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Parametric Study for Optimising Building Form and Height: An Approach toward Net Zero Energy & Carbon in Buildings

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Abstract: Due to the excessive use of natural resources and fossil fuels, our planet has started to show its weak points. Several ecological and economic crises have occurred in the last decades. The building sector is held primarily responsible for one-third of global energy consumption and greenhouse gas emissions, and the advent of COVID-19 has not improved this with its containment. For this reason, improving the energy efficiency of buildings and reaching the net zero concept have become the primary objectives of all policies. Several measures are to be undertaken to achieve this concept, ranging from passive and active strategies to the use of renewable energy. This work aims to analyse and study the morphology of the building with geometric plan and height variables to know their influences on the energy consumption of residential buildings in three different types of Algerian climates, semi-arid, arid, and Mediterranean. Using SketchUp and the cloud-based simulation tool Sefaira, the results showed that the triangular-shape based plan has the best energy consumption, allowing a reduction of 18% from the worst-case scenario, and that the difference in height can save up to 17.5%, which is worth 51 kWh/m²/year.

Keywords: building morphology; energy use intensity; greenhouse gases; net zero energy; residential buildings

1 INTRODUCTION

Strong economic growth and rapid urbanisation have resulted in standardisation and flatness in building environmental design, increasing both energy demands and greenhouse gas emissions in the building sector [1]. As a result, this sector has also become responsible for about one-third of global energy and carbon emissions and more than half of the world's electricity consumption [2].

Most of this energy is derived from air conditioning in hot climates and space heating in cold climates. At this rate, the global energy consumption and carbon emissions of buildings is expected to increase at an average annual rate of 1.5% from 2012 to 2040 [1]. Global warming resulting from this increase has become the most pressing issue facing the planet today [3]. Continuing with this trend, a global warming of 2 degrees would affect people and nature. One third of the world's population would be regularly exposed to high heat, which would lead to health problems [4].

Demand for the building sector may increase further in the future due to economic and demographic growth in southern hemisphere regions such as Africa [5]. Because of this demand and the lack of housing, Algeria has experienced a standardisation of housing types in the different regions of the country [6], resulting in the same conceptual and architectural characteristics for different needs, aiming more at the quantity than the quality, generating typical buildings that does not meet the environmental needs or the needs of users.

The residential building sector is one of the largest consumers of energy in Algeria, responsible for over 30% of CO_2 emissions and 36.6% of energy consumption, with an annual increase that continues to grow (2.6% compared to 2018, 17% compared to 2017) [7]. With this in mind, Algeria has tried to develop some programs, such as the programme of the national agency for the promotion and rationalisation of energy use (APRUE), the Algerian national programme of energy efficiency for the building sector 2016 and the renewable energy program, which aims to improve energy efficiency and reduce both the growth of energy demand and dependence on fossil fuels by using more renewable energy [8].

At the Conference of the Parties 26 (COP26), adhering countries were asked to present ambitious energy and emission reduction targets for 2030, which are in line with the main objective of this COP, namely to ensure global net zero by mid-century [4]. As the sector consuming most of the world's energy, we can conclude that the building sector is also a element of this energy transition, which is becoming necessary [9]. An energy transition in the building sector means ensuring minimum energy consumption in order to achieve optimal living comfort and use of the building [10].

In this context, the topic of Net Zero Energy Buildings (NZEB) has received increasing attention in recent years. The European Energy Performance of Buildings Directive (EPBD) defines it as a building with a very high energy performance, while the remainder must be supplied by renewable energy sources located on site or nearby. In other words, a NZEB combines the design of buildings with high energy efficiency systems and the use of on-site renewable energy [2]. Torcellini et al. also define NZEB as a building whose energy consumption is reduced to balance energy demand with energy supply from renewable energy technologies [11].

