Quantifying the effectiveness of mass proportions and the orientation for buildings on thermal performance in Tebessa, Algeria

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Abstract. Macro-Climate and Micro-Climate conditions have a great influence on energy consumption and thermal performance on both urban and architectural design scales. Integrating the passive strategies and measures are considered the best ways of dealing with different climatic conditions. The geometric shape and orientation of the buildings lie at the core of the passive strategies that significantly affect the thermal performance and energy consumption of buildings. From that end, the research aims to evaluate the thermal performance of different geometric shapes and orientations of residential buildings. The research adopts the analytical approach through the simulation of different possible scenarios using of building shapes and orientation using comprehensive environmental software “Autodesk ECOTECT”. It aims to achieve the best possible configuration that exhibit best thermal performance for use in residential buildings in the region of Tebessa (Algeria).

The results indicate significant thermal effects due to proportions of building’s shape and its orientation. Therefore, this research recommends applying passive solar design strategies, particularly with respect to the geometric shape and orientation recommendations in the first stage of the design process. The proportions of the building must be determined with a complete understanding of their impact on thermal performance and energy consumption.

Keywords: Building’s form proportions, Orientation, Thermal Performance, Cold Semi-arid Climate, Energy Efficiency.

Nomenclature

MWh  Mega Watt hour……………… MWh  L  mass length…………………..
U    U value…………………………… W/m2.K. S  mass surface…………………
W/m².K. W  mass height…………………. m  m²
V  mass width………………… m  m³
mass volume…………………

1. Introduction
Thermal performance is largely influenced by Building’s form proportions [1]. It is considered one of the main indicators for successful building design and it aims to provide the most comfortable environment for the occupants and thus minimize the energy demand for cooling and heating needs. Its importance has increased in conjunction with the energy crisis, environmental pollution and climate change caused by the massive use of energy in buildings. The composition of the building
(shape, orientation, compactness, materials ... etc.) which are in fact conceptual choices have a strong influence on energy efficiency and thermal performance of buildings. Comfort of users is the main preoccupation of designers; it affects the whole life of the building and the wealth of its occupants. Thermal comfort is sensible and sensitive especially in harsh climate conditions. In regions with prolonged summer season, the building sector consumes more energy for cooling, in offices, space cooling is the main consumer, in dwellings it is domestic hot water [2].

Many studies have been done in the subject (Lim & Kim 2018 [1], Tebbouche et al. 2017 [3], Lee et al. 2016 [4], Ling et al. 2007 [5], Ratti et al. 2003 [6] focusing on the impact of building’s shape on energy consumption. In this paper, we are interested in the evaluation of the impact of mass proportions and different shape orientations of the building on the heating and cooling loads in a specific harsh climate of Tebessa in Algeria, using simulation of different possible scenarios through Ecotect to compare the variation in thermal performance according to orientation, proportions and surface to volume ratio (S/V).

2. Methodology
This research focuses on evaluating the effect of different proportions and orientations of building shapes on their energy efficiencies. In order to achieve these objectives, several scenarios are created and tested through numerical simulation using Autodesk ECOTECT with climate data from the Tebessa region (Algeria). These scenarios are created based on the most common shapes and dimensions in the region through the variation of the following parameters: Proportions of shape, orientation and compactness ratios (S/V). The analysis of the simulation results is based on the comparison of heating and cooling loads of the different scenarios in three phases:

- Evaluation of the effect of different width to length ratio on heating and cooling loads, the effect of different orientations on the change in the thermal response of different ratios, the effect of building height (on the S/V ratio) on heating, cooling and total loads. The study is concerned with the case of the highlands in Algeria and takes as land the city of Tébessa on a latitude of 31.5N and a longitude of 8.1E and an average altitude of 860m, it is located which has a steppe climate with minor precipitations throughout the year, according to the Koppen-Geiger classification is a climate of type BSK: steppe climate (semi-arid) dry and cold. this climate generally includes (sometimes hot) and dry (winter) summers, cold winters [7].

