The influence of the architecture form in the performance analysis of a passive house in Moldavia

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Abstract. Over time, a building's energy consumption in the use phase was not decisive in the design process. However, in recent years, energy efficiency and energy autonomy have become a defining criteria in buildings' performance. In 2020, residential buildings became the space for rest, recreation, personal activities, but also for professional activities. Thus, it is essential to ensure optimal temperature, air, humidity and psychological comfort due to architectural quality. The passive house concept sets the maximum allowable energy consumption to heat the building and limit the total primary energy consumption. Passive houses improve energy-efficient buildings by ensuring a comfortable indoor environment in all seasons without requiring a conventional heat distribution system. Based on local characteristics, creating and analysing model study cases is important and could solve cities' fast development. The shape of a building influences the solar input and the total energy consumption through the total surface exposed to the outside and subject to heat loss. In order to gain knowledge about the influence of the buildings' form on energy balance, this paper presents a case study of simple shape buildings with numerical analysis according to the passive house principles in the Moldavia area of Romania. The case study of a parallelepiped model with various dimensions, varying aspect ratio and storey, was made with the planning tool Passive House Planning Package. The conclusions suggest further case studies with various roof shapes and windows' areas.

1. Introduction

One of the basic needs of life, shelter or housing, is closely connected with the natural environment. From the perspective of Le Corbusier, a French architect, the home is "a cover that meets certain requirements and establishes fair relationships between the cosmic environment and human biological phenomena"[1]. The concept of housing is a complex system of functional structures arranged according to certain relationships (individual - family - social), which function and evolve.

People spend most of their time in a home, where safety, well-being, peace, comfort are the essential elements we are looking for. Along with the components of image, perception and philosophy itself, psychological and sociological, somatic and sensory factors are equally important, defining the state of the comfort of the human body: light intensity, air temperature and humidity, air quality itself (freshness, concentration of various substances and odours), movement of air currents, noise and vibration, factors that must fall within specific value ranges in order to maintain our well-being and hygiene at high standards. The human body, as a biological organism, physically feels a state of comfort. The air temperature should be 20-25° Celsius in an indoor space, the relative humidity 45-55%, the carbon dioxide concentration below 500ppm and 30mc of fresh air per hour. The natural environment must not influence the constancy of these elements. One of the critical roles of any construction, besides the aesthetic and functional, is the guarantor of comfort and well-being at the physical level.

The first step in designing an energy-efficient house should be a rational passive design, focused on climate conditions, the building's form and orientation, offering good thermal and living comfort, even without active systems. Implementing passive solar design principles in an architectural project determines a significant reduction of energy consumption throughout the life cycle of a building without a significant impact on the initial investment or maintenance costs.
specific to passive design can be easily integrated into a contemporary architectural solution. The building’s form influences the energy balance of the building. The compact form is preferred in many cases, defined by a small shape factor (defined as the ratio between the envelope surface (A) and the building volume (V)). Also, another parameter important in the energy balance is the aspect ratio defined by the ratio between length and width of the building.

The residential field is well documented and studied from the point of view of energy efficiency. Energy consumption of residential buildings increases worldwide by about 30% annually [2]. Because of this, the residential buildings had priority in implementing energy efficiency concepts.

2. Passive House
Passive House is a concept of energy-efficient buildings, presented by Dr Wolfgang Feist from the Passive House Institute in Germany, which has had the most outstanding impact on architects, customers and researchers. The concept sets the maximum allowable energy consumption for heating the building and limits the total primary energy consumption. The passive house standard is met if a building has a heating energy consumption under 15kWh/m²yr and a total energy requirement of a maximum 120kWh/m²yr [3]. Passive houses improve low-energy houses by ensuring a comfortable indoor environment in all seasons without requiring a conventional heat distribution system [3]. According to J Schnieders, W Feist and L Rongen [4], passive houses use 80% - 90% less energy for heating than conventional buildings for the same interior space conditions for an additional cost of up to 10%. Unfortunately, most new constructions in Romania have heating energy consumption over 150kWh/m²yr, ten times higher than Passive Houses. According to the Passive House Database, there are 22 certified passive house buildings in Romania, built from 2008 till 2021. The number increases as energy-efficient buildings become a mandatory standard.

Passive House Planning Package, an Excel-based calculation program, was first launched in 1998 and is constantly evolving to verify the buildings’ compliance with the Passive House standards. Calculation sheets for the energy balance (annual and monthly), for the distribution and supply of heating and the need for electricity and primary energy, are the main elements of this calculation tool. Also, calculations are analysed regarding the windows’ characteristic values, the impact of shading, the heating load and the demand for cooling and dehumidification.

3. Review of studies for the influence of architecture form in energy efficiency balance
The shape of a building influences the solar input and the total energy consumption through the total surface exposed to the outside and subject to heat loss. In the design of a building, the ratio between its external surface and the total volume must be minimal, the ideal case being a hemisphere. Due to the problems of designing the interior space of a hemisphere, many researchers have conducted studies of the performance of parallelepiped buildings, followed by optimizations related to the planimetric shape (square, rectangle, hexagon, octagon, oval).

