Building geometry and development form optimisation in terms of the energy efficiency

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Abstract. The construction sector consumes around 40% energy for the purposes of heating. The policy of sustainable development that has been implemented for many years also transfers to actions in the construction sector. The European Union is introducing a standard of buildings with a near-zero energy demand. This standard can be achieved only by altering the manner of the design, construction and use of buildings. Such parameters like geometry or the placement of buildings relative to each other and the structure of their layout on the site, on the scale of groups of buildings, also have an impact on the energy consumption. The goal of this article is to assess the improvement of the effectiveness of actions taken in order to lower the energy demand for heating of designed buildings meant for permanent occupancy. The assessment takes into consideration the conditions of sustainable development. The analysis covers the impact of the geometry of a building and development structure on the energy balance.

1. Introduction
The problem of limiting the consumption of energy necessary to heat residential buildings in Western Europe appeared as an effect of the crisis that took place at the beginning of the 1970s. During this period, 40% of the overall consumed energy was used for heating. The first legal regulations concerning the design of residential buildings appeared. Regulations placing increasingly higher requirements in this field have been put in place. At present, the use of energy for heating purposes in the housing sector is considerably smaller. At present, the problem of limiting energy consumption is being examined in a much broader context. It is considered as an element of the strategy of sustainable development.

The novelisation of the Ordinance of the Minister of Infrastructure on the matter of the technical conditions that must be met by buildings and their placement that has remained in force since 2014 defines the minimum requirements for buildings with a "near-zero energy consumption" [1]. In order to achieve the level of building energy efficiency specified in the regulations, rules of designing such buildings should be formulated for Polish climate conditions [2].

The typically used increase in the thickness of the thermal insulation layer or replacing windows with more effective ones is no longer justifiable from an economic standpoint. Energy efficiency should be improved through other solutions.

In the article, the authors analysed the impact of geometry and development structure on the scale of a group of buildings.
2. Low-energy building design

The detailed structure of the design process depends on the specific design problem. Design theory defines the general structure of designing while solving technical problems, as well as the design of buildings and structures.

On this basis, we can define a general structure of the design process for problems of designing housing structures. This also applies to the problem of designing energy-efficient residential buildings that meet the conditions of sustainable development that is discussed in the article. The structure of design will constitute a basis for determining requirements stemming from the conditions of sustainable development in the design of housing structures.

A scheme of the process of technical design has been presented in Figure 1.

![Figure 1. A scheme of the process of technical design](image)

In the structure of the process of low-energy building design, it appears justified to distinguish, apart from the modules of designing a structure's form, function, structural system and installations, also a module for the design of its thermal protection and the assessment of solutions in terms of the requirements of sustainable development. One of the elements of this "energy-efficiency-related" module should be guidelines concerning the design of a building's geometry and development structure. The structure of the process of low-energy building design has been presented on Figure 2.
3. Methodology
3.1. Analysis criteria and decision variable sets
The building energy efficiency analysis was performed using a specialist method of assessment and with the use of expert programs.

The analyses were conducted using a computer-aided design and construction energy analysis program called DesignBuilder v. 4.2. The program employs Eurime and ASHRAE 90.1 standards, as well as weather data for Krakow provided by the Institute of Meteorology and Water Management. A complete analysis meant to optimise the design of energy-efficient buildings should be based on the principle of selecting an optimal solution from a set of all permissible solutions under properly defined assessment criteria.

The analysis presented in this article is the first stage of a comprehensive analysis and conclusions drawn from it will be the subject of subsequent calculation stages.

It is planned for the analysis to feature the following assessment criteria:
- K1 – goal function defined by the minimum value of PE
- K2 – goal function defined by the minimum value of FE
- K3 – goal function defined by minimum development cost
- K4 – goal function defined by the PMV index (thermal comfort index).
3.2. General task overview
A number of decisions, which often largely decide the shape of the final design solution, are made during the initial phases of the design process (Figure 2). These decisions include the selection of building geometry and development layout structure. Decisions concerning these problems can—to a significant degree—be determined (at this stage) by identifying needs (demand for a given type of buildings) on the one hand, while on the other, by the possibilities offered in terms of plot selection, the spatial development plan or the administrative decision concerning development planning conditions. It appears that it is important that decisions concerning building geometry selection and development layout structure be made in a manner that takes their consequences into account, including consequences concerning the energy assessment of the buildings that are possible to design (as a result of these initial decisions).

