BIOCLIMATIC ARCHITECTURE IN ALGARVE: THERMAL COMFORT STUDY OF A DETACHED HOUSE IN PORTIMÃO

Miguel Mendes Faustino Gracias - miguelgracias@hotmail.com

Instituto Superior Técnico, Lisbon, Portugal

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ABSTRACT

The increase on electric energy consumption by climatization systems, such as air-conditioning, is a fact in Portugal. Considering the foreseen climate changes, an increase on expenses related to such consumptions is expected. The target of this project resides on the study of bioclimatic strategies that lead to an improvement on comfort inside the residence, as well as on the energy efficiency, focused on the Algarve region. For that matter, a research about the bioclimatic methods used in the traditional algarvian architecture is performed in order to identify the ones that could be applied on the current context and why such practices fell into disuse. A series of bioclimatic strategies applicable to the Algarve and the solar photovoltaic system are presented. A bioclimatic study of a residence located in Portimão is performed in order to improve its thermal comfort and energy efficiency. Through the use of EnergyPlus software, analysis of the thermal adaptive comfort and the heating needs for the original state of the residence as well as for three alternative bioclimatic solutions are conducted. An ideal solar photovoltaic system is estimated, taking into consideration the real energy consumption measured throughout one year. The results confirmed that bioclimatic practices have a great potential towards both the improvement on thermal comfort and the decrease on energy consumption for climatization needs.

Index Terms— Bioclimatic Architecture, Comfort, LadyBug Tools, Algarve

1. INTRODUCTION

Portugal's energy consumption for climatization systems is in a growing tendency [1]. The despise of the recent buildings on their locations and of the local climate conditions might be some of the reasons for this [2]. Specially in regions such as the Algarve, the growing housing demands, driven by the tourism, created a fast and unsustainable growth. The ancient knowledge and practices were abandoned, particularly it's relation with the local climate [3].

Vernacular architecture in Algarve, despite being unadapted to the contemporary livings and needs, had to rely on local materials and to take as much advantage as possible of the local climatic conditions in order to provide comfort [4].These are the practices that this study relies on as inspiration for a more sustainable form of architecture.

Nowadays, to achieve the desired comfort, a big dependency of electricity for climatization was generated. This represents 42% of the total energy used in buildings, so reducing this consumption is one of the main factors on buildings sustainability [5].

There's a direct relation between temperature variation and electricity consumption [6] [7], a situation worsened by the foreseen climate change. [2].

The design of buildings according to it's location and it's local climate, is essential to sustainability, encompassing concepts such as human comfort and energy efficiency [8].

2. BIOCLIMATIC ARCHITECTURE IN ALGARVE

2.0.0.0.1. Sustainable architecture

"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." [9]

Any construction activity creates impacts. These can be economic, social or environmental, and are mostly associated to land occupation, the resource consumption (materials, water and energy), the waste production and the changes on natural ecosystems. The concept of sustainable architecture comes with the goal of providing the necessary comfort of their occupants, with the minimal environmental impact possible in the building's life cycle [5]. The environmental impact associated with buildings can be divided in four fundamental aspects: the energy spent on building use (heating, cooling, illuminations and appliances); the impact generated by construction materials that are used; water management and waste management [10].

2.0.0.0.2. Bioclimatic Architecture

Bioclimatic architecture consists in the design of buildings taking the local climate as a starting point. It takes advantage of the available natural resources, such as the sun, the wind, the rain, vegetation and construction materials, in order to provide thermal and lighting comfort and, consequentially reduce energy consumption and the environmental impact caused [11] [8].

"The shelter should filter out the dangerous impacts and let in the beneficial ones of the environment" [12]

2.1. The Algarve

Algarve is a region located in the south of Portugal. It is composed by 4996.79 km2 of land, roughly 5.4% of the entire country. There are mountains on north that borders it from the rest of Portugal and create a natural barrier from cold winds coming from north and northwest. On the south, Algarve ends on the pacific ocean but its weather and culture are mainly influenced by the Mediterranean sea and the north of Africa, given its proximity [4].

