.05.01:2005 (2005) to the maximum declared values of envelope elements available on the market. These are presented in Table 2.

Table 2. Characteristics of different envelope elements

Envelope element	Wall				Window			
	1	2	3	4	5	6	7	8
Heat transfer coef., W/m^{2}K	0.2	0.16	0.12	0.1	1.6	1.35	0.94	0.73
Solar heat gain coef.	0	0	0	0	0.61	0.61	0.49	0.49

Below (Figs 3 and 4), graphic representation of heat gain and loss balances for external envelope elements with various orientations are presented. These are determined based on STR 2.09.04:2008 "Capacity of the Building Heating System. Heat Needed for Heating Purposes" (2008). The total balance of each element during the heating season subject to their orientations is presented in Table 3.

During the warm part of the year (differently than during the heating season) the internal temperature of buildings is not regulated. Thus, heat losses through the building envelopes are not evaluated during this period of time.

These calculations are based on assumptions that the installation of external envelope elements was performed so as to avoid leaks and linear thermal bridges. These losses are not included in the balance calculations. It is also assumed that windows are not going to be opened during the heating season; it is intended that a mechanical ventilation system with heat recovery will help avoiding natural ventilation losses. However, conditioning systems in multi-storey apartment houses are not considered necessary during summertime if external shading systems are applied to openings and the cooling of internal spaces is performed by natural ventilation as needed. Climatic data confirm that the temperature during the hottest month in Kaunas is 17.7 °C and the absolute temperature maximum does not reach 35 degrees (RSN 156-94 1995). This means that it is possible to avoid both the expenditure for installation and maintenance of conditioning systems and the loss of energy and other related resources during the operation stage of the building.

Table 3. Heating season energy balance (kWh) per area of 1m^2 of envelope elements oriented toward various directions

Envelope element	Direction							
	South, Q_1	East, Q_2	North, Q_3	West, Q_4	South-east, Q_5	North-east, Q_6	North-west, Q_7	South-west, Q_8
1. (wall–1)	–19.92	–19.92	–20.91	–19.92	–19.92	–20.91	–20.91	–19.92
2. (wall–2)	–15.93	–15.93	–16.72	–15.93	–15.93	–16.72	–16.72	–15.93
3. (wall–3)	–11.94	–11.94	–12.54	–11.94	–11.94	–12.54	–12.54	–11.94
4. (wall–4)	–9.95	–9.95	–10.46	–9.95	–9.95	–10.46	–10.46	–9.95
5. (window–5)	14.15	–49.81	–96.09	–50.05	–6.05	–79.72	–79.87	–14.09
6. (window–6)	39.03	–24.93	–69.96	–25.17	18.84	–54.83	–54.96	9.84
7. (window–7)	45.73	–5.63	–41.1	–5.83	29.51	–29.67	–29.79	23.06
8. (window–8)	66.65	15.26	–19.15	15.07	50.42	–8.76	–8.87	43.95