In order to obtain information for the initial stage of the decision-making process in the design of a complex of low-energy buildings, the following optimisation task was formulated:

Given:

\[ \Omega \rightarrow \text{linear space,} \]
\[ \mathbf{K}(m \in M) \rightarrow \text{vector goal function:} \]
\[ \mathbf{K}(m \in M) : M \rightarrow \mathbb{R} \]

An \( m^* \in Q \) should be set, so that:

\[ \mathbf{K}(m^*) = \min_{m \in Q} \mathbf{K}(m) \]

where:

\[ M \subset \Omega \rightarrow \text{decision variable set,} \]
\[ Q = \{m: g(m) \geq 0\} \rightarrow \text{set of permissible solutions,} \]
\[ G = \{g(m)\} \rightarrow \text{constraints set.} \]

The following optimisation criterion was adopted in the problem being discussed:

\[ \mathbf{K} = \{K_1, K_2\} \rightarrow \text{two-element goal function set,} \]

where:

\[ K_1 = K_1(m) \rightarrow \text{minimum demand for primary energy for heating PE \([kWh/m^2a]\);} \]
\[ K_2 = K_2(m) \rightarrow \text{minimum demand for final energy for heating FE \([kWh/m^2a]\);} \]

The non-renewable Primary Energy index (PE \([kWh/m^2a]\)) informs us how much energy from renewable and non-renewable sources needs to be used to heat (cool) a square metre of the floor area of the building under analysis. This index takes into account energy loss during production, transfer and transport of energy from the place of extraction (the construction of the building).

The Final Energy index (FE \([kWh/m^2a]\)) informs us how much energy must be supplied to the building in order to heat (cool) a square metre of the floor area of the building under analysis. This index takes into account energy loss in the transfer and transport of energy inside the building.

in addition to the decision variable set:

\[ M = \{m_i\} \quad i = (1, 2, \ldots, n) \]

Class divisions were introduced into set \( M \):

\[ \mathbf{MA} = \mathbf{V} = \{v_1, v_2, v_3, v_4\} \quad v_i = m_i \in \mathbf{MA} \rightarrow \text{has a set of discrete variables} \]
\[ \mathbf{MB} = \mathbf{U} = \{u_i\} \quad i = 0 \]
\( u_i = m_j \in MB \) set of continuous decision variables. In the analysed task, this set is empty, however, during subsequent stages of the analysis, this set will include elements that are not defined in a discrete manner, but that constitutes a continuous dataset.

\[ M = MA \cup MB \land MA \cap MB = \emptyset \]

The values of discrete decision variables \( v_1, v_2 \) were defined by assigning individual solutions to integers (value of index \( i,j \)).

The set of variable discrete decision values \( MA = V = \{ v_{1,i}, v_{2,i}, v_{3,i}, v_{4,i} \} \) is finite and countable.

The discrete variable set \( MA = V = \{ v_{1,i}, v_{2,i}, v_{3,i}, v_{4,i} \} \) is composed of the following elements:

- \( v_{1,i} \) – building shape (\( v_{1,1} \) – cuboid massing, \( v_{1,2} \) – building with a pitched roof)
- \( v_{2,i} \) – type of development (\( v_{2,1} \) – detached, \( v_{2,2} \) – terraced – inner segment, \( v_{2,3} \) – terraced – outer segment, \( v_{2,4} \) – semi-detached)
- \( v_{3,i} \) – level of starting thermal protection requirements (\( v_{3,1} \) – building conforming to TC21 (Standard), \( v_{3,2} \) – building conforming to passive building standards (energy-efficient))
- \( v_{4,i} \) – Type of adopted variant of technical systems fitted inside the building (\( v_{4,1} \) – Variant A, \( v_{4,2} \) – Variant B)

The main task was given the following form:

\[ K(x^*) = K(v^*,u^*) = \min_{v \in V} \min_{u \in U} K(v,u) \]

where:
- \( V,U \) – sets of permissible \( v,u \) values.
- \( G = GA \cup GB \) - constraints set,
- \( GA \) – set of constraints placed on discrete variables; \( GA = \{ g(v) \} \),
- \( GB \) – set of constraints placed on continuous variables; \( GB = \{ g(u) \} \).