3. Energy efficiency and thermal performance of the building

3.1. Definitions
The housing sector is one of the most energy-consuming sectors all over the world. In Algeria, it accounts for more than 60% of the total energy consumption, while air conditioning in summer and winter heating are the highest contributors for this consumption. A new reflection on the quality of energy performance of buildings becomes a necessity, especially in regions with harsh climates. Architects should give the thermal performance of buildings more attention as the most important factor in energy consumption. Nayak and Prajapati [8] defined the thermal performance of a building as the process of modelling the transfer of energy between the building and its environment. The temperature difference between the inside and the outside is the main driver for the flow of energy to and from the building. It is also proportional to the thermal quality of the building’s enclosure [9]. The well-being of occupants and their productivity are strongly related to the degree of thermal comfort in the building [10]. Ghisi and Massigiano [11] reported that energy consumption in buildings is associated with their thermal performance; Heat transfer through building components such as walls, openings and floors. This thermal response in turn determines the heating or cooling energy required to maintain comfortable thermal conditions for the occupants [12]. Yu et al [13] concluded that the most important factor influencing cooling and heating energy consumption is the heat transfer coefficient of the walls followed by the building form factor.

3.2. Factors influencing the thermal performance of buildings
The thermal performance of a building depends on a large number of factors. Nayak and Prajapati [8] summarized these factors as design variables, physical properties, meteorological data, and building usage data.
a. The variables of the design: many variables must be taken into account during the design of the building:

- The shape of the building; it determines the size and orientation of the outer envelope exposed to the external environment. A good choice of shape and orientation can reduce energy consumption to 40% [14] the solar radiation received as well as the heat losses are affected by the exposed surface and the surface / volume ratio. It is an important factor determining heat loss and gain. The more compact a building is, the easier it is to meet an energy-efficiency standard. The surface-area-to-volume ratio (S/V ratio for short) has a considerable influence on a building's energy requirement [8].

- The orientation of the building controls the rate of direct solar radiation and the effect of winds on the building. The choice must respond to the expected impact of the shading and the solar course according to the latitude and the periods of the year (figure 1).

![Figure 1: Building Orientation Based on the Sun Exposure.](image)

b. Shading devices; they have a useful impact in Mediterranean and semi-arid climates. The time of the year, the tone of relative transparency of materials can affect shading [11].

c. The properties of materials: According to Rosenlund [12] the most important thermal properties of building components that affect thermal efficiency are:

- Thermal conductivity $\lambda$
- The thermal resistance of a material $R$
- Thermal transmittance $U$
- Density, porosity

d. The occupation and building operation: the use of buildings produces heat, steam and light (internal gains). The density of occupancy and the types of activities affect the total heat gain. According to Utzinger and Wasley [13], equipment and light in buildings emit heat equal to the electrical energy they consume. According to Lykartsis et al [15] “Buildings that are cooled or heated mechanically can also overheat if the ventilation system is, undersized or poorly controlled. overheating is therefore a function not only of temperature but of the humidity, air speed and the clothing and activity of the occupants”.

3.3. **Shape and orientation, strategy for climate adapted design:**
Designers are now moving towards climate-friendly design as one of the means that has proven to be effective in saving energy. Mikler et al [16] defined passive design as an approach to building design that uses building architecture to minimize energy consumption and improve thermal comfort. The shape of the building and the building elements are carefully considered and optimized according to the local microclimate.
Climate design strategies depend on the use of opportunities to adapt to local climate, some of these strategies remain the same in different climates [17]. The layout, shape and orientation of buildings in addition to the spacing between them are the most important strategies affecting indoor thermal comfort. In addition, the building envelope is highly influential because it separates the indoor environment from the outside [18].

Bahadori-Jahromi et al. [19] concluded that retrofitting an older building uses four to eight times less resources in comparison to new buildings. However, certain buildings are more challenging retrofitting due to their baseline energy performance, which is the result of many conceptual proprieties including shape and orientation.