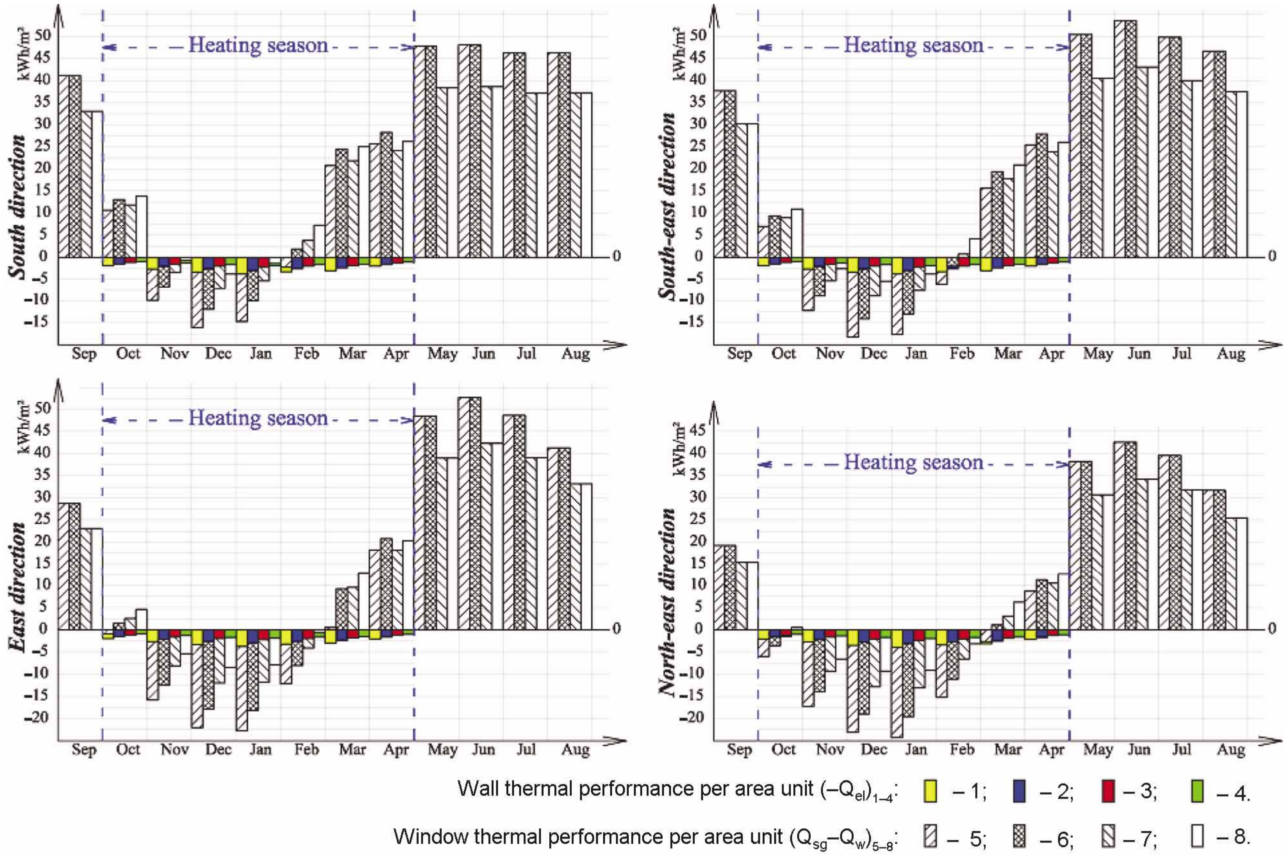


Fig. 3. Representation of the energy balance of windows and walls per area of 1 m^2 oriented to S, S-E, E, N-E: Q_{sg} – solar gains per window area unit; Q_w – heat losses per window area unit; Q_{el} – heat losses per wall area unit