In the analysed task, given the adopted formulating method, set \( GA = \emptyset \) (all variable values \( v \in V \) are permissible values).

Meanwhile, the constraint set \( GB = \emptyset \) (because in this task set MB is an empty set).

3.3. Detailed optimisation problem formulation

3.3.1. Assumptions. General assumptions (building parameters)

**Building geometry**

The analysis includes assumptions concerning the geometry of an individual segment.

- Building floor plan in the shape of a rectangle,
- Condition of a fixed building segment footprint area \( A_z = 105 [m^2] \),
- Storey height \( h = 3 [m] \).

**Building divisions depending on the featured technical installations - Variants.**

The analysis was performed for buildings designed in two different energy standards;

1. **Standard buildings**, that meet the current requirements of TC2017 concerning the thermal insulation properties of external partitions
2. **Passive buildings**, that meet requirements concerning the thermal insulation of external partitions that are characteristic of passive buildings.

In addition, buildings were divided into Versions A and B (Table 1) depending on their technical installations.
Table 1. Division of buildings into Versions A and B

| Installation                | VERSION A          | VERSION B          |
|----------------------------|--------------------|--------------------|
| Heating                    | Gas                | Gas boiler         |
| Domestic hot water         | Gas furnace        | Gas furnace        |
| Air conditioning           | None               | Electrical         |
| Ventilation                | Natural            | Natural            |
| Lighting                   | Standard           | LED                |
| Infiltration level at a pressure level of 50Pa | 7 air exchanges per hour | 1,5 air exchanges per hour |
| Number of occupants        | 4                  | 4                  |
| Domestic hot water consumption | 1,5m³ per person   | 1,5m³ per person   |
| Fresh air intake           | 10 l/s/person      | 10 l/s/person      |
| RES                        | None               | none               |

Material and structural wall solutions

The following material and structural solutions of external partitions were assumed for the purposes of the analysis.

a) External wall
A two-layer partition was assumed in all of the analysed buildings. The structural layer was assumed to be composed of autoclaved aerated concrete masonry blocks, with the thermal insulation layer composed of mineral wool with an external texture (Table 2).

Table 2. External wall

| Building conforming to: | External wall structure                              | U coefficient [W/m²K] [3] |
|-------------------------|------------------------------------------------------|---------------------------|
| TC2017                  | - lime plaster with cement 1cm                       | 0,20                      |
|                         | - rock wool 13 cm, λ = 0,034 [W/(m·K)]               |                           |
|                         | - aerated concrete masonry unit 30 cm, λ = 0,25 [W/(m·K)] |                           |
|                         | - lime plaster with cement 1cm                       |                           |
| passive                 | - lime plaster with cement 1cm                       | 0,15                      |
|                         | - rock wool 18 cm, λ = 0,034 [W/(m·K)]               |                           |
|                         | - aerated concrete masonry unit 30 cm, λ = 0,25 [W/(m·K)] |                           |
|                         | - lime plaster with cement 1cm                       |                           |

b) Internal wall (between segments)
Segments in a terraced development were assumed to be divided by an internal single-layer wall composed of autoclaved aerated concrete masonry units 30 [cm].

c) Flat roof
A flat roof on a reinforced concrete slab was assumed (Table 3). The thermal insulation layer was assumed to be made of Styrofoam sheets.

Table 3. Flat roof

| Building conforming to: | Flat roof structure              | U coefficient [W/m²K] |
|-------------------------|----------------------------------|-----------------------|
| TC2017                  | - bituminous waterproofing       | 0,15                  |
d) Pitched roof
A collar beam roof was assumed to be used. Thermal insulation with mineral wool sheets. Ceramic tile roofing (Table 4).