The main principle in choosing the shape of the building is the ability to minimize the heat transfer by the envelope. According to Goulding et al [20], reducing the ratio of surface area to volume can improve thermal performance. Many factors influence the shape of the building such as planning and use of the building, self-shading ... etc. the shape of the building influences the flow of the wind over the airflow patterns, as well as the potential for use of natural light [20]. In general, geometric variables including length, height, and depth control objective values such as building volume and areas [8]. The compactness ratio S/V controls the exterior heat loss and gain, small S/V ratios imply minimum heat gain and minimum heat loss [1].

4. Simulation protocol
Simulations were conducted during the months of January to December. The HVAC system was assumed to be full air conditioning with the heating and cooling set point assumed to be 18.00°C and 26.00°C respectively. The use of buildings (hours of operation) has been assumed to be continuous. The study focuses on incident solar radiation as one of the most important variables in the semi-arid cold climate affecting heating and cooling energy consumption.

The exterior walls have a U value of 1.77 W/m².K. The U-values of the roof are 0.896 W/m².K. It has been assumed that the heat transfer values, the U value for the walls, the roof and the floor have reached the minimum requirements for maximum U values, as recommended by the Algerian Code for Energy Efficient Building. For solar radiation calculations, ECOTECT uses direct and diffuse radiation data recorded per hour from the weather file (epw).

In order to better understand these integrated parameters, the research will study the rectangular shape in more detail, since it considers the most popular form in residential buildings, the simulation is divided into 3 sections: The first section will present a study of 12 different geometries with a different ratio (w/L) to examine the correlation between the increase in the ratio (w/L) with the increase in heating, cooling and total loads compared to the most compact geometry reference (1x1x1) 0E). The second section will study the effect of changing orientation on the change in the thermal response of different ratios. The third section will focus on the effect of building height on heating, cooling and total loads.

Justification for choosing the different ratios and orientations should be added here.

4.1. Parametric investigation
The simulation studies the effects of a number of parameters in the two main response variables, energy requirements and incident solar radiation. The combinations of parameter values analyzed in this study are summarized in the table 1.
Table 1: Different simulation scenarios (variation of proportion and orientation parameters) Source: authors using ECOTECT

| Form | A | B | C | D |
|------|---|---|---|---|
| Ratio W/L | 1/1 | 1/1 | 1/1 | 1/2 |
| Height | 1/1 | 1/1 | 2/1 | 1/1 |
| Ratio S/V | 6 | 6 | 5 | 5 |
| Orientation | 0°E | 45°E | 0° | 0°E |

| Form | E | F | G | H |
|------|---|---|---|---|
| Ratio W/L | ½ | 1/2 | 1/2 | 1/4 |
| Height | 1/1 | 1/1 | 2/1 | 1/1 |
| Ratio S/V | 5 | 5 | 4 | 4.5 |
| Orientation | 45°E | 90°E | 45°E | 0°E |

| Form | I | J | K | L |
|------|---|---|---|---|
| Ratio W/L | ½ | 1/2 | 1/2 | 1/2 |
| Height | ½ | 2/1 | 2/1 | 1/2 |
| Ratio S/V | 3.5 | 4 | 4 | 3.5 |
| Orientation | 0°E | 0°E | 90°E | 90°E |
5. Simulation and results

The results of the simulation were expressed in terms of annual heating and cooling loads (in MWh).