2.2. Vernacular Architecture

Vernacular architecture in Algarve, has a close relation with the surroundings and the climate. The implantation of a house, its form and solar orientation, all factors work together in order to maximize direct solar gains and give protection from the prevailing unwanted winds. The predominant orientation is south, with small variations, and where the wind has bigger impact, we can often see east orientation. The rectangular shape with the greater openings facing south to maximize solar gains in winter, and the limitation of the openings in other orientations to the strictly necessary for natural illumination. The west side in most houses often presents no opening.

Fig. 1. Housing of rectangular floor plan in schist and rammed earth, plastered with lime, located in Bensafrim, Lagos.

The shading systems adopted ranged from the eaves of the roof, porches, balconies and even vegetation. They help blocking unwanted solar radiation on the summer season at the same time they allow it in on the winter season. The use of lime on exterior walls coating reflects light and consequently eases temperatures.

Fig. 2. Typical patio from Algarve. Decades of 1950/1960. Source: Artur Pastor

The high thermal inertia of the construction materials used (earth and stone) reduces the temperature range inside the house providing cooler temperatures on summer and warmer temperatures on winter (Figure 3).

Fig. 3. Housing of rectangular floor plan in rammed earth, plastered with lime and sunrise oriented, located in Montinhos do Burgau, Lagos.

The integration of patios next to the residences is another important characteristic of this style, it allows the cooling by ventilation of the interior spaces of the house. These patios are often covered by vegetation which provides an extra cooling level through evaporative properties of plants (Figure 2).

2.3. Tourism and the loss of identity

"Modernization, through industrialization, erased the memory of the place and the place was also capable of erasing the memory." [13]

In the turn of the nineteenth century, with the Industrial Revolution, architecture in Algarve was based on the construction of eclectic buildings, mixing different styles but maintaining the traditional structure [3]. In the 30's, with the spreading of reinforced concrete, architecture started to change, trying to express the shapes suggested by this new material. [3].

The adoption of materials such as the reinforced concrete, allied to the growing tourism industry, were the main causes for the abandonment of traditional architecture practices [13].

2.4. Energy and thermal comfort

The temperature variation has an impact on thermal comfort and consequentially on energy consumption [6] [7]. Other climate elements such as, the rain, relative humidity, solar radiation and wind velocity also have influence over energy consumption [14].

The housing in Algarve region has a vulnerability towards summer and winter months mainly because of the conservation of the buildings, the social-economic factors and the lack of bioclimatic approaches in Algarve's current constructions. [2] [15].

The reduction of energy consumption can be achieved using bioclimatic strategies. Through renewable energy sources, replacement of lighting and other electric equipment for more efficient ones and overall, the changes of living habits.

3. BIOCLIMATIC ARCHITECTURE STRATEGIES

3.1. Climatic Context

Analyzing the climate context is fundamental to a proper implementation of a bioclimatic project. Data such as temperature, humidity, wind speed and direction, rain, clouds, radiation levels, among others, enables comprehension around the climate of a place [11].

3.2. Localization, Form and Solar orientation

In Mediterranean climates, such as the Algarve, in order to define location, solar orientation and form both the heating and the cooling needs should be taken into consideration. The attention to prevailing winds should have a special importance because they should be able to cool the house on summer, without compromising the winter months. [12] [11].

3.3. Shading

Shading strategies are important in reducing solar incidence on windows and exterior walls [16]. The form and the location of shading devices and the morphology of the surrounding vegetation should take the solar path into consideration to minimize gains on summer and to enable those gains on cooler months [12]. The east and west sides on summer get much more energy then other orientations and are the most difficult sides to shade, due to the solar angle. Vertical blades or high density vegetation are the best option to protect those sides. The south side is easier to shade. Simple balconies or porches allow the desired shading on summer and let the radiation in on the cooler months.

The roof eaves, balconies, porches or vegetation and even neighbour buildings are good examples of this strategy found on vernacular architecture [10].

3.4. Reflexivity of materials

Different material colors correspond to different reflexivity values of solar radiation. Light color, such as white, reflect most of the solar radiation, preventing over heating of those thermal masses. In Algarve this strategy is widely used with the lime painting of the exterior walls. On the interior walls this strategy is beneficial too since it improves lighting, reducing the need for artificial lighting which is a heating load [16].