Table 4. Pitched roof

| Building conforming to: | Roof structure | U coefficient [W/m²K] |
|------------------------|----------------|---------------------|
| TC2017                 | roof tiles     | 0,15                |
|                        | battens        |                     |
|                        | bituminous waterproofing |         |
|                        | rafter + mineral wool 15 cm $\lambda = 0,035$ [W/(m²·K)] |         |
|                        | mineral wool 8 cm |                     |
|                        | drywall 1,2 cm, $\lambda = 0,35$ [W/(m²·K)] |         |
| passive                | roof tiles     | 0,15                |
|                        | battens        |                     |
|                        | bituminous waterproofing |         |
|                        | rafter + mineral wool 15 cm $\lambda = 0,035$ [W/(m²·K)] |         |
|                        | mineral wool 8 cm |                     |
|                        | drywall 1,2 cm, $\lambda = 0,35$ [W/(m²·K)] |         |


e) Floor slab between storeys
Wooden flooring 3 cm, $\lambda = 0,4$ [W/(m·K)]
Concrete screed 5 cm, $\lambda = 1,3$ [W/(m·K)]
Styrofoam 3 cm, $\lambda = 0,038$ [W/(m·K)]
Reinforced concrete 10 cm $\lambda = 1,7$ [W/(m·K)]

f) Slab on grade
All of the analysed structures are assumed to have a slab on grade (Table 5).

Table 5. Slab on grade

| Building conforming to: | Slab on grade structure | U coefficient [W/m²K] |
|------------------------|--------------------------|---------------------|
| TC2017                 | Wooden flooring 3 cm, $\lambda = 0,4$ [W/(m·K)] | 0,30                |
|                       | Concrete screed 5 cm, $\lambda = 1,3$ [W/(m·K)] |                     |
|                       | Styrofoam 10 cm, $\lambda = 0,032$ [W/(m·K)] |                     |
|                       | Waterproofing |                     |
|                       | Reinforced concrete screed 10 cm, $\lambda = 1,7$ [W/(m²·K)] |         |
| passive                | Wood flooring 3 cm, $\lambda = 0,4$ [W/(m·K)] | 0,15                |
|                       | Concrete screed 5 cm, $\lambda = 1,3$ [W/(m·K)] |                     |
Styrofoam 20 cm, $\lambda = 0.032$ [W/(m·K)]
Waterproofing
Reinforced concrete screed 10 cm, $\lambda = 1.7$ [W/(m·K)]

**g) Windows**
The calculations were performed under the assumption that wooden window frames were used, in accordance with the following table 6.

**Table 6. Windows**

| Building conforming to: | Solar transmittance coefficient [\text{-}] | U coefficient [W/m²K] |
|-------------------------|--------------------------------------------|-----------------------|
| TC2017                  | 0.75                                       | 1.1                   |
| passive                 | 0.69                                       | 0.79                  |

**Discrete decision variables (Table 7)**

**Table 7. Discrete decision variables.**

| Variable | Description                | Variable $v_i$ value set |
|----------|----------------------------|--------------------------|
| $v_{1,i}$ | Development type           | $v_{1j}$ i=1 - Detached, i=2 – Terraced, inner segment, i=3 - Terraced, outer segment, i=4 – Semi-detached |
| $v_{2,j}$ | Building geometry          | $v_{2,1}$ j=1 - 2 storeys with a flat roof, $v_{2,2}$ j=2 - 2 storeys with a pitched roof |
| $V_{3,k}$ | Energy efficiency level    | $V_{3k}$ k=1 Standard, k=2 – Energy-efficient |
| $V_{4,l}$ | Variant type               | $V_{4l}$ l=1 Variant A, l=2 – Variant B |

Set of permissible decision variable values:
$V = xV_i = \{v_{1k}\}, \quad i=1,2,3,4; j=1,2; k=2; l=2$