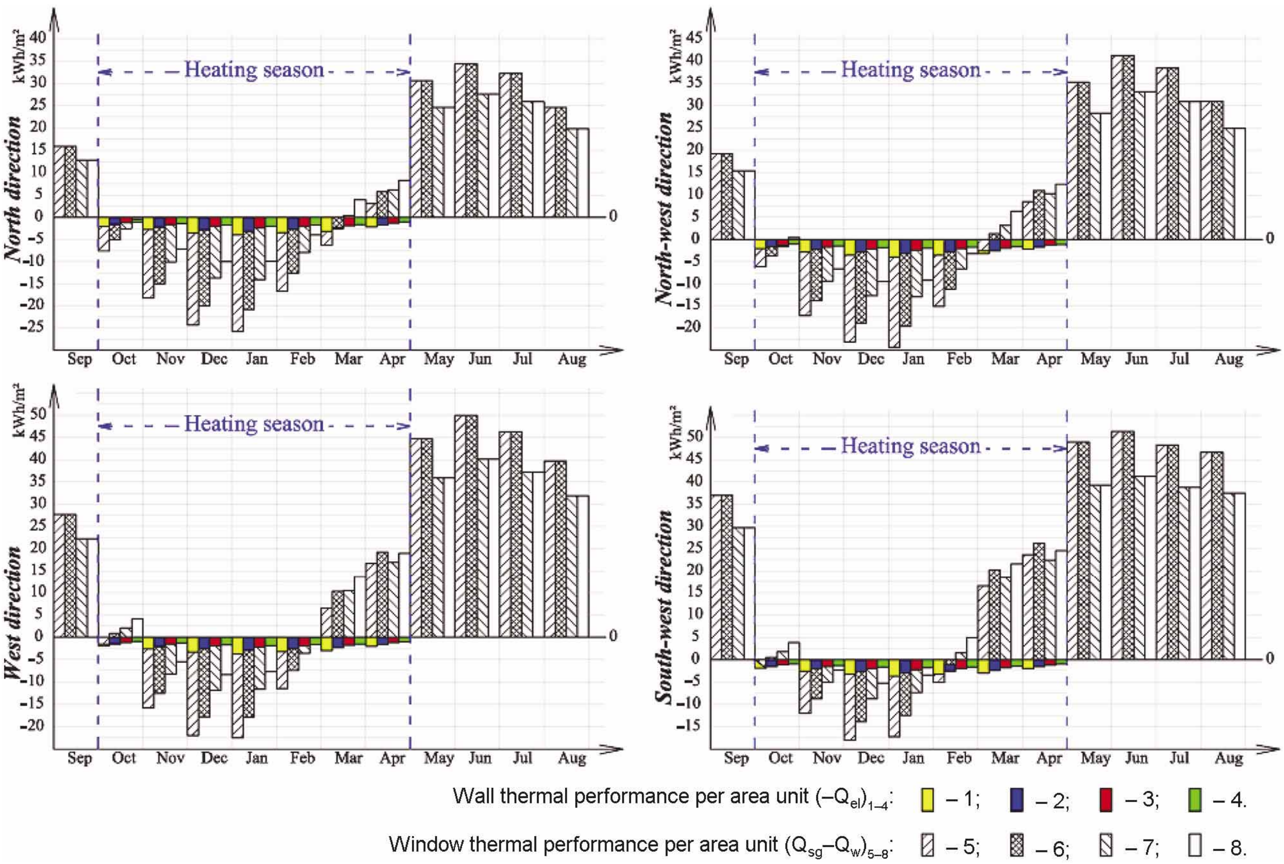


Fig. 4. Representation of the energy balance of windows and walls per area of 1 m^2 oriented to N, N-W, W, S-W: Q_{sg} – solar gains per window area unit; Q_w – heat losses per window area unit; Q_{el} – heat losses per wall area unit

The data presented in Table 3 provide a possibility of choosing a quantity- and quality-wise efficient combination of transparent and opaque envelope elements for the operation stage of a building, subject to their orientation. The results confirm the following: under Lithuanian climatic conditions, a window meeting the minimum normative requirements (window–5) facing south demonstrates better energy balance during the heating season than the most efficient wall solution (wall–4); the most efficient window solution (window–8) in all other directions except for north demonstrates a better energy balance during the heating season than the best wall solution (wall–4); and the most efficient window solution (window–8) in every direction is more efficient than the wall solution meeting the minimum normative thermal requirements (wall–1).

4.3. Determination of the most efficient shape of a building

On this basis, the search for the building shape solution that reclaims the most energy during the operation stage of a building is performed. To that end, the most efficient external elements – window (window–8) and wall (wall–4) – are used, while in the first case the facades are turned toward the cardinal directions (S-E-N-W) and in the second case – toward the intercardinal directions (SE-NE-NW-SW). Because constraints on the number of floors can be applied to a multiunit residential building (e.g. a land lot has a limitation in maximal building height, such as $n = 4$), as part of the study, two building volume searches are conducted, of which one plans for this constraint.