3.5. Thermal insulation

Thermal insulation strategies, provide a reduction of the thermal gains and losses. These insulation should be applied through the external face of the walls [16]. In coastal areas with a Mediterranean climate, when the thermal insulation is present, a reduction of the thermal masses should be taken into consideration in order to reduce the amount of masses that need to be cooled down on summer nights [11].

3.6. Thermal inertia

Thermal inertia capability of materials provide a reduction of temperature ranges inside the house [12]. Materials with a strong thermal inertia are called thermal masses [16]. Earth and stone are examples of materials with strong thermal inertia.

3.7. Windows and types of glass

The translucid areas are responsible for most of the energy transfers between the interior and exterior of a building. These transfers are made by radiation, conduction and convection (infiltration) [15]. Although direct radiation gains are the main contribution of the solar gains [16], the infiltration of air through the windows is an important factor on a building's energy performance [17]. For the Mediterranean climates, double glass windows should be used [11].

3.8. Natural Lighting

Natural lighting, when correctly incorporated in a building, contributes to the energetic efficiency as well as the health and well-being of its occupants [10].

3.9. Passive heating systems

3.9.1. Direct solar gain systems

This heating system is the simpler and most effective one. Direct solar gains are achieved through the translucid elements of the building. For a correct application of this strategy, in Algarve only the south facing wall should be considered, according to the time of the year when the heating is necessary. Shading devices should be considered on summer months to prevent over heating [18].

3.9.2. Indirect solar gain systems

3.9.2.1. Trombe walls

Trombe wall are system that accumulate energy from the sun in thermal masses, in order to release it to the inside when it's needed [19]. This system should be carefully designed to avoid over heating inside the building and effective shading devices should be incorporated [20].

3.9.2.2. Water walls and columns

This system is similar to the trombe walls but the thermal mass is from water walls or columns of water right next to windows [19].

3.9.3. Isolated solar gain systems

3.9.3.1. Greenhouses

Greenhouses combine direct and indirect solar gains. This strategy heats a zone in order to transfer that energy to the zone that needs heat afterwards [20]. Greenhouses should have the ability to be completely deactivated in the hotter months.

3.10. Passive cooling systems

3.10.1. Natural ventilation

Natural ventilation has two important roles: to provide cooling on a building and to promote the renovation of air, needed for the health of its occupants, so a minimal rate of air renovation should be considered [16].

When outside temperatures are lower than inside temperatures, natural ventilation strategies should be addressed in order to cool the space down. The night is the optimal time to apply this strategy to cool thermal masses. But to prevent over cooling the ventilation should be controlled through the closing of windows, avoiding cold sensation in the morning [16] [10].

3.10.1.1. Unilateral ventilation

This is the least effective type of ventilation, but if it's the only option available the windows should be at different heights and as far as possible from one another [11].

3.10.1.2. Cross ventilation

Cross ventilation is one of the most effective ventilation strategies. It consists on having openings in opposite sides of the rooms. These openings located next to the ceiling help removing the hot air from the room and if they are located next to the ground they induce a cooling sensation to the occupants, due to air movement [16].

3.10.1.3. Chimney effect

The chimney effect is a form of vertical ventilation. This solution is very effective in high buildings and is a good solution when the wind is not enough to provide other forms of ventilation [16].

3.10.2. Ground cooling

The earth has a small range of temperatures, so it's a good option to provide cooling in the summer. In Algarve buildings were implanted directly into the earth, making a good use of this strategy.

3.10.3. Evaporative cooling

This strategy uses the properties of plants and water to cool the air before entering the building. The presence of water or plants increase humidity values, therefore, cooling the air. [19] [16]. In Algarve, this strategy is widely used, mainly through vegetation on courtyards.

3.10.4. Radiative cooling

The best solution for this strategy is the use of movable devices to cover the outer wall and the roof during the day and uncover them during the night, providing cooling. This strategy is not very common nowadays due to its ineffectiveness in thermal isolated elements.

3.11. Photovoltaic solar energy

Photovoltaic solar systems convert solar radiation to electricity. These system are easy to install and have relatively low investment costs as well as operational and maintenance costs [21]. It's the most used active system in Portugal [22].