**Table 8. Graphical representation of set $V_{1,i}$**

| $V_2$ set elements | Building scheme | Usable floor area of an individual segment [m²] | Volume of an individual segment [m³] |
|--------------------|-----------------|-----------------------------------------------|-------------------------------------|
| $V_{1,1}$          |                 | 105                                           | 258                                 |
A theoretical site was assumed for development with single-family buildings, composed of small buildable plots meant for a sample development layout featuring 10 houses in the following variants: detached, terraced and semi-detached, while conforming to building placement standards of as specified in Construction Law. Energy calculations were performed for typical construction technology in compliance with the Ordinance of the Minister of Infrastructure on the matter of technical conditions that are to be met by buildings and their placement, as well as for energy-efficient building technology. In the case of buildings constructed using typical (traditional) technology, the requirements that are to be met after the first of January 2021 were considered. The same variants of development built using energy-efficient technology were comparatively analysed. The subject of the analysis was a set of variants of small single-family houses with 6 x 10 m floor plans, with two storeys and no cellar, with a habitable loft (Table 8).

\[ V_{1,1} \] - A high-density single-family detached development was assumed, with limited plot space, which requires a full suite of building services. Plot size: 14 x 25 m (350 m²), building footprint dimensions of 6 x 10 m, with a usable floor area of 105 m² per building, and a volume of 258 m³ per building. Each building features a ground floor and a habitable loft, without a cellar or additional attic. Distance from the property line to a wall with window openings is a minimum of 4 m.

\[ V_{1,2} \] - A high-density single-family terraced development was assumed, with limited plot space, which requires a full suite of building services. Plot size: 14 x 25 m (350 m²), building footprint dimensions of 6 x 10 m, with a usable floor area of 105 m² per building, and a volume of 258 m³ per building. Each building features a ground floor and a habitable loft, without a cellar or additional attic.

\[ V_{1,3} \] - A high-density single-family semi-detached development was assumed, with limited plot space, which requires the a suite of building services. Plot size: 14 x 25 m (350 m²), building footprint dimensions of 6 x 10 m, with a usable floor area of 105 m² per building, and a volume of 258 m³ per building. Each building features a ground floor and a habitable loft, without a cellar or additional attic. The building is assumed to be located at the property line (the parting wall is assumed to be placed at the property line).

Table 9. Graphical representation of the elements of set \( V_{2,j} \).

| \( V_2 \) set elements | Building scheme | Usable floor area of an individual segment [m²] | Volume of an individual segment [m³] |
|------------------------|-----------------|---------------------------------------------|-----------------------------------|
| \( V_{2,1} \)          |                 | 105                                         | 258                               |
V2,1 - A single-family residential development with a pitched roof, building footprint dimensions of 6 x 10 m, with a usable floor area of 105 m² per building, and a volume of 258 m³ per building. Each building features a ground floor and a habitable loft, without a cellar or additional attic. Distance from the property line to a wall with window openings is a minimum of 4 m.

V2,2 - In a development system with a decision variable defining buildings as having two full storeys and a flat roof, with a usable floor surface of 105 m² and a volume of 261 m³. The buildings feature a ground floor and one additional habitable floor, without a cellar or attic.

Energy savings analyses concerning the preparation of domestic hot water were also performed for all of the development variants presented above. The use of flat fixed solar collectors, installed on the southern roof surface, at an angle of 45 degrees was assumed, which provides the best conditions in terms of sunlight. The results concerning solar installations are tentative and are based on averaged meteorological data. Depending on weather conditions, actual results can differ from those that were assumed. Panels with an area of 3 m², with an averaged power of 25.84 kWh/(m²*a) were factored in the calculations (Table 9).

4. Results of the analysis
After analysing all of the variants of the analysis, the results have been demonstrated in the table and plots below (table 10, Figure 3).