Seeking for a study that is closer to realistic conditions, additional constraints are imposed on external envelopes of the building volume that correspond to requirements of structure installation and normative facility insulation (STR2.02.01:2004 (2004)): the total transparent area of the building envelope is set to be no less than 1/6 of the total area of the heated building; the total area of windows is allowed to vary between 10–70% compared to the area of the entire facade, and the minimum length of the edges of the building is limited to 9.5 metres.

These data allow delineating values of the facade weight coefficient EF_i required for external envelope maximisation when oriented toward different points of the compass. When the window efficiency is greater than that of the wall, it is granted the maximum limitary area intended for windows; when the wall efficiency within a facade is greater, the area of this envelope component is maximised accordingly, with the aforementioned conditions satisfied. The *EF* values are presented in Table 4.

Table 4. A representation of EF_i influence coefficients

	South		East		North		West	
	Area coeff.	Balance Q_1	Area coeff.	Balance Q_2	Area coeff.	Balance Q_3	Area coeff.	Balance Q_4
Wall–4	0.3	–9.95	0.3	–9.95	0.9	–10.46	0.3	–9.95
Window–8	0.7	66.65	0.7	15.26	0.1	–19.15	0.7	15.07
EF$_i$	***43.67***		***7.697***		***–11.329***		***7.564***	

	South-east		North-east		North-west		South-west	
	Area coeff.	Balance Q_5	Area coeff.	Balance Q_6	Area coeff.	Balance Q_7	Area coeff.	Balance Q_8
Wall–4	0.3	–9.95	0.3	–10.46	0.3	–10.46	0.3	–9.95
Window–8	0.7	50.42	0.7	–8.76	0.7	–8.87	0.7	43.95
EF$_i$	***32.309***		***–9.27***		***–9.347***		***27.78***	

To determine the limits of the building volume dimensions that have the potential to attract the maximum quantity of solar energy gains, the *what-if* analysis with Microsoft Office Excel *Solver* tool is used. Based on the constraints presented and the data from Table 4, it determined proportions of the building both with unlimited height (*House 1*) and with a height of $n = 4$ (*House 2*). The achieved limitary building proportions are the same in both cases, i.e. when oriented toward S-E-N-W as well as SE-NE-NW-SW. The results in comparison with the reference building ($House_{ref}$) are presented in Table 5.

Energy balances influenced by building shape and external envelope components are presented in Table 6. To facilitate comparison, analogous distributions of transparent and opaque envelopes in the facades are applied to $House_{ref}$.

Under Lithuanian climatic conditions, in comparison to $House_{ref}$, the potential gains of the building oriented toward the cardinal directions (*House 1*) are 13984.97 – 9139.58 = 4845.39 kWh or 5.4 kWh/(m^{2}year) greater; while those of *House* 2 are 3632.15 kWh or 4 kWh/(m^{2}year) greater. Buildings oriented toward the intercardinal directions have somewhat less of this potential.

Table 5. Parameters of the most efficient house shape to absorb solar gains during the heating season in comparison with $House_{ref}$

	x_1	x_2	x_3	n	Envelope surface areas, m^2							*GE*	*RGE*
					South* or South-east*	East or North-east	North or North-west	West or South-west	Roof	Ground	Total		
House ref.	15	15	12.8	4	192	192	192	192	225	225	1218	1.35	1
House 1	10.5	9.5	28.8	9	302.4	273.6	302.4	273.6	100	100	1352	1.50	1.111
House 2	23.7	9.5	12.8	4	302.4	121.6	302.4	121.6	225	225	1298	1.44	1.064

* indicates orientation of the main facade

x_1 – length; x_2 – width; x_3 – height; h – floor height; n – number of floors

Table 6. Heating season energy balance per vertical components of building envelopes oriented toward S-E-N-W; SE-NE-NW-SW

