Influence of Arborization in Building Energy Consumption and Thermal Comfort: A Numerical Study in Tropical Climate

Daniel Austin Ortega, Engineering student[1], Ulises Jiménez, M.Sc.[1,2], Dafni Mora, Ph.D.[1,3], and Miguel Chen Austin, Ph.D.[1]
[1]Research Group Energética y Confort en Edificaciones Bioclimáticas, Faculty of Mechanical Engineering, Universidad Tecnológica de Panamá, Panamá, [daniel.austin, ulises.jimenez, dafni.mora, miguel.chen]@utp.ac.pa
[2]Centro de Investigaciones Hidráulicas e Hidrotécnicas (CIHH), Avenida Domingo Díaz, Ciudad de Panamá, Panamá
[3]Centro de Estudios Multidisciplinario en Ciencias, Ingeniería y Tecnología (CEMCIT-AIP), Avenida Domingo Díaz, Panamá

***Abstract*– Throughout the years the human has managed to adapt to its environment by empirically applying bioclimatic design strategies, which has allowed it to survive over the years. Today these strategies have been studied and perfected. This paper shows the direct relationship between different tree configurations and the decrease in electricity consumption, comparing internal gains, electricity consumption, humidity percentage, and PMV index, using dynamic simulations. Results showed evidence of one of the many benefits that arborization entails, the inclusion of trees in the microclimate of a building has a significant and positive influence on the performance of both thermal comfort and electricity consumption. A tree planting strategy configured as a barrier to prevailing winds (in front of the facades with windows) allows obtaining the best results.**

***Keywords*— arborization, energy efficiency, green structure index, thermal comfort, tropical climate.**

I. INTRODUCTION

Environmental and energy history are closely linked to each other; we depend on natural resources to produce energy, affecting the environment. The tremendous environmental changes that occurred during the 20th century are a consequence of the energy system for three reasons. First, because since 1890, it is based on fossil fuels, the combustion of which has local and global effects such as pollution and climate change. Second, fossil fuels allowed the development of new technologies, which exponentially increased the environmental impact caused by activities such as mining, agriculture, or forestry. Other energy sources such as hydroelectricity and nuclear energy have also been the cause of essential disturbances in the environment [1].

Starting in the 21st century, new questions arise about the damage that modern man with all his practices was causing the planet and the introduction of environmental awareness, resources are depleted, and alternative methods must be found to be used over the years To avoid deterioration of the same, it is an arduous task that is still being dealt with. The lack of integration between the city and the natural environment has been causing the degeneration and degradation of urbanized spaces.

Then urban sustainability and sustainable development arises, to try to create spaces that respect the natural environment so that cities come to be seen as a place that can be built on sustainable bases, transforming them not into imbalances of the micro and macro climate but in a space that respects the local fauna and flora, but that allows us to function and carry out our daily activities.

Scientists have already proven the climatic changes caused by human activities and that they can shape future climates. This means that cities, together with the various activities carried out by man, are creating a different climate dynamic on the planet and in the urban context. A suitable climate provides ease of movement for people, as studies have shown positive psychological repercussions.

A. Characteristics of arborization

Urban arborization is the management of trees for their contribution to urban society's physiological, sociological, and economic well-being. Arborizing involves forests, smaller groupings of trees, and individual trees planted in various configurations to get the most benefit from this practice [1].

Treeing means filling a certain site with trees; it connotes the process of planting trees. However, this arborization cannot merely be planting trees at random; it requires planning. Correct urban trees reflect the culture and degree of civilization of a city, and it is one of the most important elements of its valorization because it promotes improvements in the quality of life and makes the environment more pleasant. It influences the microclimate's maintenance and is one of the most important elements that make up the urban ecosystem [1].

When looking for a tree species that meet specific characteristics for a good tree planting process, we could fall into the practice of monoculture, which would become a plant species that monopolizes all or most of the cultivated land in a region. To avoid this, the selected tree species should be mainly native (own) of the country, since introducing a new species could bring disadvantages such as uniformity, which destroys the renewability of the total ecological system [2].

Forest monocultures generate desiccation and washing of soils in areas where the jungle or forest cushioned the fall of rainwater. Monocultures generate a new ecological vulnerability because they reduce genetic diversity and

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destabilize nature and hydrological systems, making them economically unviable. Sustainable agriculture is based on the recycling of nutrients from the soil. Sustainability reflects the reproductive capacity of a system in its biological diversity or its hydrological and climatic stability [2].