The analysis defined 38 variants based on 4 decision variables V1,i; V2,j; V3,k; V4,l

K1 and K2 goal function values have been presented, in addition to the demand for heating energy for each variant.

| No. | DESCRIPTION | V1,i | V2,j | V3,k | V4,l | PE kWh/m²a | EF kWh/m²a | Heating kWh/a |
|-----|-------------|-----|------|------|------|-----------|-----------|-------------|
| 1   | ENERGO single-family detached development pitched roof W1 | v1,1 | v2,2 | v3,2 | v4,3 | 94.08     | 86.56     | 9 595,33    |
| 2   | ENERGO single-family terraced development pitched roof W1 S outer | v1,3 | v2,2 | v3,2 | v4,1 | 94.84     | 87.25     | 9 671,56    |
| No. | Description                                  | v1,4 | v2,2 | v3,2 | v4,1 | v4,2 | v4,3 | v4,4 | v4,5 | v4,6 | v4,7 | v4,8 | v4,9 | v4,10 | v4,11 | v4,12 | v4,13 | v4,14 | v4,15 | v4,16 | v4,17 | v4,18 | v4,19 | v4,20 | v4,21 | v4,22 | v4,23 | v4,24 | v4,25 | v4,26 | v4,27 | v4,28 | v4,29 | v4,30 | v4,31 | v4,32 | v4,33 |
|-----|----------------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 3   | ENERGO single-family semi-detached development pitched roof WA | v1,4 | v2,2 | v3,2 | v4,1 | 96.47 | 88.86 | 21 072,69 |
| 4   | ENERGO single-family terraced development flat roof W1 | v1,3 | v2,1 | v3,2 | v4,1 | 99.25 | 91.28 | 8 120,85 |
| 5   | ENERGO single-family detached development flat roof W1 | v1,1 | v2,1 | v3,2 | v4,3 | 99.31 | 91.35 | 8 127,07 |
| 6   | STANDARD single-family terraced development pitched roof A | v1,2 | v2,2 | v3,1 | v4,1 | 100.66 | 92.61 | 10 541,86 |
| 7   | STANDARD single-family semi-detached development pitched roof WA | v1,4 | v2,2 | v3,1 | v4,1 | 100.89 | 92.93 | 22 395,51 |
| 8   | STANDARD single-family detached development pitched roof A | v1,1 | v2,1 | v3,1 | v4,1 | 101.51 | 93.40 | 10 631,36 |
| 9   | STANDARD single-family terraced development flat roof A | v1,2 | v2,1 | v3,1 | v4,1 | 105.55 | 97.07 | 8 962,69 |
| 10  | STANDARD single-family detached development flat roof A | v1,1 | v2,1 | v3,1 | v4,1 | 106.79 | 98.22 | 9 069,00 |
| 11  | ENERGO single-family terraced development flat roof W1 N outer | v1,3 | v2,1 | v3,2 | v4,1 | 108.03 | 99.36 | 11 012,63 |
| 12  | ENERGO single-family terraced development pitched roof W1 N inner | v1,2 | v2,2 | v3,2 | v4,3 | 112.13 | 103.11 | 11 427,14 |
| 13  | STANDARD single-family terraced development pitched roof W1 N inner | v1,2 | v2,2 | v3,1 | v4,3 | 115.07 | 105.84 | 12 044,59 |
| 14  | ENERGO single-family terraced development flat roof W1 N inner | v1,2 | v2,1 | v3,2 | v4,3 | 115.87 | 106.50 | 9 471,91 |
| 15  | STANDARD single-family terraced development flat roof A | v1,2 | v2,1 | v3,1 | v4,1 | 118.37 | 108.83 | 10 046,66 |
| 16  | STANDARD single-family terraced development flat roof W1 N inner | v1,2 | v2,1 | v3,1 | v4,3 | 120.35 | 110.63 | 10 212,48 |
| 17  | ENERGO single-family semi-detached development flat roof WA | v1,4 | v2,1 | v3,2 | v4,1 | 129.14 | 118.98 | 22 962,24 |
| 18  | STANDARD single-family semi-detached development flat roof WA | v1,4 | v2,1 | v3,1 | v4,1 | 138.69 | 127.77 | 25 268,94 |
| 19  | STANDARD single-family terraced development flat roof A N | v1,2 | v2,1 | v3,1 | v4,1 | 147.98 | 113.36 | 11 868,58 |
| 20  | ENERGO single-family terraced development pitched roof W2 N inner | v1,2 | v2,2 | v3,2 | v4,4 | 241.38 | 132.21 | 9 471,16 |
| 21  | ENERGO single-family semi-detached development pitched roof WB | v1,4 | v2,2 | v3,2 | v4,2 | 244.85 | 126.03 | 17 610,46 |
| 22  | ENERGO single-family terraced development pitched roof W2 S outer | v1,3 | v2,2 | v3,2 | v4,2 | 245.87 | 125.77 | 8 141,33 |
| 23  | ENERGO single-family terraced development flat roof W2 N outer | v1,3 | v2,1 | v3,2 | v4,2 | 250.50 | 133.79 | 9 251,62 |
| 24  | ENERGO single-family terraced development pitched roof W2 | v1,1 | v2,2 | v3,2 | v4,4 | 256.20 | 129.28 | 8 141,33 |
| 25  | STANDARD single-family terraced development pitched roof W2 N inner | v1,2 | v2,2 | v3,1 | v4,4 | 270.99 | 142.51 | 9 868,10 |
| 26  | STANDARD single-family semi-detached development pitched roof WB | v1,4 | v2,2 | v3,1 | v4,2 | 274.99 | 136.82 | 18 331,85 |
| 27  | STANDARD single-family terraced development pitched roof B | v1,2 | v2,2 | v3,1 | v4,2 | 276.03 | 137.59 | 8 739,34 |
| 28  | STANDARD single-family terraced development pitched roof B | v1,2 | v2,1 | v3,1 | v4,2 | 280.92 | 145.49 | 9 842,09 |
| 29  | STANDARD single-family terraced development flat roof W2 N inner | v1,2 | v2,1 | v3,2 | v4,4 | 316.79 | 177.02 | 10 430,77 |
| 30  | ENERGO single-family terraced development flat roof W2 N inner | v1,2 | v2,1 | v3,2 | v4,4 | 320.69 | 167.28 | 19 387,38 |
| 31  | ENERGO single-family terraced development flat roof W2 | v1,3 | v2,1 | v3,2 | v4,2 | 327.24 | 168,59 | 8 841,94 |
The optimal solution considering both criteria: K1 (PE) K2 (FE) is the variant corresponding to decision variable set (v1,1; v2,2; v3,2; v4,3) which is an energy-efficient building in a detached development with a pitched roof—variant W1