Depending of the tilt angle of the photovoltaic panels we can maximize either winter, summer or the maximum annual production. Algarve has a great photovoltaic generation potential, so adopting these systems is a good solution to reduce the dependency on fossil fuel energy [18].

3.12. Thermal comfort metrics

The adaptive comfort model was defined to have in consideration buildings without air conditioning, assuming that through natural ventilation strategies the occupants of a building can adapt to different climate contexts [23] [24]. The implementation of this metric along with the recovery of bioclimatic practices of vernacular architecture, is a good contribution to the sustainability of architecture [1]. A study was performed in order to optimize this metric to the Portuguese scenario. It concluded that with this optimization the energy savings are even greater than with the original model [25].

To be able to compare results between simulation, the thermal autonomy concept was introduced. This concept consists on the percentage of time in which the temperatures are within the comfort range [26].

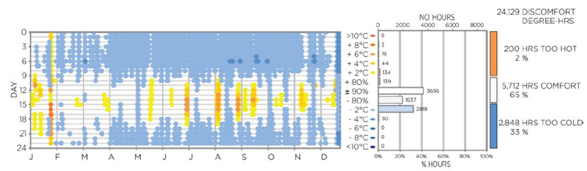

Fig. 4. Thermal autonomy visualization example. Reference: [26]

4. CASE STUDY

The case study is a single family house built in 1969, located in Portimão, Algarve. With a total area of 458.28m2, it's composed by two floors and it's 26 meters above sea level.

4.1. Caracterization of the House

The next two figures depict the ground floor (Fig. 5) and the first floor (Fig. 6) plans.

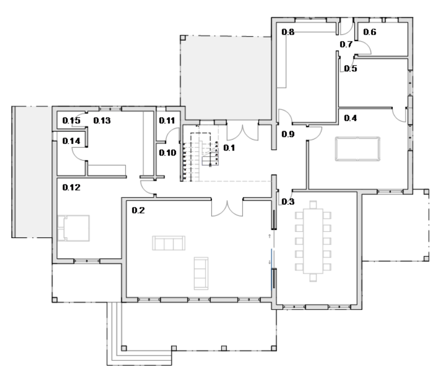

Fig. 5. Ground floor plan.

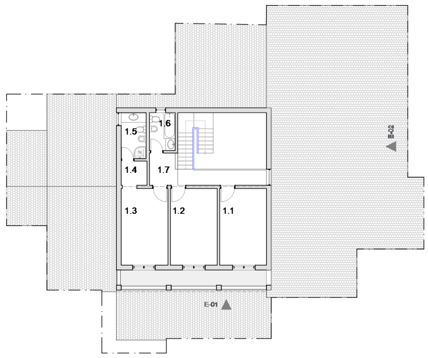

Fig. 6. First floor plan.

The table 1, has a list of all the spaces of the house, divided by floors.

Table 1. Dimension of the interior spaces of the house.

Floor	Space	Area [m2]	Legend
	Hall	24.75	0.1
	Living Room	54	0.2
	Dining Room	35	0.3
	Gaming Room	28.9	0.4
	Office	12.9	0.5
	Laundry	6.51	0.6
	Kitchen entrance	2.1	0.7
Ground	Kitchen	22.94	0.8
	Distribution corridor	7.4	0.9
	Bathroom entrance	5.03	0.10
	Social Bathroom	2.78	0.11
	Suite (room)	22.4	0.12
	Suite (dressing room)	16.4	0.13
	Suite (bathroom)	4.81	0.14
	Locker room	1.93	0.15
	Room 1	13.78	1.1
	Room 2	13.78	1.2
	Room 3	13.78	1.3
First	Dressing room (3)	2.4	1.4
	Bathroom (room 3)	4.42	1.5
	Bathroom (rooms 1 and 2)	3.76	1.6
	Mezzanine	8.85	1.7
Total		308.62	

4.1.1. Constructive elements

All the constructive elements were defined to run the simulations, exterior and interior walls and openings.

4.1.2. Bioclimatic Aspects

4.1.3. Solar orientation and form

The house in study is south oriented with a seven degrees deviation to east. There are some buildings limiting its solar gains but since the southeast-southwest side is unobstructed, therefore the solar incidence is ideal on winter months.