By not considering the importance of natural elements such as trees, it is not taken into account that physical elements such as buildings increase temperatures in large urban centers, creating heat islands (accumulation of heat due to various factors used in urban morphology) [3].

Poor building construction and design also play an important role, especially through wasteful energy consumption, poor quality insulation materials, and inefficient building management. Besides, close planning of buildings' height and layout can create suffocating urban heat cannons [4].

B. *Influence of vegetation in buildings energy performance*

When starting an arborization process to use its benefits for thermal reduction purposes, indirectly increasing energy performance, various elements must be considered. Most of the time, when choosing a tree species, the tree's visual and spatial characteristics are mainly focused. Although these are very important, the percentage of evapotranspiration of the tree should not be ignored, which is the combination of two processes: the evaporation of water that occurs on a certain surface and the transpiration that occurs in the stomata of the plants, which in essence, transforms the water absorbed by the roots into steam [5].

Attempts have been made to quantify the impact that the phenomenon of evapotranspiration has on energy saving, trying to know exactly how much the temperature in the surroundings of the building changes, since the decrease in temperature will determine how much energy can be saved by decrease the heat gain of the room. This depends on the volume of water that a certain tree can transpire, and the amount of mass evaporated in a certain time.

For example, the University of Arizona Saxena proposed a model that tries to relate trees' effect on air temperature; this is the main variable in the energetic analysis of evapotranspiration. They determined that to know the reduction in temperature, it is necessary to know how much is evaporated and moisture dispersion in the atmosphere. First, the reference evapotranspiration was estimated, and then the evapotranspiration for a specific tree was estimated (the one to be modeled). The volumetric evapotranspiration rate was then calculated. This water volume rate represents the total water transpired and evaporated in the area covered by the tree [5].

A model was proposed in Cairo to find a vegetation configuration dense enough to mitigate the urban heat island and save energy in buildings. For this, they chose a small area in Cairo's center due to its high density of buildings. Three scenarios were applied in various simulations: one with 30% more trees than the original area, one with 50%, and another with 30% and 70% more grass than the actual situation [6]. Between the cases, the air temperature, the wind speed, the relative humidity, and the physiologically equivalent temperature are compared with the DesignBuilder software. Thus, it was found that through the addition of trees and layers of grass, the air temperature is reduced due to two phenomena: shade and evapotranspiration during the day and at night. The trees that were used have high foliage. One of the factors by which they realized that evaporation is more significant in the day than at night was the difference in latent heat flow compared to sensible heat flow because perspiration happens more in the day (as the stomata, where evapotranspiration happens, is open during the day only). The best scenario in the study was where the number of trees was increased by 50%, compared to the scenario with 30% trees and 70% grass was the same, but the grass needs more water [6].

The Heriot-watt University of Edinburgh proposed a model that takes advantage of the shade given by a belt of trees. According to the study, the belt of trees' capacity will depend on the protection they provide and how much they reduce the wind speed. This capacity will be determined by its porosity, height, length, width, species of trees, the distance between the trees, and the distance from the building. To estimate which belt of trees is viable to reduce electricity consumption, they designed an optimal arrangement and determined the relationship of wind speed [7].

The disposition of the belt of trees has to be perpendicular to the wind (mainly from the South West). Therefore, it was decided to place the protection trees blocking these winds at 150 ° North. The trees in the protection belt were chosen as deciduous to receive sun rays in winter. The recommended trees should have 40% porosity, and to prevent the wind from entering, shrubs were planted at the base of the row of trees. It was shown that the protective belt of trees could reduce the consumption of heating energy for office buildings [7].

Modeling urban trees with dynamic simulations linking vegetation with temperature and urban air quality tells us how to plant barriers can potentially affect urban air quality, functioning as barriers between traffic emissions and the population by deposition of pollutants in vegetation. The impact of trees on the street is more complex than it appears, and careful design of vegetation structures is needed to optimize benefits and reduce unintended consequences. The health of the street must be evaluated through the vegetation characteristics such as its height, species, density, distance from the road, leaf density index [5].