In terms of energy use for heating, the most beneficial decision variable set was (v1,3; v2,1; v3,2; v4,1) which denoted an energy-efficient building as an outer segment in a terraced development with a flat roof—variant W1

5. Conclusion

The subject of the analysis was a comparison of energy performance, including PE and FE indices, for typical traditional and energy-efficient buildings. This analysis was performed for single-family detached houses, semi-detached buildings and single-family terrace buildings, with energy performance calculated separately for an outer and inner building, under varied sunlight conditions. The analysis did not consider additional, renewable energy sources, with the basis for calculations being the use of gas and electric power obtained from the power grid. More favourable U coefficient parameters for energy-efficient buildings were obtained solely by using insulation materials with lower λ values and by increasing the thickness of the insulation. The unfavourable impact of the uncontrolled air infiltration through the air leaks was minimised.

The lowest energy consumption level with an independent installation set, both in traditional and energy-efficient buildings, was observed in the case of outer buildings in the terraced developments,
with a southern orientation. A similar level of energy consumption was observed in the single-family buildings without windows on the northern side. Meanwhile, the highest energy demand was observed in an inner building in a terraced development, that only had two external walls capable of obtaining solar energy and two common walls with adjacent buildings.

References

[1] Regulation of the Polish Minister of Transport, Construction and Maritime Economy On 5 July 2013. Amending the Regulation on technical conditions to be met by buildings and their location (Dz.U. 2013 poz. 926), 2013.

[2] Regulation of the Polish Minister of Infrastructure and Development of the 3rd of June 2014 on the matter of the methodology of calculating the energy performance of buildings, dwellings or parts of buildings constituting independent wholes, 2014.

[3] PN-EN ISO 6946:2008 European Standard – “Building components, building elements – Thermal resistance and heat transfer coefficient – Calculation method” Polish edition, 2008.