The transition to NZEB can be done by following a path based on passive bioclimatic design and then using energy-saving systems to finally balance the rest with renewable energy. The integration of passive design measures into buildings has been the subject of much research, with one of its measures being the optimization of building morphology. According to Pacheco, the design phase of a building is the best time to study and integrate passive strategies. When these strategies are implemented at the very beginning of the construction phase, it allows for a reduction in the implementation costs compared to the case where they would be installed during the later stages of the construction. One of these strategies is the study of the building morphology that influences the heating and cooling requirements, which can be done by studying the following indices: compactness, form factor, and climate [12]. The studies of Menezo et al. on a single morphological group (parallelepiped), which was chosen for its representativeness of the majority of the structures already built, have shown that the more compact the building, the lower the energy consumption. And that climatic variation (temperatures, solar irradiation) is one of the most important parameters in the study of building morphology [13]. Catalina et al.'s various works confirm that building morphology is an important design parameter in the process of finding an energy-efficient project, with a significant impact on daylighting [14]. Straube says that the ratio of envelope area to floor area is important in all building types and that simple, more compact forms are better in terms of energy efficiency, but also less expensive to build and maintain. He points out that the German energy code goes so far as to prescribe higher thermal resistance values for less compact buildings than for others [15]. Hemsath & Alagheband Bandhosseini were able to determine with a sensitivity analysis on the morphology of the building by studying different ratios of geometric dimensioning and different variables of stacking in height, that these two aspects have, in some cases, depending on the location and climate, a greater impact on the energy performance of a building than the materials used in the envelope or other energy-efficiency variables [16].

That is why our article aims to fill the various gaps in knowledge about the impact of building morphology on energy consumption in the three Algerian climates studied. The research will take place on a basic parallelepiped building with a residential function, whose characteristics, configuration, and structure represent a typical and standard reference case of the Algerian building stock, so that subsequently several other variables of shape and height are introduced.

The first part of this research uses a simulation tool, which is the Sefaira plugin integrated into the modelling software SketchUp, to collect information on the impact of the morphology of the building on the energy consumption and emissions of the different variables. The second part aims to calculate the cost that can be saved by changing variables, to finally have optimal variables for each climate.

2 METHODS

The purpose of this article is to compare the different performances of eight types of form: rectangular, square, triangular, trapezoidal, circular, H, O and C; and eight variables of height, which are: 2, 3, 4, 5, 13, 26, 39, and 52 floors, under three different climates Algerian climates, semi-arid with the climate of Constantine, arid with the climate of Ghardaïa and Mediterranean with the climate of Algiers. The goal is to generate a comparative analysis of the various variables to see how they differ in terms of energy performance, CO_2 emissions, and economic aspects, and to try to provide an optimal shape and height for each climate (Based on our comprehensive observations, studies of the Algerian building stock and the state of the art, the aforementioned variables were considered to be the most representative of the basic forms and heights).

In order to have a fair comparison with comparable results, all the shapes and heights used are made with the same construction materials established according to the DTR3.2/4 and summarized in Tab. 1 [17] and with the same fenestration ratio (22%).

Table 1 Components of the basic model

		Thickness (m)	λ ($Wm^{-1}K^{-1}$)	R (m^2KW^{-1})	*U-Value* ($Wm^{-2}K^{-1}$)
External wall	Plaster	0.02	0.35	0.06	0.95
	Brick	0.10	0.48	0.21	
	Air gap	0.05	0.11	0.45	
	Brick	0.15	0.48	0.31	
	Cement	0.02	1.15	0.02	
Internal wall	Plaster	0.02	0.35	0.06	3.10
	Brick	0.10	0.48	0.21	
	Plaster	0.02	0.35	0.06	
Floor	Tile	0.01	2.1	0.00	5.63
	Mortar	0.02	1.15	0.02	
	Slab	0.20	1.45	0.14	
	Mortar	0.02	1.15	0.02	
Roof	Bitumen	0.02	0.23	0.09	4.13
	Slab	0.20	1.45	0.14	
	Mortar	0.02	1.15	0.02	

The study of the different shapes and heights has been relativised by using the formula of compactness and relative compactness to facilitate the comparison.

The geometry and morphology of the building can be defined using the building form factor (L_b) (also called building characteristic length), which is defined as the ratio of the heated volume of the building (Volume) to the sum of all heat loss surfaces that are in contact with the exterior, the ground or adjacent unheated spaces (Exterior surfaces) (see Eq. (1) [14].

$$L_b = \frac{Volume}{Exterior\ surfaces}. \tag{1}$$

Another indicator that can be used is the relative compactness of the building (R_c). The R_c of a shape is derived from the comparison of its volume to area ratio to the most compact shape with the same volume (see Eq. (2)) [14].

$$R_c = \frac{\left(\frac{V}{S}\right) Building}{\left(\frac{V}{S}\right) Ref\ Form} = \frac{(Surface\ Area)\ Ref\ Form}{(Surface\ Area)\ Building}. \tag{2}$$

The methodology and path used can be summarised in Fig. 1.