5.1. The ratio of width to length

As shown in the graph in Figure 2 the heating loads are reduced by 42.9% by increasing the width-to-length ratio (W/L) from 0.25 (H) to 1 in East-West (0E) orientation (Table 1: A(1/1), D(1/2), H(1/4)). About 39.2% of this reduction occurs by increasing the ratio (W/L) from 0.25 (H) to 0.5 while only 6.1% of the reduction occurs by increasing the ratio (W/L) of 0.5 to 1. Cooling loads are reduced by 36.7% increasing the width ratio (W/L) from 0.25 to 1 in East-West orientation (0E). About 35.9% of this reduction occurs by increasing the ratio (W/L) from 0.25 to 0.5 while only 1.2% of the reduction occurs with increasing ratio (W/L) from 0.5 to 1. Note that the change in the ratio (W/L) affects the total area exposed and the relationship between its two main components, the roof and the walls. As the ratio (W/L) increases and the building reaches the square shape (W/L = 1), the exposed area decreases with the same tendency to decrease heating, cooling and total loads.

![Figure 2: Cooling loads and heating loads (MWh) by ECOTECT for various W/L ratios (A, D, H)](image)

5.2. Orientation:

The effect of changing the orientation by keeping the (W/L) ratio fixed at ½ (Table 1, variants D, E and F) creates a difference in the total loads despite the same ratio difference (S/V) is explained by the fact that while increasing the Width ratio in east-west orientation (0E) decreases the surface of the south and north facades, increasing the width ratio in the north-south orientation (90E) decreases the surface of the east and west facades which are considered the most critical facades as incidental radiation on the eastern facades in the morning and the west facades in the afternoon are much larger than those of the south facades in the middle of the day. Figure 3 illustrates the position of the low latitude of the sun in the morning and evening of summer periods that increase the incident solar radiation on the east and west facades in comparison with the high latitude position of the sun on the south façade.

![Figure 3: Sun course and exposure of building facades, Source: google.com](image)

Changing the orientation of the building from east-west orientation (0E: Table1, D) to north-south orientation (90E: table1, F) may increase the effect of the width ratio. Total loads are reduced by 45.7% by increasing the ratio of width to length (W/L) from 0.25 (Table 1, H) to 1 (Table 1, A) to the North-South orientation (90E). In addition, increasing the ratio of width to length (W/L) from 0.5 to 1 reduced
total load by about 7.9% in North-South orientation compared with only 3.5% in the case of East-West orientation. To do this, more attention must be paid to the width ratio in the North-South orientation, even between the ratio of the shapes of the width between 0.5 and 1 (Figure 4,6).

The effect of orientation by affecting the role of width-to-length ratio in reducing energy consumption is more visible in cooling requirements. Increasing the ratio of width to length (W/L) from 0.25 to 1 in the North-South orientation (90E) (Table 1, H, A) reduces cooling loads by about 48.2% compared to 36.7% in East-West orientation (0E). Increasing the ratio of width to length (W/L) from 0.5 to 1 (Table 1, D, A) reduces cooling loads by about 9.8% in North-South orientation (90E) compared to only 1.2% in East-West orientation (0E). Figure (5,7).

It is considered that changing the orientation of simulated shapes with different width-to-length ratios (W/L) allows the required energy to be changed, as it affects the amounts of solar radiation on the different components of the building surface. As the shape approaches the square shape, the effect of the orientation in the change of the total charges is decreased. This is due to the four equal sides of the square shape that make the east-west orientation (0E) and the north-south orientation (90E) have the same performance. Instead, the worst orientation in this case is (45E) (Table1, B,E) with an imperceptible difference in the total loads. Figure (6).
The effect of changing orientation is not remarkable in heating loads. While changing the orientation from (0E) to (90E) increases the total loads, the effect of changing the orientation is more visible in the cooling loads. About 20.5% of the cooling charges can be increased with the changing orientation from (0E) to (90E) in the form with a width / length ratio (W/L) equal to 0.25 (Table 1, H). This percentage gradually decreases with the increase of the ratio (W/L) to reach 2.8% in the case of the square form (W/L = 1) with the changing orientation of (0E) to (45E) (Table 1, A,B). Figure (7) illustrates the percentage increase in cooling loads for different orientations.