The house is organized in such a way that most rooms (except bathrooms, kitchen, laundry, hall and office) have windows facing south (Fig. 7). On the west side there are only two small bathroom windows.

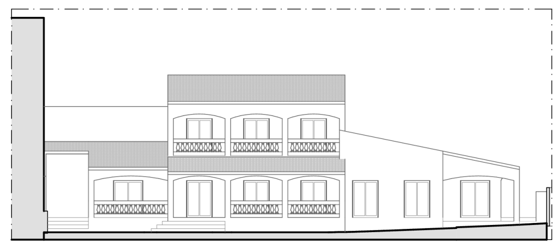

Fig. 7. South view.

On the east side there are three windows, one fully exposed on the first floor, and two, shaded by vegetation on the ground floor.

4.1.4. Shading

On the south facade there are two completely exposed windows on the dining room, and all the other windows are shaded by balconies or porches that block most of the direct radiation on summer. (Fig. 8) On the east and west side there are vegetation shading solutions and there's shadow from existing constructions.

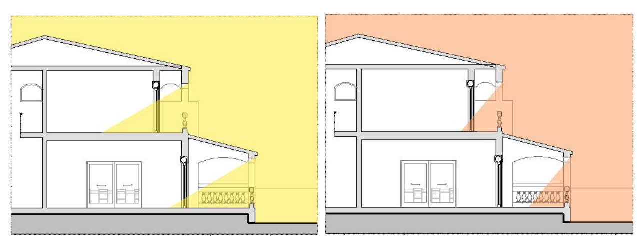

Fig. 8. Direct solar incidence in the winter (left) and summer (right) solstices on the living room and the first floor rooms.

4.1.5. Exterior reflective coating

Although the house is not painted white or with lime, it has a pale pink color. This color doesn't have the reflexivity values of white but it also presents high levels.

4.1.6. *Thermal inertia*

The thermal inertia identified in the house, are present on the marble floors of the entrance hall, the living room and the access and social bathroom. These don't get solar gains access but they can work as a cooling load on summer and heating load on winter due to its direct implantation on the ground.

4.1.7. *Natural Ventilation*

The house has a variety of natural ventilation options. The one that's most interesting is the chimney effect, represented in the figure 9. Through the manipulation of doors and exterior openings it's possible to have unilateral ventilation (3.10.1.1), cross ventilation 3.10.1.2 situations and, due to the thermal mass in some floors, night ventilation.

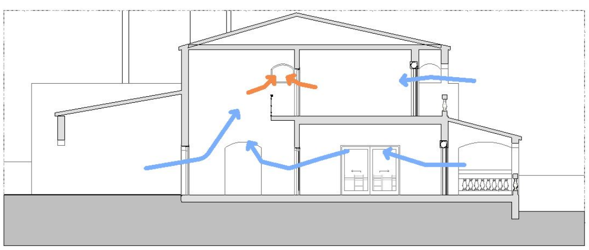

Fig. 9. Chimney effect scheme on the habitation hall.

4.1.8. *Real Electricity Usage*

The consumption profile was obtained through an intelligent electricity meter installed by the author. On the next image (10) it's presented the annual (2021) consumption profile on a 3d chart. The colour legend ranges from dark blue for no consumption, until red, for the maximum value measured, 5.9KwH.

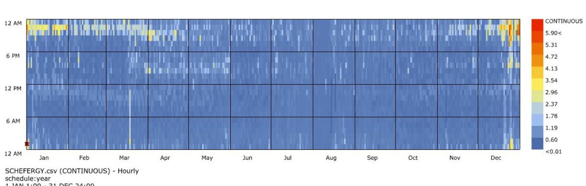

Fig. 10. Annual chart of the consumption measured in a year (2021)

4.2. Energetic Models

4.2.1. *Reference Model*

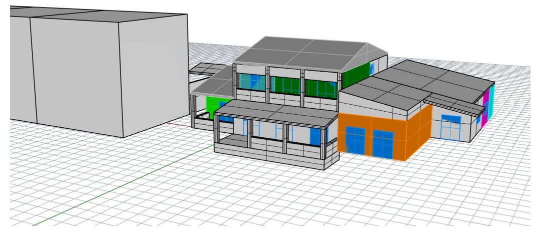

Fig. 11. Energy Model (South View)

Using the *Rhino 6* and the *EnergyPlus*, with the *LadyBug Tools* plugin, an energy model of the house in study was created. It was defined one thermal zone for each space of the house. This option has to do with the will to simulate and analyze local passive strategies influence on specific zones individually. A modulation of the local context was done and the materials assigned to the construction were previously defined above.