3 RESULTS AND DISCUSSION

Using the data for occupancy, HVAC, building materials, footprint, height, and volume, it was found that the results generated by the simulation differ from climate to climate, with the highest total consumption for the Constantine climate, followed by the Ghardaïa climate, and finally by the Algiers climate.

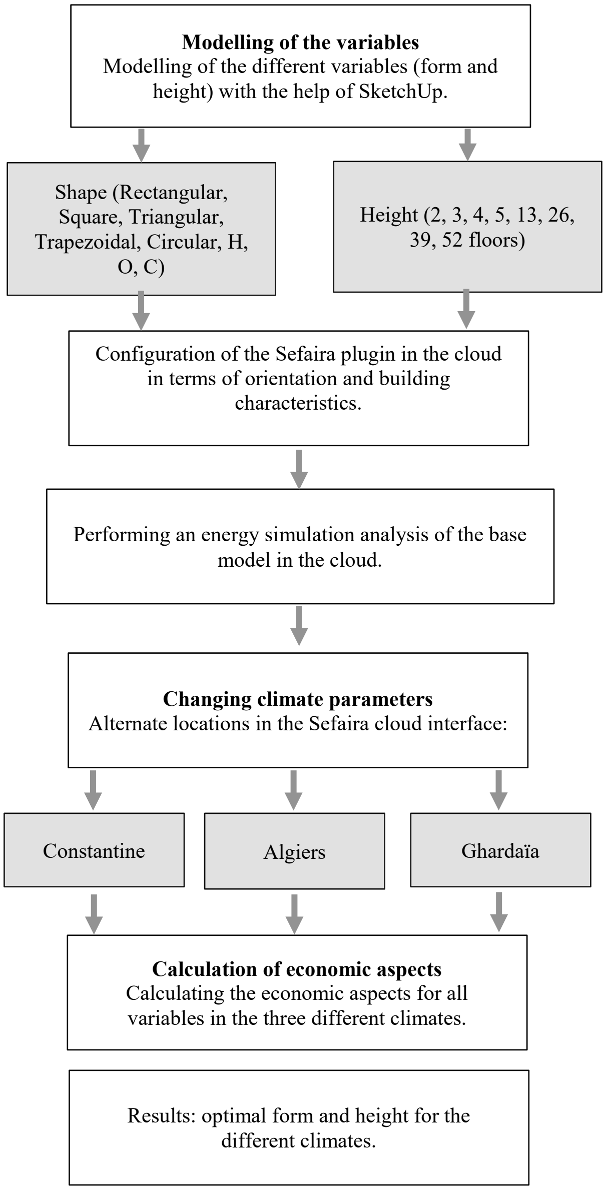


Figure 1 Overview of the flow and arrangement of research methods

For the semi-arid climate of Constantine, the most energy-efficient shape, is the triangular, with a savings of 12.9 kWh/m²/year with the basic parallelepiped shape, and a total of 55.3 kWh/m²/year from the worst case.

For the Mediterranean climate of Algiers, the change in shape does not allow for a big difference in energy consumption, with the cubic shape being the most economical, allowing to save 2.1 kWh/m²/year on the basic shape, with a maximum saving of 13.8 kWh/m²/year compared to the most unfavourable shape.

For the arid climate of Ghardaïa the results are almost the same as for Constantine, but with a clear decrease in energy consumption. For this climate, the difference between the most optimum form (Triangle) and the basic form (Rectangle) is 7.1 kWh/m²/year, and 31.7 kWh/m²/year with the most unfavourable form (C), as seen in Fig. 2.