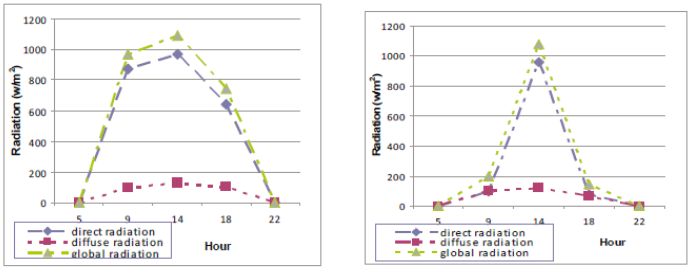
In some simulations where the pollution was high, planting trees was contradictory to mitigate the pollution because the deposition was not enough to clean the air and only increased the concentrations of pollutants, so planting low shrubs was recommended. These simulations led them to the conclusion that urban vegetation alone cannot eliminate air quality problems. The aerodynamic effects of trees are stronger than the positive effects of deposition, leading to reduced street ventilation and increased pollutant. Most of the time, tree plantations are for thermal purposes without considering that some configurations could affect air quality [8].

A thermal modeling of the urban microclimate in the Republic of Biskra on the impact on vegetation in external thermal conditions shows that, when analyzing the effects of vegetation and shaded areas, it was found that the air temperature decreases as a consequence of the decrease in surface temperature. A stage proposed with presence and absence trees (Fig. 1) [9].

Fig. 1 Proposed scenarios, with vegetation and without vegetation [9].

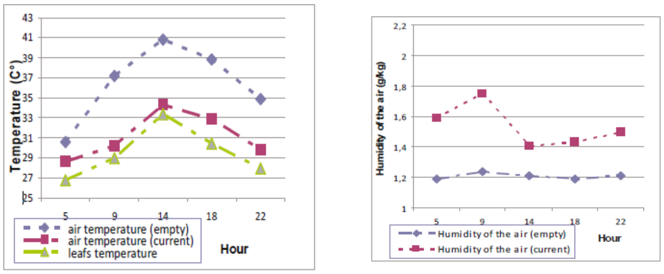
Based on a three-dimensional ENVI-met model, they quantified vegetation's impact at three levels: the amount of thermal radiation, air temperature, air humidity, and wind speed.

The increase in vegetation caused profound changes with respect to the incident solar radiation transmitted to the street next to the garden. The difference in radiation between the vegetated and non-vegetated scenery is noticeable. The solar flux transmitted to the treeless scene is higher (Fig 2). Due to the trees' shade, the surface temperature decreases and as the vegetation cover increases [9]. The air temperature also changed in both scenarios (Fig. 3(a)).



(a) (b)

Fig. 2 Radiation on stage) without vegetation, and (b) with vegetation [9].



(a) (b)

Fig. 3 (a) Temperatures and (b) humidity in the air [9].

The simulation took place in a dense space. The water in the soil and evapotranspiration helped to refresh the air. The evapotranspiration of a tree can reach up to 400 liters per day, representing a cooling effect equivalent to 5 units of radiation for 20 hours. The absolute humidity of the vegetated scene is higher than that of the non-vegetated scene (Fig. 3(b)). An inverse correlation can be observed between the absolute humidity value and the air temperature values in this area, which means an increase in air temperature causes a decrease in humidity and vice versa.

C. *Motivation and objetive*

The increases in the average temperature due to phenomena such as heat island and the greenhouse effect have aroused scientific interest in obtaining solutions that reduce this problem. One of the consequences that this brings is the indiscriminate use of air conditioning equipment.

Trees have different effects that help reduce the electricity consumption of a building to seek thermal comfort in humid tropical countries where temperatures are high most of the year.

In Panama, 45.51% of electrical energy is obtained from combustion processes, of which 62% is consumed for conditioning and refrigeration purposes. Thus, this project aims to evaluate the effect or influence that arborization has in reducing the thermal gains received by a four-stories dwelling located in Panama under a tropical climate.

II. METHODOLOGY

Arborization, as mentioned before, requires planning to fully reflect its benefits; therefore, a methodology is necessary. The first variable that must be considered at the time of arborization is why the tree is being planted. The second variable would be the planting site, what are the characteristics of the planting site, the available dimensions, the average pH of the soil, the availability of water, the presence of cables, height above sea level, precipitation in the region, the average temperature of the region, the topography of the area, and if there are any regulations. The third variable refers to the plant to guarantee the success of the arborization. This variable is the most important because more specific data on the plant, its characteristics, and requirements are considered [10].