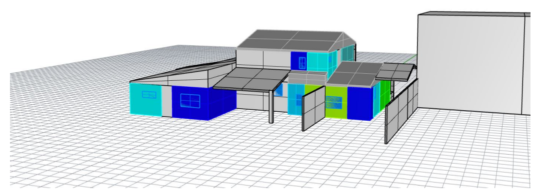

Fig. 12. Energy Model (North View)

4.2.2. *Alternative Models*

4.2.2.1. *Natural Ventilation (solution 1)*

On this alternative model it was simulated the adaptive comfort improvement with the use of natural ventilation as a cooling passive strategy. The configuration of the natural ventilation (NV), wasn't done by a schedule, but through temperature difference between the inside and the outside. This way, it was defined that the maximum outside temperature was 25°C and the minimum inside temperature was 25°C for NV to occur. Another definition was the need to exist a positive temperature differential between indoor and outdoor temperatures (outdoor temperatures lower than indoor temperatures).

4.2.2.2. Thermal insulation from the exterior side and Replacement of the windows (solution 2)

On this second alternative model the same analysis were made. Here, it was simulated an upgrade of all the exterior walls thermal insulation and the replacement of the old single glass windows by double glass ones and with lower infiltration rates.
To simulate this a layer of *expanded cork agglomerate* was added to the outside side of the exterior wall and the U-value of the windows and their infiltration rate were changed to 1.98 W/m2-K and 0.0001 m3/s per square meter of facade respectively. [27]

4.2.2.3. Joint Solution (solution 3)

Here it was simulated the application of solutions 1 and 2 together.

5. RESULTS AND DISCUSION

5.1. Reference Model

The results confirmed the efficiency of this house on limiting solar gains on summer months but due to the oversize of the shading devices those solar gains are weak on winter making the house cold. The thermal autonomy obtained in this simulation was of 41.17% with only 3.2% of time with hot sensation against 55.62% with cold sensation.

The heating loads simulation showed a necessity of 25855.44kWh of energy.

5.2. Alternative Model 1 (Natural Ventilation)

The thermal autonomy obtained in this simulation was of 42.34% with only 1.57% of time with hot sensation against 56.09% of time with cold sensation. This represents a reduction of 51.03% of time with hot sensation compared with the reference model.

The heating loads simulation gave us a necessity of 25862.98kWh of energy, an increase of 0.03% compared with the reference model.

5.3. Alternative Model 2

The thermal autonomy obtained in this simulation was of 57.63% with 3.83% of time with hot sensation against 38.54% of time with cold sensation. This represents an increase of 19.6% of time with hot sensation and a reduction of 30.71% of time with cold sensation compared with the reference model.

The heating loads simulation gave us a necessity of 11290.22kWh of energy, a reduction of 56.33% compared with the reference model.

5.4. Alternative Model 3 (1 and 2)

The thermal autonomy obtained in this simulation was of 59.32% with 0.42% of time with hot sensation against 40.26% of time with cold sensation. This represents a reduction of 73.27% of time with hot sensation and a reduction of 28.22% of time with cold sensation compared with the reference model.

The heating loads simulation gave us a necessity of 8887.5kWh of energy, a reduction of 65.63% compared with the reference model.