House S–E–N–W	Envelope component	Southern facade		Eastern facade		Northern facade		Western facade		Total component area, m²	Total gains, kWh	%
		Area, m²	Balance, kWh	Area, m²	Balance, kWh	Area, m²	Balance, kWh	Area, m²	Balance, kWh			
Ref.	Wall	57.6	–573.12	57.6	–573.12	172.8	–1807.488	57.6	–573.12	***345.60***	***9139.58***	100
	Window	*134.4*	*8957.76*	*134.4*	*2050.944*	*19.2*	*–367.68*	*134.4*	*2025.408*	***422.40***		
1	Wall	91.09	–906.35	82.08	–816.70	273.06	–2856.21	82.08	–816.70	***528.08***	***13984.97***	153
	Window	*212.35*	*14153.13*	*191.52*	*2922.60*	*30.34*	*–581.01*	*191.52*	*2886.21*	***625.71***		
2	Wall	91.09	–906.35	36.48	–362.98	273.06	–2856.21	36.48	–362.98	***436.88***	***12771.73***	140
	Window	*212.35*	*14153.13*	*121.6*	*1855.62*	*30.34*	*–581.01*	*121.6*	*1832.51*	***485.87***		

House SE–NE–NW–SW	Envelope component	South-east wall		North-east wall		North-west wall		South-west wall		Total component area, m²	Total gains, kWh	%
		Area, m²	Balance, kWh	Area, m²	Balance, kWh	Area, m²	Balance, kWh	Area, m²	Balance, kWh			
Ref.	Wall	57.60	–573.12	57.60	–602.50	57.60	–602.50	57.60	–573.12	***230.40***	***7962.62***	100
	Window	*134.40*	*6776.45*	*134.40*	*–1177.34*	*134.40*	*–1192.13*	*134.40*	*5906.88*	***537.60***		
1	Wall	91.09	–906.35	82.08	–858.56	91.09	–952.80	82.08	–816.70	***346.34***	***12028.33***	151
	Window	*212.35*	*10706.69*	*191.52*	*–1677.72*	*212.35*	*–1883.54*	*191.52*	*8417.30*	***807.74***		
2	Wall	91.09	–906.35	36.48	–381.58	91.09	–952.80	36.48	–362.98	***255.14***	***10498.54***	132
	Window	*212.35*	*10706.69*	*121.60*	*–1065.22*	*212.35*	*–1883.54*	*121.60*	*5344.32*	***667.90***		

The calculation results confirm that the ability of a building to reclaim a greater quantity of solar energy during the heating season depends on its shape, the physical characteristics of its external envelope elements, and its orientation. In order to determine whether the *House 1* and *House 2* gains during the operation stage will offset the 11% and 6.4% increase (that is reflected by *RGE* in Table 5) in materials for external envelope and energy needed to attain, transport, and utilise them, the total energy balance of the building lifecycle (including the resource extraction, transport, building construction, operation, and demolition stages) must be determined. Such calculations require an additional study, which is planned to be the next stage of the work of authors.

5. Discussions

In this paper, it has been determined that a less compact building has a greater potential to reclaim solar energy during the heating season than a compact one, provided the characteristics of transparent facade elements are used rationally. The results of the study allow considering that in time, as the thermal characteristics of the elements improve and their production technologies are perfected, this can significantly compensate for additional energy use (due to the larger area of external envelope and related installation costs) during the construction stage.

The maximisation of the area of the external envelope of a building is to be sought provided sufficient efficiency is proven for the entire operation stage. The calculations have demonstrated that this method of determining a building shape can be justified when the designs take full advantage of the potential of transparent elements.

The minimal amount of glass in a facade is regulated by hygiene norms based on insulation requirements, while the maximum can result in not only large energy gains during the heating season but also facility overheating during the warm period. In order to avoid possible discomfort that would require installation of an air conditioning system and additional energy consumption during the operation stage, it is useful to consider installing effective external measures against the sun, which could also serve as decorative elements of a building and contribute to the variety of architecture.

Regulations pertaining to a land lot and its surroundings that cover building height, density, orientation, and other requirements, can limit possible architectural and layout solutions. However, the measures scrutinised in this paper allow finding a solution in the context of such limitations and take the maximum advantage of the shape and external envelope characteristics as well as minimise energy resource needs during various stages of the building lifecycle. For example, compactness is sought for where solar gains are lacking.

