Energy performance calculations for randomly generated buildings – selected results and possible applications of the developed model

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Abstract. The main goal of our research was to find relationships between building parameters and their importance to building energy efficiency. We developed a numerical model, which generates data describing single family houses with different, random sets of parameters. The collections include: building geometry, facade orientation, thermal properties of partitions, types and sizes of glazing, airtightness, types and sizes of unconditioned buffer zones. The model was used to generate a large amount of different building cases, allowing statistical analysis of building energy efficiency on an unprecedented scale. The research shows, that applying this method allows identifying relationships that would otherwise be very difficult to discover and describe, in particular by examining only existing buildings.

1. Introduction
Proper building design in terms of energy efficiency needs a close look on every aspect of its structure. An energy efficient building should not have weak spots in terms of building shape, its thermal insulation, avoidance of thermal bridges, a proper window layout and high airtightness.

The analysis of the impact of building parameters on its energy efficiency is always burdened with an error resulting from a subjective approach to comparison. Distinguishing individual variables and observing the effects of changing their value on the building’s energy response is an often made arbitrary simplification in the analysis. In real situations, the variability of the parameters describing the building and their values are often subject to various random factors that cause that the actual buildings may have a random distribution of envelope features, including its shape, level of insulation, percentage of glazed areas, orientation towards the world sides or the type of climb technology.

One can find many research in which the relation between building parameters and its energy efficiency are discussed in terms of building shape [1][2][3], insulation thickness [4], glazing size [5], environmental impact [6] and many, many more. But, practically in all of them the selection of analyzed parameter values was planned.

On the one hand, the values of these parameters may be limited by regulations, but on the other hand, the practice shows that many existing buildings may have some solutions that deviate from standards adopted in a given system and time, resulting from local conditions, including, for example, the investor’s budget.

We have tried to reproduce these real-world conditions by the means of procedural modelling (random selection of building parameters described by geometrical and constructional rules).
Procedural modeling is at the moment widely used for computer games applications, but also in architectural research, like for analysis of building with same type of geometry (round buildings) [7] or for simulation of a group of architectural buildings that share similar typological features (sacral buildings) [8].

Our research is an attempt to objectify the assessment of the impact of individual parameters through random selection of building variants on a statistical scale, and to track the dependence between all parameters taken into account in calculating the energy performance of buildings.

The research was divided into two stages.

In order to analyze the impact and interdependencies of parameters describing the features of the building, which are important for its energy efficiency, we first constructed a model randomly generating buildings in typical forms of single-family housing. The model selects the values of geometrical and thermal variables in a random way, but in order to make a comparison, a constant value of the heated volume of the building for all randomly drawn variants was adopted.

In the second step was submitting the generated data of individual variants to a prepared calculation sheet, and determining their energy performance in accordance with [9].

This procedure does not create a completely objective picture of the interdependencies between the energy parameters of buildings (selection of only some shapes of buildings, their heated volume, or range of parameter values), nevertheless, it allows to get insights into a more general scale of energy efficiency of buildings and not only to individual solutions.

2. Model of randomly generated building parameters

2.1. Analysed building shapes

The whole building generation procedure was carried out in MS VBA (Visual Basic for Applications) by the means of MS Excel software. Only most common building shapes were taken under consideration (Fig. 1a - Fig. 1d):

- rectangular base and gable roof (further called “barn”),
- rectangular base and flat roof (further called “brick”),
- rectangular base and hipped roof (further called “envelope”),
- L-shaped base and flat roof (further called “L-shape”).

![Figure 1. Analysed building shapes: a) rectangular base, gable roof, b) rectangular base, flat roof, c) rectangular base, hipped roof, d) L-shaped base, flat roof, e) diagram of connection between unconditioned buffer zone and the building](image-url)
Every kind of shape was described by randomly generated geometrical parameters, by use of VBA Rnd function. This includes variables such as lengths (L., L_{\text{min}}), widths (W, W_{\text{min}}), height (H) and, for gable and hipped roof buildings, angle of roof slope (\alpha). After a set of randomly generated geometrical values were created, the building heated volume was calculated and if it didn’t meet the criteria, the drawing process was repeated. To allow comparison between generated cases, a constant heated building volume of 600 \pm 1.5 \text{m}^3, has been fixed. This essentially gives a rather average sized single family house. The generation of geometries ends with calculation of the A/V ratio (known also as shape coefficient).

Additionally, an external, unconditioned buffer zone (Fig. 1e) is added (or not) in a random way. It is adjacent to one of the building facades. Depending on the draw result, the buffer when present, could reduce some of the heat losses through the joint wall (when the draw result was an opaque walled buffer zone) or could add some heat gains to the heated space from solar radiation (when the draw result was an fully glazed buffer zone). Also the rotation of the building from the north direction in 45 degree increments was a matter of random value.