Table 2. Comparison of thermal autonomy of alternative models with the reference model

		Comfort [%]	Hot [%]	Cold [%]
Ref. Model	Mean Value	41.17	3.20	55.62
	Variation	-	-	-
Alt. Model (1)	Mean Value	42.34	1.57	56.09
	Variation	2.84	-51.03	0.84
Alt. Model (2)	Mean Value	57.63	3.83	38.54
	Variation	39.68	19.60	-30.71
Alt. Model (3)	Mean Value	59.32	0.42	40.26
	Variation	44.09	- 73.27	-28.22

This last solution that combines both strategies had best results than any other simulations. Through the table 2 we can observe that, relatively to the discomfort caused by heat the last simulation had better results than the individual strategy simulations (Alternative models 1 and 2) individually. The over heating caused by the improvement of the exterior shell of the building was softened by natural ventilation, the same way that the improved outer shell intensified the effect of natural ventilation, conservating its energy.

About the discomfort from cold temperatures, natural ventilation had a small impact over cooling the house. Curiously the heating load needs, was even less that the alternative model 2 (improvement of the outer shell).

Table 3. Comparison of heating loads of the alternative models with the reference model

	Heating Loads [KwH]	Variation [%]
Ref. Model	25855.44	-
Alt. Model (1)	25862.89	0.03
Alt. Model (2)	11290.22	-56.33
Alt. Model (3)	8887.50	-65.63

5.5. Photovoltaic system

The result of the estimation was 2.42kWh, so a simulation with a 2.5kW photovoltaic system was performed. The simulation gave a total of 3996.05kWh of energy produced in a year.

In the figure 13, there's an annual graph of usage vs injection of electricity.

Fig. 13. Annual distribution of the usage vs injection of electricity on the grid.

Through the table 4 we understand that with this system there's a 33% reduce of the electricity bought from the grid but, on the other hand, 68.77% of the produced energy gets wasted or is sent back to the grid.

Table 4. Summary of solar system results.

	Energy [KwH]
Total electricity usage	3780.55
Energy generated by the photovoltaic solar system	3996.05
Used energy from the photovoltaic solar system	1247.94
Used energy from the grid	2532.61
Unused energy from the photovoltaic solar system	2748.11

6. CONCLUSIONS AND FUTURE WORKS

A look into the past, prior to the Industrial Revolution, and to the impacts of mass tourism, demonstrated the bioclimatic quality of vernacular architecture in Algarve. Before the dissemination of electricity for household needs, the emergence of concrete and other constructive technologies and the ease on goods transportation, humans could only rely on materials from the surroundings. Using these factors and through knowledge acquired and shared between generations, people learned to make maximum use of such materials always aligned with the climate of the place. In sum, with this study we concluded that the vernacular architecture was bioclimatic.

Considering the influence of bioclimatic strategies on the thermal comfort and energetic efficiency, simulations were performed for a existing habitation in Portimão. The bioclimatic and the energetic simulations confirmed: the fundamental role of the sun on the passive heating of the spaces; the success of natural ventilation on the passive cooling; the importance of improving the surroundings in order to take advantage of the energy collected from the bioclimatic strategies employed.

Therefore, we confirmed that the bioclimatic practices have an important role on the thermal comfort felt inside the buildings, as well as on the energetic efficiency, since the needs for heating and cooling are reduced. Furthermore we also concluded that these strategies shouldn't be used individually but together with each other, developing a bioclimatic system, or as Le Corbusier puts "a machine for living".

6.1. Future Works

In view of this study and the information obtained, there are other interesting aspects that could be further explored, these are as follows:

- Use the energetic model developed in order to better understand the thermal behavior of the building through:
  - The comparison of the results obtained with the adaptive comfort model optimized for Portugal, proposed by Manuel Guedes [1].
  - Other bioclimatic strategies shown in this dissertation, including solutions regarding the architectural shape of the studied house, such as the demolition of parts of the house in order to maximize solar gains.
  - The influence of different solutions present on the building on the thermal behavior of each space individually and the house in general.
  - The different strategies of natural ventilation that could be employed through the use of other softwares that enable the study of airflows in order to understand how the wind circulates in the house.

- Deepen the question of sustainability in algarvian constructions, exploring concepts such as "hydric stress", increasingly important in Algarve, through proposal of solutions for hydric efficiency and waste management using energy producing systems (biogas).

- The development of a guide similar to "Arquitectura Sustentável em Moçambique - Manual de Boas Práticas", coordinated by Professor Doutor Manuel de Arriaga Brito Correia Guedes, but adapted to the specificities of Algarve.

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