The same trend can be observed in the heating and cooling loads as shown in Figure (9). Cooling loads are increased by 37.6% by increasing the building height from 1/2 to 2/1. The larger effect of the increase in building height can be seen in the heating loads. About 107.6% of the increase in heating loads occurs by increasing the height of the building from 1/2 to 2/1 passing by 1/1 (Table 1: I, D, J).
Changing the orientation of the simulated forms with the difference in height is considered to have the ability to change the required energy because it affects the amounts of solar radiation on the various components of the building surface. The results indicate that the total loads for the simulated forms are increased by 2.8% by changing the orientation of the East-West orientation (0E) towards the North-South orientation (90E) for the shape with 2/1 (Table 1, J, K) and 35.08% for the 1/1 form (Table 1, D, F). This ratio decreases to 1.7% in the case of the form with a height 1/2 (Table 1, I, L) Figure (9).

The combination of these studies resulted in:
- The surface/volume ratio is the main responsible for the thermal response in different geometric shapes.
- Total loads are reduced by 39.6% by increasing the width-to-length ratio (W/L) from 0.25 to 1 at East-West (0E) orientation.
- The reduction in total charges is more remarkable by increasing the ratio (W/L) from 0.25 to 0.5. About 37.4% of the total load reduction occurs by increasing the ratio (W/L) from 0.25 to 0.5 while only 3.5% of the reduction occurs by increasing the ratio (W/L) from 0.5 to 1.

6. Conclusion
Parametric studies were conducted using the Autodesk ECOTECT simulation program to study the effect of shape on thermal performance and energy consumption. Therefore, the study involved understanding the relationship between building geometry, proportions, ratios, and thermal performance. This part has treated geometries as an autonomous building to avoid the effect of adjacent buildings. For the sake of clarity, the study focused on the main aspects that define the form of construction which is the ratio surface/volume, the ratio width, the height of the building, the geometry of the building. The orientation of the building is another aspect that affects the relationship between the building facades and the incident solar radiation that results.

The effect of the S/V ratio
S/V ratios and its effect on the thermal performance of the buildings
- The modification of the ratio (W/L) affects the total exposed surface and the relationship between its two main components, the roof and the walls.
- The total loads for the simulated forms are increased by 11% by changing the orientation of East-West orientation (0E) towards the North-South orientation (90E) for the aspect ratio with width (W/L) equal to 0.25.
- The impact of changing orientation is not remarkable in the heating loads. While changing the orientation from (0E) to (90E) increases the total charges, it reduced the heating loads by 1.6% in the form with a width / length ratio (W/L) equal to 0.25.
- The greatest effect of changing orientation can be noticed in cooling loads. About 20.5% of the cooling charges can be increased by changing the orientation of (0E) to (90E) in the form of a width / length ratio (W/L) equal to 0.25.
- The increase of the total loads required by the building geometries with the same ratio (S/W) due to the height increase is more related to the reduction of the ratio (roof / walls) which increases the vertical surfaces of the building’s walls.

7. Recommendations:
- It is important to eliminate the heat transfer rate between the building envelope and the surrounding environment in the means of conduction, convection and radiation in order to maintain the thermal equilibrium.
- It is necessary to use passive solar design strategies by controlling the architectural elements and material properties of a building in relation to climatic factors.
- Sufficient reporting must be made in the semi-arid cold climate, especially for the shape and configuration of the building, as solar radiation is the most important parameter in this climate.
- The compact form is recommended in the semi-arid cold climate.
- More attention must be paid to the width-to-length ratio in the North-South orientation, even between width-to-length shapes between 0.5 and 1.
- It is recommended to pay more attention in the orientation of the selection, especially in shapes with the smallest aspect ratio.
- Orientation East-West (0E) is considered the optimal orientation in all cases, while orientation from (70E) to (90E) is considered the worst orientation in all cases except the square form which at the worst orientation equal to (45E), with a different noticeable energy consumption.
- It is recommended using shapes with the ratio (roof/walls) between 0.4 and 0.6, which is preferable for the needs of cooling and heating.

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