2.2. Other building parameters – sequence of generation

All the below mentioned parameters were randomly drawn from an established range of values (Table 1).

After selecting the form of the building and the presence of unconditioned buffer zone (opaque or fully glazed one), the algorithm chose building airtightness – n_{50} [1/m], the air exchange rate in buffer zone – n [1/m], the share of thermal bridge in transmission losses [%] and wind sheltering class (no sheltering, average or good sheltering).

Depending of the drawn building shape, there were groups of external walls and roofs, from which specific cases were selected, described by their thickness [m], U-value [W/(m^2 K)] and unitary heat capacity [J/(m^2 K)]. After that, internal walls and floors were added corresponding to the wall and roof type. Internal walls were described by the percentage of usable floor area covered by them [%], thickness [m] and unitary heat capacity [J/(m^2 K)]. The existence of internal floors depended on building height and they were described by their number [pcs], thickness [m] and unitary heat capacity [J/(m^2 K)]. At this moment the internal air volume [m^3] and usable floor area [m^2] for every building case could be calculated.

The next step was to create glazed areas in building external walls, by drawing percentage of glazing (independently on every façade) [%] and parameters such as U-value [W/(m^2 K)] and g-value [-] (also known as Solar Heat Gain Coefficient). After a set of randomly generated windows was created, the sum of glazed area [m^2] was calculated and if it didn’t meet the criteria required by polish technical regulations [10] (being not smaller than 1/8 of usable floor area), the drawing process was repeated.

The final step was to calculate every external partition area depending on its orientation (windows, walls and roofs) and to save generated parameters, for every created case, in a way that made energy calculations possible. Every case is ultimately described by set of 105 parameters.

For analysis purposes the algorithm drew 5040 random, non-repeatable building cases (1260 cases for every building shape). Afterwards, the energy performance calculations were performed by use of MS Excel software, for every building case.

2.3. Energy calculation procedure

The calculation of the heating and cooling energy demand was performed according to Polish energy performance certification (EPC) calculation regulations [11]. It is based on monthly steady-state computing method in accordance with PN-EN ISO 13790 [9] standard by use of our own created spreadsheet file in MS Excel software.

The weather data for energy calculations were taken for Wroclaw city location (Lower Silesian Voivodship, Poland) from government website [12]. We assumed natural ventilation system in all building cases.
We are aware, that there are many more accurate energy calculation tools, such as dynamic simulation modelling software based on Energy Plus engine, but this method was used intentionally to analyse the potential of our research in practical applications and efficient estimations.

**Table 1.** List of generated parameters for energy performance calculations.

| Parameter                  | Description                                                                 | Additional information, value range, value increment, units       |
|----------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------|
| Building type              | Selection of building type (1 of 4)                                         | 1) rectangular base, gable roof, 2) rectangular base, flat roof, 3) base, hipped roof 4) L-shaped base, flat roof |
| Building dimensions        | Generating random set of L, W, L_{min}, W_{max}, H and α values depending of chosen building type. Every set of dimensions gives the same heated volume (600 ± 1.5 m³) | L, W = 3.5 ÷ 20.0, [m], L_{min}, W_{max} = 3.5 ÷ 20.0, [m], H = 3.5 ÷ 12.0, [m], α = 0 ÷ 60, by 1, [degrees] |
| Number of floors           | According to building height, proper number of floors is assigned          | H < 6.0 m - 1 floor, H ≥ 6.0 m - 2 floors, H ≥ 9.0 m - 3 floors     |
| Building orientation       | Building rotation angle counted from the north                             | 0 ÷ 315, by 45, [degrees]                                           |
| Partition types            | Set of partition parameters depending of chosen building type and technology | 59 types of roofs (14 pitched roofs, 36 flat roofs, 9 ceilings to unheated attic) |
|                            | All partitions are described by U-value [W/(m²K)], thickness [m], unitary heat capacity [J/(m²K)] | 57 external walls, 10 internal walls, 3 internal floors, 7 ground floors |
| Glazing types              | Set of glazing parameters including U-value [W/(m²K)], g-value [-], orientation [degrees], percentage of glazed facade [%] depending of chosen building type | 5 window sets described by: U_w = 0.5, 0.8, 1.0, 1.3, 2.0, [W/(m²K)], g = 0.30, 0.50, 0.60, 0.67, 0.75, [-] percentage of glazing, 0 ÷ 90, [%] sum of glazing area ≥ 1/8 of usable floor area |
| Thermal bridging           | Percentage of thermal bridge share in transmission losses                   | 1 ÷ 20, continuous variable, [%]                                     |
| Thermal mass               | Depending on drawn partition parameters and window areas the building heat capacity is calculated | calculated as a sum of heat capacities for all partition areas, [J/K] |
| Internal walls             | Functional layout of building (small or big rooms) is simulated by the percentage of usable floor area covered by internal floors | 0 ÷ 20, [%]                                                       |
| Airtightness               | Airtightness of building construction by means of n_{50} value             | 0.5 ÷ 10, continuous variable, [1/h]                                 |
| Wind sheltering            | Class of wind sheltering (1 of 3)                                          | no sheltering, average or good sheltering [-]                        |
| Buffer zone                | External, unheated space connected to the one of the external building walls | no buffer zone, opaque or fully glazed buffer zone, opaque buffer zone walls made from the same materials as building (9 types) |
| Air change ratio in buffer zone | Number of air changes per hour in buffer zone by means of n value       | 0.5 ÷ 10, continuous variable, [1/h]                                 |
3. Results