Viewed in a different light, the research data can be useful in developing new residential locations. By anticipating the size, proportions, and orientation of a residential building, energy and other resource needs during construction and operation stages can be forecasted, which is useful for implementation of the EBPD strategy (Directive 2010/31/EU 2010).

In residential building design, questions of compactness are closer related to guidelines that strive for a maximum output for minimum input, rather than limits imposed on the variety of architectural solutions. This argument is confirmed by the graphs presented in Fig. 5, based on a studied multiunit building. Various proportions for rectangular buildings with an area of 900 m² (graph on the left) and their corresponding *GE* values (graph on the right) are presented. Fig. 5 also shows that the spectrum of these values falls within various limits of deviation from GE_{ref} (i.e., of reference building with 4 storeys and dimensions $x_1 = x_2 = 15$ m):

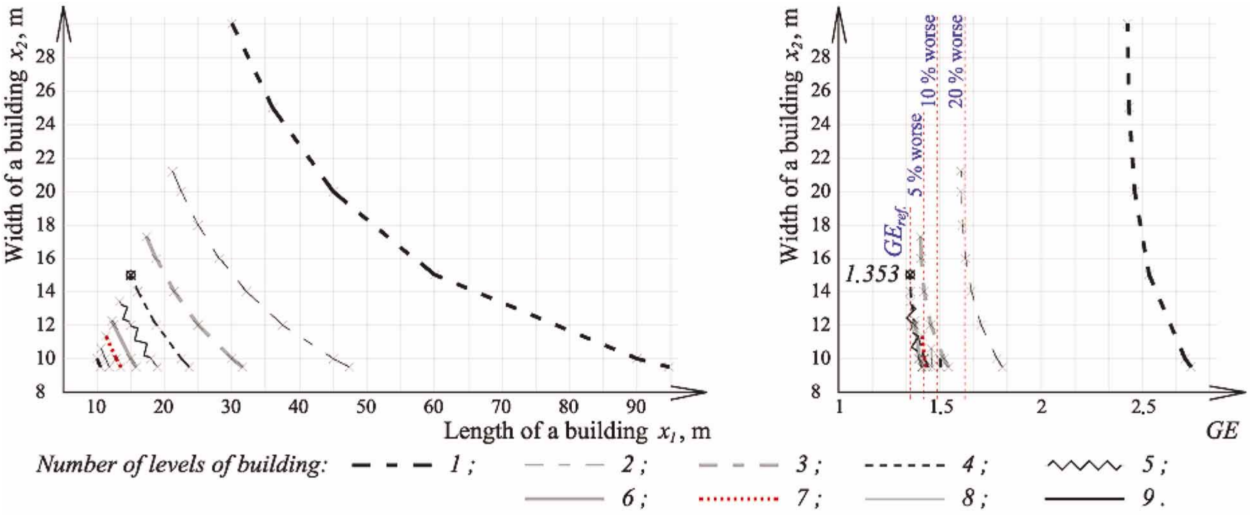


Fig. 5. Graph of the relationship between dimensions x_1 and x_2 of a building with an area of 900 m^2 and the number of storeys ranging from 1 to 9 (storey height h = 3.2 m), and graph of the corresponding GE values

The limits of deviation (5%, 10%, 20%) from GE_{ref} value delineated in the right part of Fig. 5 are an RGE representation (RGE_n = 1.05; 1.10; 1.20). They show that the GE_{ref} solution is the best one in terms of compactness, but it is not the only good one if the deviation is acceptable: RGE can be a standardised indicator (showing permissible deviation), the determination of which during the pre-design stage can govern the preparation of architectural and layout solutions with predictable construction material quantities needed and corresponding heat losses during the operation stage of a building.

In order to use RGE, the GE_{ref} of the reference building has to be known in each case. To avoid inaccuracies and simplify the use of these indicators in normative documents and recommendations, tables of calculated GE_{ref} values can be supplied. An example of such table is provided below (Table 7), where the mean storey height is equal to 3.2 m. The values presented are for buildings with internal area values (S) that fall within limits of 50–2500 m^2.