In areas with much sunlight, another characteristic needed in a tree is having evergreen or long-lasting leaves. An evergreen tree always maintains the foliage; each year, only a part of its leaves dies while the youngest remain. By analyzing the three variables, selecting the right tree for the right site can be filtered.

Unlike other countries that need deciduous trees, the leaves when arriving at an unfavorable season die until a good season arrives. When winter arrives, it favors them that the leaves fall to take advantage of the sunlight and reduce electricity consumption. On the contrary, in Panama, we need perennial trees because of the need to block sunlight to avoid high temperatures [11].

In this way, the methodology used in the present work, described below, consists of conducting dynamic simulations using the DesignBuilder software, in which a 3D model of a dwelling is constructed based on the country's current regulations. The thermal behavior of said building is simulated in passive mode (without the use of air conditioning) and active (with air conditioning). Subsequently, different arborization scenarios are defined, in which the energy performance of the building is evaluated in terms of thermal comfort (in passive mode) and electricity consumption for cooling (in active mode).

A. *Definition of Arborization Scenarios*

The green structure index (Fi) was used to distribute the trees in the arborization. This index represents the distance for the type of landscape that considers the number of separation plots in the landscape distribution [13]. A large value of Fi implies that the parcels are far from each other. Its definition is as presented in (1), together with (2) and (3) [13]:

$$Fi = Di/Si \qquad (1)$$

where $Di = 1/2\sqrt{Ni/A}$, and $Si = Ai/A$. Here, S_i is the area index for landscape type i that represents the tree cover index. Ni represents the number of tree patches and A represents the total area in m^2. Di indicates the distance used for the landscape type that only considers spacing into patches.

In Fig. 4, it can be observed that a large value of Fi indicates that the sets of trees are separated from each other, reflecting the degree of separation of the landscape distribution [13].

To demonstrate the benefit of the reduction in electricity consumption, different scenarios were organized with different configurations of the positioning of the trees (see Table I).

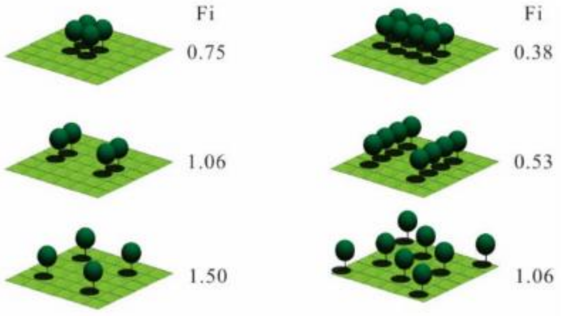


Fig. 4 Types of tree distribution according to the Fi index [13].

TABLE I

CALCULATION OF THE F_I FOR EACH SCENARIO OF TREES

Scenario	A (m^2)	Ai	Ni	Fi
Fi1	3912	4	2	11.05
Fi2		8	2	5.53
Fi3		4	4	15.64
Fi4		16	4	3.9

B. *Description of the four-story dwelling*

For this study, a four-story dwelling was constructed in DesignBuilder software, based on the Sustainable Building regulations proposed by the National Secretary of Energy. The dwelling has a total area per floor of 400 m^2, with a height of 3.30 m (Fig. 5). In Table II, the different materials of which the building is composed, and their transmittance value, are presented.

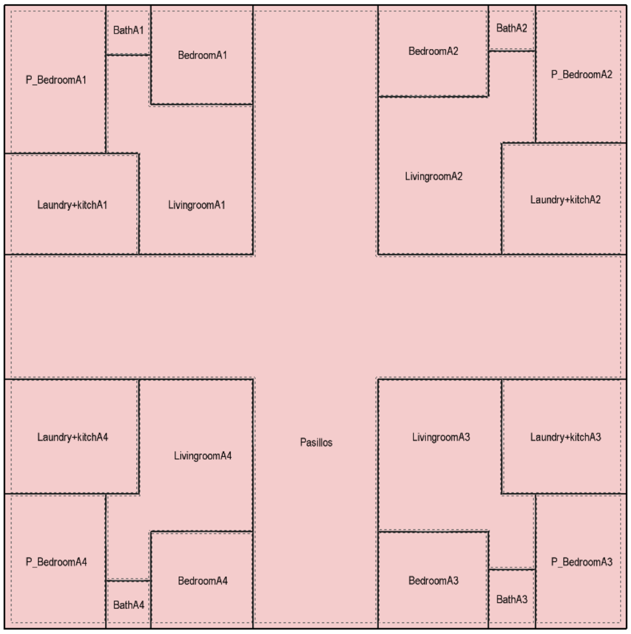


Fig. 5 Dwelling plan view.