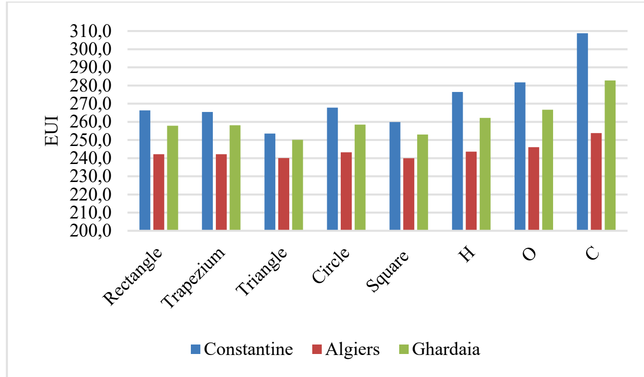
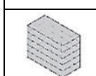
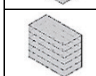
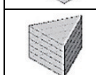
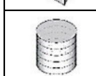
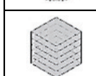
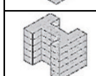
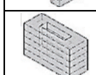
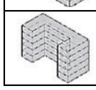


Figure 2 Energy consumption of different forms in the three climates

Table 2 The different simulated forms and their initial data

Type	Foot print m²	Height m	Perimeter m	Volume m³	Exterior Surface m²	L_b	R_c
	200	15.30	60.00	3060	1318	2.32	0.89
	200	15.30	62.36	3060	1354	2.26	0.86
	200	15.30	64.72	3060	1390	2.2	0.84
	200	15.30	50.15	3060	1167	2.62	1
	200	15.30	56.57	3060	1266	2.42	0.92
	200	15.30	90.00	3060	1777	1.72	0.66
	200	15.30	107.20	3060	2040	1.5	0.57
	200	15.30	88.48	3060	1754	1.74	0.67

After calculating the different indicators, such as the building shape factor (L_b) and the relative compactness factor (R_c) represented in Tab. 2 we deduced that the most compact shape is the cylindrical shape, which was used as a reference shape for the calculation of the relative compactness, followed by the cube, the parallelepiped, the trapezoidal shape, the triangular shape, the C-shape, the H-shape, and finally the O-shape. It seems that the compactness of the shapes is not a decisive element and that it does not have a great effect on the energy consumption, based on the results we gathered. The number of three-dimensional junctions (corners) seems to be the most decisive element in increasing energy consumption, as it can be seen for the different climates with the triangular base form as the optimal shape and the H, O, or C shapes as the most unfavourable shapes.

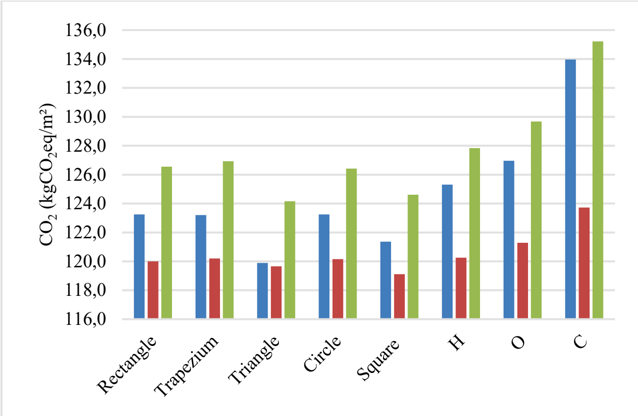


Figure 3 CO_2 emissions of different forms in three different climates.

For the CO_2 emissions obtained from the simulation software, we could note that the emissions in the climate of Ghardaïa are the greatest, followed by Constantine and then by Algiers. However, the order of the various forms is nearly identical to the order of energy consumption, allowing a maximum reduction between the optimal and the most unfavourable forms of 14.1 $kgCO_2eq/m^2$, 11 $kgCO_2eq/m^2$, 4.6 $kgCO_2eq/m^2$ for the climates of Constantine, Ghardaïa and Algiers. It can be noted that the CO_2 emissions are related to the consumption of heating and air conditioning than to the total consumption of the building, as seen in Fig. 3.