Table 7. Geometric characteristics of reference buildings (storey height h = 3.2 m)

Area, m^2	GE_{ref}	n	Side length, m	Area, m^2	GE_{ref}	n	Side length, m
50	*3.56*	2	5	600	*1.55*	4	12.25
75	*3.09*	2	6.12	700	*1.47*	4	13.23
100	*2.81*	2	7.07	800	*1.41*	4	14.14
125	*2.62*	2	7.91	900	*1.35*	4	15
150	*2.48*	3	7.07	1000	*1.30*	5	14.14
175	*2.34*	3	7.64	1200	*1.23*	5	15.49
200	*2.23*	3	8.16	1400	*1.16*	5	16.73
250	*2.07*	3	9.13	1600	*1.12*	5	17.89
300	*1.95*	3	10.0	1800	*1.07*	6	17.32
350	*1.85*	3	10.80	2000	*1.03*	6	18.26
400	*1.77*	3	11.55	2250	*0.99*	6	19.36
450	*1.71*	4	10.61	2500	*0.96*	6	20.41
500	*1.64*	4	11.18	…			

All of this leads us to believe that by manipulating compactness of a building and characteristics of external envelope elements, it is possible to not only find the maximum energy efficiency result of the building based on the environment and land lot conditions but also standardise the usage limits of these measures, which would allow a superior building energy efficiency result to be achieved.

6. Conclusions

It is worth expressing the base indicator of compactness using the A/S ratio with the area of the external envelope of a building (A) and the useful (heated) area (S), as this indicates how efficiently a building's geometry is used, which the A/V ratio does not reflect. In this case, we can refer to the A/S non-dimensional ratio as "Geometric Efficiency" (GE).

The study has demonstrated that the geometric efficiency of buildings can vary within especially wide limits, which results in a difference in resource needs of up to several percent during the implementation stage of a project.

Relative Geometric Efficiency (*RGE)*, which is equal to GE/GE_{ref}, is proposed to assess the compactness of a building. RGE indicates the level by which geometric efficiency *(GE)* of a designed building deviates from its reference (optimal) GE_{ref} value.

It was determined that under Lithuanian climatic conditions during the heating season and depending on orientation of the facades, the suggested recommendations regarding application of transparent and opaque external wall areas make it possible to markedly reduce the energy demand of a building.

Calculations made according to the presented methodology have demonstrated that depending on its shape and assuming an identical percentage of glassed area during the heating season, gains for a 900 m^2 building can vary up to 53% or 5.4 kWh/m^2. In this case, compact buildings have the potential to save resources during the construction stage of a project, while less compact buildings have an opportunity to reclaim more renewable energy during the operation stage (by orienting the largest facades in a southern dir.). In order to avoid possible overheating of facilities due to solar gains, in this case it is recommended to standardise the requirement to install suitable external protective measures.

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ARCHITEKTŪROS SPRENDINIAI, DIDINANTYS ENERGINĮ PASTATŲ EFEKTYVUMĄ

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Santrauka

Projektuojant pastatų tūrius yra galimybė, pasitelkus architektūrinius sprendinius, pasiekti didesnį energinį efektyvumą viso jų gyvavimo laikotarpiu, tačiau šiuo metu tuo naudojamasi nepakankamai. Darbe atlikta architektūrinių sprendinių lyginamoji analizė, kurios metu pristatomi sprendimai, leidžiantys sumažinti energijos, prarandamos per pastato išorės atitvaras, kiekį atsižvelgiant į vietos klimato sąlygas, bei padidinti pastato suvartojamos energijos kiekį naudojant atsinaujinančiųjų šaltinių energiją.

Reikšminiai žodžiai: A/S santykis, A/V santykis, energinis efektyvumas, geometrinis efektyvumas, pastato gyvavimo ciklas, kompaktiškumas, energijos poreikis, saulės energijos pritekėjimas, tvarumas.

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