Results below show relations between analysed parameters with randomly chosen values and their impact on building energy efficiency presented with EU_{H} energy index (index of usable energy for heating and ventilation purposes).

3.1. Thermal insulation quality of building envelope – mean U-value and thermal bridges

Thermal insulation quality of building should be a key aspect of every structure design and it consists from U-value for all external partitions and their junction type expressed by amount of thermal bridges share in transmission losses.

A properly insulated building, with low value of mean thermal transmittance coefficient of its envelope (average U-value) should be a good entry point into energy efficiency. Analyzing results shown on Fig. 2, where the relation between mean U-value of building envelope and EU_{H} energy index (usable energy index for heating and ventilation purposes) is presented, displays some interesting cases. The majority of the results show that when the mean U-value increases we should expect also higher EU_{H} energy index value.

But there are exceptions, like the one shown by a red arrow, which has a very high energy demand despite one of the lowest mean heat transfer coefficient for its envelope (mean U-value = 0.323 W/(m²K); EU_{H} = 289.8 kWh/(m²a)). Looking for other parameters of this case we see that this is a “barn” type shape which is rather compact (A/V = 0.81 m⁻¹), has wide, but short basis (L = 18.7 m; W = 4.8 m), high - 18.3% share of thermal bridges in transmission losses, only one floor and high amount of internal walls (18.5% floor area) which gives a very low usable floor area (A_f = 60.42 m²). Almost 71% of window are located on NE, N or NW façade. The building has very low airtightness (n_50 = 8.6 l/h).

On the other hand, one can find cases like the one shown by a green arrow, which has a rather low energy need despite two times worse envelope in terms of thermal insulation (mean U-value = 0.685 W/(m²K); EU_{H} = 75.9 kWh/(m²a)). Looking for other parameters of this case we see that this is a “brick” type shape which is a quite compact (A/V = 0.73 m⁻¹), has closer to square basis (L = 7.9 m; W = 11.8 m), low – 4.1 % share of thermal bridges in transmission losses, two floors and a very low amount of internal walls (1% floor area) which gives a 2.5x higher usable floor area than the previous one (A_f = 153.44 m²). It is interesting, that in this case 54% of windows are located on NE, N or NW facades and the structure has low airtightness (n_50 = 6.0 l/h).

A building, with low U-value partitions should also have properly designed partition junctions to avoid thermal bridges. Results, shown on Fig. 3, present the relation between share of thermal bridges in transmission losses through building envelope and EU_{H} energy index. The tendency in the results
show that when the share of thermal bridges in transmission losses increases we should expect also a slight increase in EU\textsubscript{H} energy index value.

But there can be cases, like the one shown by a red arrow, which has a very high energy demand index despite one of the lowest share of thermal bridges (thermal bridges share = 3,0%; EU\textsubscript{H} = 535.64 kWh/(m\textsuperscript{2}a)). Looking for other parameters of this case we see that this is a “brick” type shape which is a compact one (A/V = 0.74 m\textsuperscript{-1}), has almost square basis (L = 9.5 m; W = 10.8 m), poorly insulated partitions (mean U-value = 0.986 W/(m\textsuperscript{2}K)), very low airtightness (n\textsubscript{50} = 9.8 1/h), only one floor and rather high amount of internal walls (14.0% of floor area) which gives a low usable floor area (A\textsubscript{f} = 74.66 m\textsuperscript{2}). About 47% of windows are located on NE, N or NW facades.