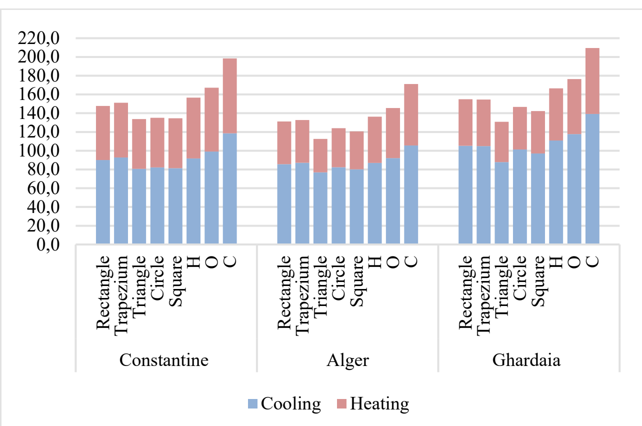


Figure 4 Heating and cooling consumption of different heights in three different climates

For air conditioning, there is a similarity across all climates with the triangular shape as the most optimal shape, followed by the square and circular shape. For heating, the regions of Algiers and Ghardaïa share the same optimal shape as they do air conditioning, but with a change for the city of Constantine, which is now the circular shape as seen in Fig. 4.

Thanks to the different changes in shape, a budgetary saving in energy costs can be made compared to the basic shape (rectangular), with a maximum of –54 DA/m²/year for the city of Constantine, –9.1 DA/m²/year for the city of Algiers, and –33 DA/m²/year for Ghardaïa. Conversely, by choosing the most unfavourable form (O), one can arrive at a rate of loss equal in maximum to 177 DA/m²/year for the city of Constantine, 48.6 DA/m²/year for the city of Algiers, and 104 DA/m²/year for the city of Ghardaïa. Due to changes in shape. All the results are summarised in Fig. 5.

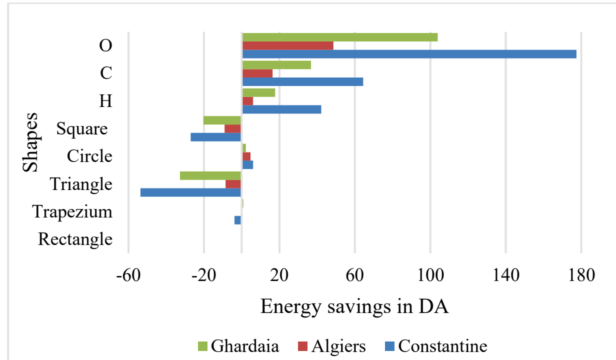


Figure 5 Economic potential of different forms in three different climates

The results concerning the change in shape can be summarised in Tab. 3, ranking the various shapes from the most optimal form, identified as number 1, to the least favourable, denoted as number 8:

Table 3 Simulation results summary of different forms

	1	2	3	4	5	6	7	8
EUI								
Constantine	T	S	Tz	R	C	H	O	C
Alger	S	T	R	Tz	C	H	O	C
Ghardaïa	T	S	R	Tz	C	H	O	C
CO_2								
Constantine	T	S	Tz	R	C	H	O	C
Alger	S	T	R	Tz	C	H	O	C
Ghardaïa	T	S	C	R	Tz	H	O	C
Air conditioning								
Constantine	T	S	C	R	Tz	H	O	C
Algiers	T	S	C	R	H	Tz	O	C
Ghardaïa	T	S	C	Tz	R	H	O	C
Heating								
Constantine	C	T	S	R	Tz	H	O	C
Algiers	T	S	C	R	Tz	H	O	C
Ghardaïa	T	S	C	Tz	R	H	O	C
Economy								
Constantine	T	S	Tz	R	C	H	O	C
Algiers	S	T	R	Tz	C	H	O	C
Ghardaïa	T	S	R	Tz	C	H	O	C
Optimal								
Constantine	T	S	Tz	R	C	H	O	C
Algiers	S	T	R	Tz	C	H	O	C
Ghardaïa	T	S	C	Tz	R	H	O	C

With: T = Triangle; Tz = Trapezium; R = Rectangle; S = Square; C = Circle

Using the same data in terms of occupancy, HVAC, building materials, and the footprint of the basic module, which is a rectangular shape and changes with the number of floors, it could be seen that there was a change in energy consumption, and this also varied for each climate.