Studies on the shape of buildings and the outdoor climate have been made: research on the shape of the building based on passive strategies that provide the comfort of the interior [5], research on the use of the sun for heating [6] and research on the effect of urbanization on urban climate - the effect of the island of urban heat [7]. In the study conducted by M Premrov, M Žigart and V Žegarac Leskovar [8], 216 models of box-type buildings were analysed parametrically, with wooden frame structure, with variations on thermal transmittance, size of glazed areas, orientation, the ratio of facades, horizontal and vertical volumetric extension in several cities: Ljubljana, Helsinki, Munich, London, Athens and Madrid. The size of the glazed surfaces and their positioning linearly influence the energy balance, and the shape of the building has an impact on the building's energy efficiency.

The rapid development of cities requires a detailed study of buildings' shape, from micro to macro scale. Okeil A., in his article “A holistic approach to energy-efficient building forms” [9], highlights the lack of sets of design guidelines for achieving energy-efficient forms of construction throughout the year, forms that can create building blocks to increase the performance of the whole city. The analysis compares three types of residential neighbourhoods at a latitude of 48 degrees, as shown in
figure 1: Linear, block (conventional) and RSB (Residential Solar Block - energy efficient). The residential solar block (RSB) is an energy-efficient form of construction, optimized to avoid winter shading, functional and aesthetic. Several types of housing can be organized in RSB: apartments, garden apartments (on the roof of other apartments), terraced houses. The analysis results highlight the advantages of the RSB form: functional, versatile, social, aesthetic, high sun exposure, increased airflow, the possibility of green roofs in direct connection with housing [9].

The main output of the current study and these previous studies is to offer architects general information on buildings' energy-efficient design parameters.

![Figure 1. Three types of residential neighbourhoods: linear, block, RSB [9]](image)

4. Numerical study

The presented numerical research is based on a case study of a parallelepiped model with various dimensions (square plan vs linear plan, one-story house vs two-story house) made of good thermal envelope elements (U=0.10 W/ m²K), with windows on the south façade of the buildings but also on west and east. The study analyses the energy performance in the Moldavian Area of Romania, in the North-East of Romania, with characteristics of temperate climate, hill area, detailed in Table 1.

| UM                              | Values  |
|---------------------------------|---------|
| Average annual temperature      | °C      |
| Maximum positive outdoor temperature | °C  |
| Maximum negative outdoor temperature | °C  |
| Length of the heating period    | days/year |
| Total solar radiation on the south vertical surface in the heating period | kWh/ m² |
| Total solar radiation on the west/east vertical surface in the heating period | kWh/ m² |

The study was made with the planning tool Passive House Planning Package to calculate energy flows and energy needs for heating and cooling. The planning tool PHPP 9 is based on EN ISO 13790, which shows high levels of precision and accuracy in calculating energy balances.

The first comparison is between two single-storey models with a constant occupied floor area of 64 m², a constant heated volume of 192 m³ and a varying aspect ratio (the ratio between length and width): a square plan (1A) and a linear plan (1B). Both models have a constant window surface of 50% of the south façade. The first model, with the square plan, has the heating energy consumption 22,7kWh/m²yr and the thermal load of 16,2W/ m², while the second model, with the south façade
larger than the western and eastern one, has the heating energy consumption 22.9 kWh/m²yr and the thermal load remain 16.2 W/m². The aspect ratio of the first model (1) is slightly preferred rather than the aspect ratio of the second one (1.52), as shown in Table 2.

Table 2. First comparison – model 1A and model 1B

| Nr. | Shape | Storey Area (m²) | Volume (m³) | Aspect ratio (L/W) | South Window % | West Window % | East Window % | Heating Energy Consumption (kWh/m²yr) | Thermal Load (W/m²) | Frequency of the overheating period (%) |
|-----|-------|------------------|-------------|-------------------|----------------|--------------|-------------|-------------------------------------|--------------------|----------------------------------------|
| 1A  |       | 1                | 64          | 1                 | 50             | 0            | 0           | 22.7                                | 16.2               | 40.4                                   |
| 1B  |       | 1                | 64          | 1.52              | 50             | 0            | 0           | 22.9                                | 16.2               | 40.2                                   |

The second comparison is between two models: a single-storey model (1A) and a two-storey model (2A) with a constant occupied floor area of 64 m² and a constant heated volume of 192 m³. The previous calculations indicated that the first model, a single-storey with a square plan, has a heating energy consumption 22.7 kWh/m²yr and a thermal load of 16.2 W/m². In comparison, the two-storey model, with the same occupied area floor and the same window surface, has the heating energy consumption 20.5 kWh/m²yr and the thermal load of 14 W/m², as shown in Table 3. The results show that the two-storey houses are preferred rather than single-storey ones. Besides, if choosing to design a single-storey house to gain solar radiation, the area of the south-oriented window should be larger than in two-storey house designs.