On the other hand, there are cases like the one shown by a green arrow, which has a rather low usable energy index (EU\textsubscript{H} = 32.3 kWh/(m\textsuperscript{2}a)) despite very high thermal bridges share in transmission losses (16.8%). Looking for other parameters of this case we see that this is an “envelope” type shape which is a little bit more compact (A/V = 0.74 m\textsuperscript{-1}), has short, but wide basis (L = 5.1 m; W = 12.0 m), with highly insulated envelope (mean U-value = 0.215 W/(m\textsuperscript{2}K)), three floors and a rather high amount of internal walls (13.0% of floor area) which gives almost 2x higher usable floor area than the previous one (A\textsubscript{f} = 121.92 m\textsuperscript{2}). It is interesting, that in this case about the same as previous (42%) of windows are located on NE, N or NW facades. It is worth mentioning that the structure has very high airtightness (n\textsubscript{50} = 1.1 1/h).

3.2. Airtightness factor – n\textsubscript{50}

An energy efficient building, should also present high airtightness of the structure expressed by low values of n\textsubscript{50} coefficient. The Fig. 4 presents the relation between airtightness factor of building envelope and EU\textsubscript{H} energy index. The tendency of the results show that when the share of thermal bridges in transmission losses increases we should expect also slight increase in EU\textsubscript{H} energy index value.

But there can be some different results, like this one shown by red arrow, which has a very high energy needs despite one of the highest airtightness coefficient values (n\textsubscript{50} = 1.1 1/h; EU\textsubscript{H} = 511.5 kWh/(m\textsuperscript{2}a)). Looking for other parameters of this case we see that this is also a “brick” type shape which is compact (A/V = 0.82 m\textsuperscript{-1}), that has narrow and long basis (L = 4.2 m; W = 16.0 m), with poorly insulated partitions (mean U-value = 1.137 W/(m\textsuperscript{2}K)), has high – 16.6% share of thermal bridges in transmission losses, two floors and rather high amount of internal walls (13.0% floor area) which gives a rather low usable floor area (A\textsubscript{f} = 81.92 m\textsuperscript{2}). In this case about only about 10% of windows are located on NE, N or NW facades.

![Figure 4. Relation between airtightness factor of building envelope and usable energy index for heating purposes for all analysed cases](image)

![Figure 5. Relation between shape coefficient of building and usable energy index for heating purposes for all cases](image)
On the other hand, there can be cases like the one shown by green arrow, which has a rather low energy needs despite 8 times worse envelope in terms of airtightness ($n_{50} = 8.8$ 1/h; $EU_H = 53.9$ kWh/(m$^2$a)). Looking for other parameters of this case we see that this is also a “brick” type shape which is a compact one (A/V = 0.72 m$^{-1}$), that has closer to square basis (L = 7.4 m; W = 8.2 m), with well insulated partitions (mean U-value = 0.254 W/(m$^2$K)), has medium (11.5%) share of thermal bridges in transmission losses, has three floors and a very low amount of internal walls (2% of floor area) which gives a usable floor area of $A_f = 137.21$ m$^2$. In this case about 56% of window are located on NE, N or NW facades.

3.3. Shape coefficient – A/V

It is said, that compact shape is highly anticipated in energy efficient design, especially in small residential buildings. The Fig. 5 presents the relation between shape coefficient of building envelope and $EU_H$ energy index. There is no clearly seen tendency of the results between A/V and $EU_H$ energy index values. We can observe building with low and high A/V ratios which are practically the same in terms of $EU_H$ energy index.

Also there can be seen other cases, like this one shown by red arrow, which has a very high energy needs despite very compact shape (A/V ratio = 0.74 1/m; $EU_H = 535.64$ kWh/(m$^2$a)), which is the same case as the one shown in the thermal bridges section by the red arrow. It is “brick” type shape which, that has almost square basis (L = 9.5 m; W = 10.8 m), with poorly insulated partitions (mean U-value = 0.986 W/(m$^2$K)), has very low (3.0%) share of thermal bridges in transmission losses, only one floor and rather high amount of internal walls (14.0% of floor area) which gives a low usable floor area ($A_f = 74.66$ m$^2$). Also about 47% of windows are located on NE, N or NW facades and the building has very low airtightness ($n_{50} = 9.8$ 1/h).

On the other hand, there can be cases like the one shown by green arrow, which has a low energy needs despite, far from optimal, shape (A/V ratio = 0.95 1/m; $EU_H = 46.5$ kWh/(m$^2$a)). Looking for other parameters of this case we see that this is a “L-shaped” geometry type (L = 16.5 m; $L_{min} = 6.7$ m; W = 17.1 m; $W_{min} = 4.1$ m), has low (3.0%) share of thermal bridges in transmission losses, has only one floor and a low amount of internal walls (6% floor area) which gives usable floor of $A_f = 114.40$ m$^2$. In this case 27% of window are located on NE, N or NW facades and the structure has very high airtightness ($n_{50} = 1.2$ 1/h).