The Constantine climate has the highest energy consumption compared to the other climates, with a maximum of 303.8 kWh/m²/year for the 2-story building. The 26-storey building has the most optimal consumption and saves up to 52.7 kWh/m²/year. It should be noted that the results for the Algiers climate are similar and that there is only a slight difference between the optimal number of floors (4 floors) and the most energy-consuming number of floors (52 floors) of about 3.8 kWh/m²/year. The climate of Ghardaïa also does not have a big difference between the optimal number of floors (13 floors) and the most energy-consuming number of floors (2 floors), with about 7.3 kWh/m²/year. It can be seen that the variation in energy consumption does not have a specific relationship with the number of floors, but that there is a trend in all climates of decreasing EUI until an optimal height is reached, and then increasing again as the number of floors increases.

Table 4 The different simulated heights and their initial data

N° Levels	Surface m²	Footprint m²	Height m	Perimeter m	Volume m³	Surface. Ext m²	L_b	R_c
2	400	200	6.12	60	1224	767	1.6	1.00
3	600	200	9.18	60	1836	951	1.93	0.81
4	800	200	12.24	60	2448	1134	2.16	0.68
5	1000	200	15.30	60	3060	1318	2.32	0.58
13	2600	200	39.78	60	7956	2787	2.85	0.28
26	5200	200	79.56	60	15912	5174	3.08	0.15
39	7800	200	119.34	60	23868	7560	3.16	0.10
52	10400	200	159.12	60	31824	9947	3.2	0.08

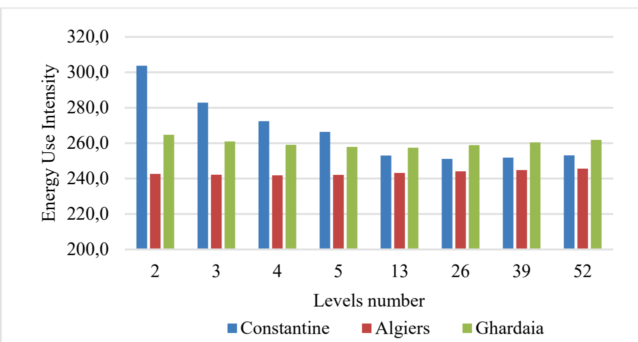


Figure 6 Energy consumption of different building heights in three different climates

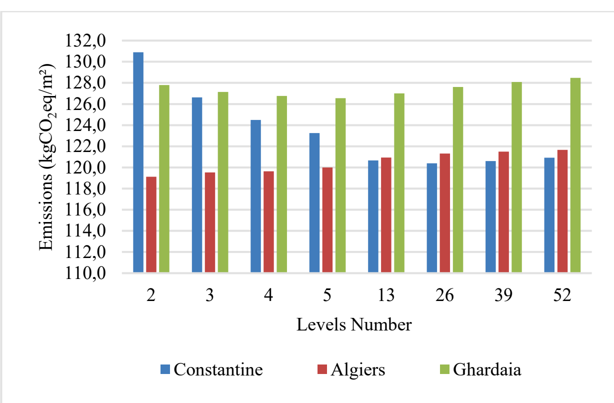


Figure 7 CO_2 emissions of different forms in three different climates

CO_2 emissions are stable at different heights for the two climates of Ghardaïa and Algiers, ranging between 126 and 128 $kgCO_2eq/m^2$ for Ghardaïa and 119 and 121 $kgCO_2eq/m^2$ for Algiers. On the other hand, the climate of Constantine has a large difference between the most optimal case of 26 floors and the most unfavourable case of 2 floors, with a total of 10.5 $kgCO_2eq/m^2$ of CO_2 as can be seen in Fig. 7.

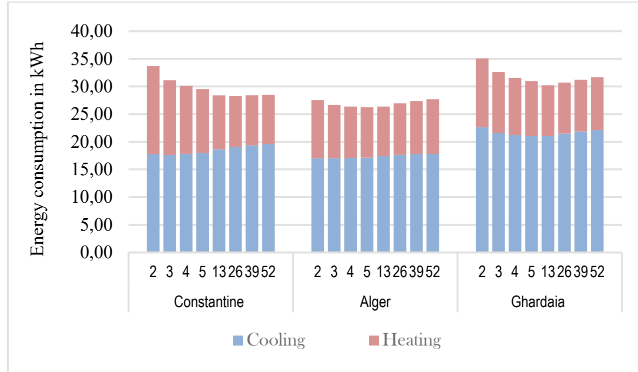


Figure 8 Heating and cooling consumption of different heights in three different climates