Table 3. Second comparison – model 1A and model 2B

| Nr. | Shape | Storey Area (m²) | Volume (m³) | Aspect ratio (L/W) | South Window % | West Window % | East Window % | Heating Energy Consumption (kWh/m²yr) | Thermal Load (W/m²) | Frequency of the overheating period (%) |
|-----|-------|------------------|-------------|-------------------|----------------|--------------|-------------|-------------------------------------|--------------------|----------------------------------------|
| 1A  |       | 1                | 64          | 1                 | 50             | 0            | 0           | 22.7                                | 16.2               | 40.4                                   |
| 2A  |       | 2                | 64          | 1                 | 50             | 0            | 0           | 20.5                                | 14                 | 40.7                                   |

The third comparison is between four single-storey models with a constant occupied floor area of 64 m², a constant heated volume of 192 m³ and a varying window's position: only on the south façade of the building (1A), on south and east façades (3A), on the south and west facades (3B) and on south,
east and west facades (3C). The previous calculations indicated that the first model, a single-storey with square plan and windows only on the south façade, has a heating energy consumption 22.7 kWh/m²yr and a thermal load of 16.2 W/m². The second model, with the same area and volume but with windows also on the west façade (16% of the west façade), has the heating energy consumption 24.4 kWh/m²yr and the thermal load of 17.4 W/m². The frequency of the overheating period also increased by 3.6%. The third model, with the same area and volume, but with windows on the south façade (50% of the south façade) and on east façade (16% of the east façade), has the same heating energy consumption (24.4 kWh/m²yr) and thermal load (17.4 W/m²). The fourth model, with the same area and volume, but with windows on the south façade (50% of the south façade), on east façade (16% of the east façade) and west façade (16% of the west façade), has the heating energy consumption 26.1 kWh/m²yr and the thermal load of 18.7 W/m². The frequency of the overheating period also increased by 6.3%. The results of this third comparison conclude that the glazing areas are better placed on the south-oriented building envelope to obtain an increased share of solar gains useful for the building's passive heating. However, a good and evenly distributed natural illumination is also influenced by space's comfort factor, gained by positioning some windows on other building facades (west and east facade).

| Nr. | Shape | S Area (m²) | Volume (m³) | Aspect ratio (L/W) | South Wind Windows (%) | West Wind Windows (%) | Heating Energy Consumption (kWh/m²yr) | Thermal Load (W/m²) | Frequency of the overheating period (%) |
|-----|-------|------------|------------|-------------------|------------------------|----------------------|--------------------------------------|-------------------|---------------------------------------|
| 1A  | 1     | 64         | 192        | 1                 | 50                     | 0                    | 22.7                                 | 16.2              | 40.4                                  |
| 3A  | 1     | 64         | 192        | 1                 | 50                     | 16                   | 24.4                                 | 17.4              | 43.6                                  |
| 3B  | 1     | 64         | 192        | 1                 | 50                     | 16                   | 24.4                                 | 17.4              | 43.6                                  |
| 3C  | 1     | 64         | 192        | 1                 | 50                     | 16                   | 16                                   | 26.1              | 46.3                                  |

The essential heat source is solar energy, which heats the indoor air through incident solar radiation. The percentage of glazing area in the south façade was kept constant in the first two comparisons. The windows' characteristics were chosen to assure a high level of heat insulation and light transmission: \( U_g = 0.50 \text{ W/m²K} \), \( U_f = 0.73 \text{ W/m²K} \), \( g = 0.52 \). If the overheating period's frequency is over 10%, the solution is the shading systems, such as vegetation, roof consoles, light exterior window shading systems, that reduce by 10% to 40% of the energy required for cooling (Maleki, 2011). The use of vegetation (trees, intensive vegetation, green facades, green roof) offers increased comfort to building users through shading, protection against wind, pollution and noise. Planting deciduous trees and shrubs, which shade the southern side of buildings, reduces the temperature by 5 degrees Celsius on the thermal envelope's surface (Kamal, 2012). Evergreen trees are planted on the west and east sides to protect the building from wind and sun at sunrise and sunset.
5. Conclusions
The general conclusion from the presented study and the reviewed studies is that the building shape influences the energy balance. The presented study results can lead to optimal design solutions for single and two-storey houses with a constant floor area and a varying building aspect ratio and storey. The general results' benefit is to set basic guidelines for architects for a quick estimation of buildings' energy performance, designed in different shapes.

The recommendations for the climate area of the Moldavian Area in Romania are to design compact forms with an aspect ratio near 1, with at least two storeys and small windows on west and east facades. Generalizing, those guidance lines could work on almost all zones of cold temperate climate areas.

There are still a series of parameters which is recommended to be further analysed. The south-oriented window ratio could vary as the house's interior space is designed, and it can influence the energy balance. Furthermore, in Romania's climate condition, a flat roof is not recommended. It would also be helpful to analyse a similar case with a slope roof and roof windows, as the zenithally light makes a significant contribution to well-being.

6. References
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