4. Conclusions and discussion

The presented material shows, that most of the parameters considered crucial for the energy efficiency of the building do not directly correlate with the $EU_H$ energy index. It is quite clearly visible, that even with some very “weak” parameters values of the building, one can achieve acceptable energy efficiency. Also its possible to end up with a very energy inefficient building, when some very favorable values are spoiled by other, not well enough defined.

We found that all cases with high energy demand (shown by red arrows on figures above) have mainly two things in common: low usable floor area and rather high internal wall to floor ratio. By looking on the building cases with low energy demand (shown by green arrows), they have much higher usable floor area values and noticeably smaller internal wall to floor ratio, but there can be also one or two very weak parameter values.

It may come as a surprise and is somewhat unintuitive, that among buildings with low demand for usable energy there are buildings of both higher and lower than average mean U-values, with a fragmented and compact shape, large and small share of thermal bridges in transmission losses, high and low airtightness. In our opinion, this proves the very complex interdependencies between these parameters - there are many cases (including even in the ones mentioned in detail) when "deficiencies" of one of the features can be “compensated” with the appropriate values of other features. When in a building collection in which it is possible to use very different (with a large range of values) parameters, this compensation is so effective that we obtain variants of buildings with the same energy demand, but with very different configuration of features. So, if it was possible to determine - within
certain ranges - sets of discussed parameters, it would be very big help in the process of building design.

The above-described cases do not exhaust the possibility of analyzing data obtained through the computer generation of building variants. This is both an advantage and a disadvantage of the adopted method. When looking for specific solutions to be used in real conditions (for a given climate zone), you can focus on buildings with the least energy demand and analyze the values of individual parameters. However, if one wants to obtain generalized results a method other than considering individual solutions will be required.

However, it should be noted that the lack of clear correlations also results in problems with indicating the optimal arrangement of features and so to say: in creating an energy efficiency importance ranking of building parameters. The number of specific variants that meet decent standards of useful energy demand is high and comparing individual configurations becomes virtually impossible. This indicates the need for applying methods of data grouping, e.g. like SOM method (Self-Organizing Maps), enabling effective data mining.

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References
[1] Depecker P, Menezo C, Virgone J and Lepers S. 2001 Design of buildings shape and energetic consumption Build and Environ 36 pp 627–35
[2] Ourghi R, Al-Anzi A and Krarti M, 2007 A simplified analysis method to predict the impact of shape on annual energy use for office buildings Energy Conv and Manag 48 pp 300-5
[3] Premrov M, Žigart M and Leskovar VZ, 2018 Influence of the building shape on the energy performance of timberglass buildings located in warm climatic regions Energy 149 pp 496-504
[4] Barulio-Gonzalo M and Bovea MD, 2017 Environmental and cost performance of building’s envelope insulation materials to reduce energy demand: Thickness optimisation Energ and Build 150 pp 527-45
[5] Persson ML, Roos A and Wall M, 2006 Influence of window size on the energy balance of low energy houses Energ and Build 38 pp 181-8
[6] Lotteau M, Loubet P and Sonnemann G, 2017 An analysis to understand how the shape of a concrete residential building influences its embodied energy and embodied carbon, Energ and Build 154 pp 1-11
[7] Edelsbrunner J, Havemann S, Sourin A and Fellner DW, 2017 Procedural modeling of architecture with round geometry Comp & Graph 64 pp 14-25
[8] Tepavcevic B, Stojakovic V, 2013 Procedural modeling in architecture based on statistical and fuzzy inference Autom in Constr 35 pp 329-37
[9] PN-EN ISO 13790: 2009, Energy performance of buildings. Calculation of energy use for space heating and cooling (in Polish)
[10] Dz. U. 2015, poz. 1422, Obwieszczenie Ministra Infrastruktury i Rozwoju z dnia 17 lipca 2015 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie (in Polish), with later changes
[11] Dz. U. 2015, poz. 376, Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 27 lutego 2015 r. w sprawie metodologii wyznaczania charakterystyki energetycznej budynku lub części budynku oraz świadectw charakterystyki energetycznej (in Polish), with later changes
[12] https://www.miir.gov.pl/strony/zadania/budownictwo/charakterystyka-energetyczna-budynkow/dane-do-obliczen-energetycznych-budynkow-1/ (access: 13.04.2018)