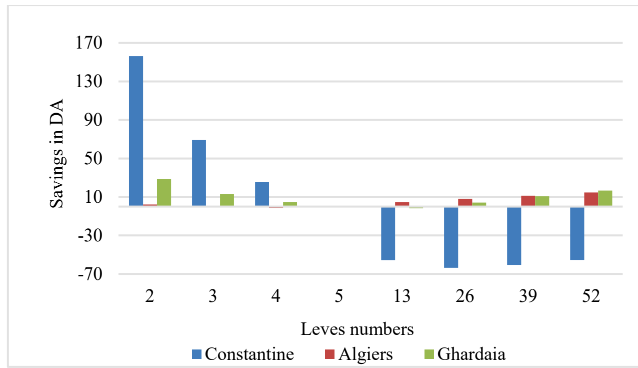


Figure 9 Potential economies of different heights in the three studied climates

Table 5 Simulation results summary of different heights

	1	2	3	4	5	6	7	8
EUI								
Constantine	26	39	13	52	5	4	3	2
Algiers	4	5	3	2	13	26	39	52
Ghardaïa	13	5	26	4	39	3	52	2
CO_2								
Constantine	26	39	13	52	5	4	3	2
Algiers	2	3	4	5	13	26	39	52
Ghardaïa	5	4	13	3	26	2	39	52
Air conditioning								
Constantine	3	2	4	5	13	26	39	52
Algiers	2	3	4	5	13	26	39	52
Ghardaïa	13	5	4	26	3	39	52	2
Heating								
Constantine	52	29	26	13	5	4	3	2
Algiers	13	5	26	4	39	3	52	2
Ghardaïa	13	26	39	52	5	4	3	2
Economy								
Constantine	26	39	13	52	5	4	3	2
Algiers	4	5	3	2	13	26	39	52
Ghardaïa	13	5	26	4	39	3	52	2
Optimal								
Constantine	26	39	13	52	5	4	3	2
Algiers	4	5	3	2	13	26	39	52
Ghardaïa	13	5	26	4	39	3	52	2

The air conditioning results show a stable energy consumption for the majority of the heights in all three climates, reaching a maximum of 1.79 kW difference in the city of Constantine. On the other hand, a greater difference can be seen for heating, with a maximum of 6.97 kW for that climate.

For the economic aspect, a saving of up to –64 DA/m² (26 floors) and a loss for the most favourable case of 156 DA/m² (2 floors) compared to the basic height (5 floors) can be achieved for the city of Constantine, while for the other two climates, only a saving of 2 DA/m²/year and –1.3 DA/m²/year can be achieved for Ghardaïa and Algiers, respectively, Fig. 9.

The results concerning the change in height can be summarised in Tab. 5 which ranks the various heights from the most optimal, identified as number 1, to the least favourable, denoted as number 8.

4 CONCLUSION

Nowadays, the design of a sustainable built environment poses some challenges, usually related to energy consumption, carbon emissions, human wellbeing, the depletion and scarcity of natural resources, and fossil fuels, but it plays a key role in the society's sustainable development as a whole. The objective of the study was to generate a comparative analysis for the different variables to see their differences in terms of energy performance, CO_2 emissions and financial energy savings, the following conclusions were reached:

- It seems that the compactness of the shapes is not a decisive element for the choice of the optimal shape and that it does not have a big effect on the energy consumption as stated in the art review; instead, the number of three-dimensional junctions (corners) seems to be the most decisive element in increasing energy consumption, as can be seen in the different climates with the triangular based shape as the optimal shape and the H, O, or C shape as the most unfavourable shapes.
- It is very difficult to generalise and give an optimal shape for energy consumption for a whole country. The optimal shape differs according to the climate, but also according to the initial characteristics of the building.
- There is a trend in all climates of decreasing EUI until an optimal height is reached, and then increasing again as the number of floors increases.
- The change of shape allows a financial saving of up to 54 DA/m²/year for the most favourable case.
- The change in height can allow the semi-arid climate of Constantine, unlike the other two climates, to have perceptible savings in terms of EUI, CO_2, and economic aspects.
- It was noted that CO_2 emissions are related to heating and air conditioning consumption plus the total consumption of the building.

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