TABLE II

TRANSMITTANCE VALUES FOR EACH ELEMENT OF THE ENVELOPE

Envelope elements	U (W/m^2K)
Exterior walls (cement 100 mm and plaster (x2) 5mm)	2.534
Flat roof (200mm concrete, 67.1mm insulation, 200mm air gap and 10mm plaster)	0.459
Partitions (cement 100 mm and plaster (x2) 5mm)	2.663
Internal floors (Ceramic 10 mm, cast concrete 200 mm)	2.864

According to the analysis of the meteorological data, to take advantage of the prevailing winds, the facades with windows are oriented North-South, and in all scenarios, trees have been placed in front of these two facades (Fig. 6).

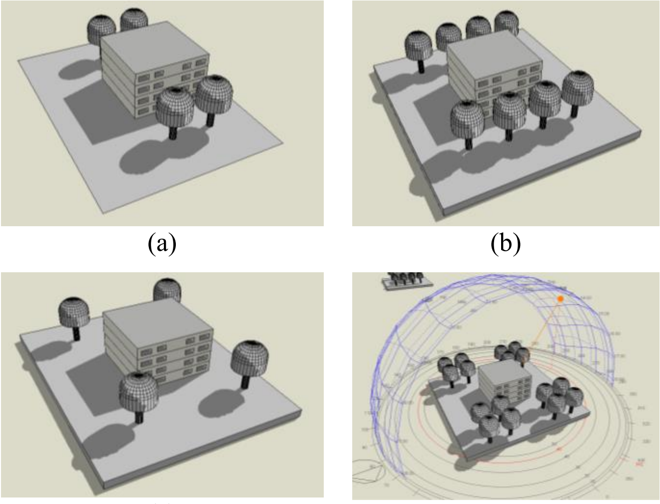

(a) (b) (c) (d)

Fig. 6 Scenarios for dwelling simulation: (a) Fi1, (b) Fi2, (c) Fi3, and (d) Fi4.

The dwelling occupancy profiles used for the simulations are defined in Table III. The activities considered are those of a typical departmental building, assuming that there is a standard family of four members in each apartment. The electrical consumption of the appliances is also presented in Table III. It should be noted that air conditioning is not found in all areas within the building. The areas that have air conditioning are: Bedrooms, living room.

TABLE III
PROFILES OF OCCUPATION AND USE OF EQUIPMENT

Household appliance	Number of hours switched on per week							Total hours
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	
A/C	24	24	24	24	24	24	24	168
Coffee maker	2	2	2	2	2	2	2	14
Computer	6	6	6	6	6	24	24	78
washer	Off	Off	Off	Off	Off	Off	3	3
Lights(laundry & kitchen)	3	3	3	3	3	3	3	21
Lights (principal bed)	6	6	6	6	6	24	24	78
Lights (secondary bed)	6	6	6	6	6	24	24	78
Lights (Livingroom)	8	8	8	8	8	24	24	88
Lights (Bath)	5	5	5	5	5	5	5	35
Microwave oven	2	2	2	2	2	2	2	14
Iron	Off	Off	Off	Off	Off	Off	3	3
Refrigerator	24	24	24	24	24	24	24	168
Dryer	Off	Off	Off	Off	Off	Off	3	3
Dryer	8	8	8	8	8	24	24	88

C. *Thermal comfort and energy performance evaluation*

To evaluate the performance of the building, the dynamic simulation results are compared between each of the proposed arborization scenarios, together with the scenario without trees. The meteorological data used corresponds to simulation data provided within the software for Panama City. Panama City is under tropical savanna climate conditions (Awi) according to the classification of Köppen.Geiger.

For performance in terms of thermal comfort, conventional indicators of comfort are used: Operative temperature, humidity, and the predicted mean vote (PMV), of the indoor environment in their monthly averages in terms of the average of all zones of the building in passive mode for each scenario. The passive mode operation consists of the use of natural ventilation 24 hours a day, and the ventilation flows are set to be estimated depending on the wind speed and direction levels provided by the meteorological data. According to Panama building regulations, indoor temperature levels, which define thermal comfort, must be 23.5 - 28.5 ° C, with relative humidity between 60 - 80%. For the PMV indicator, typically used in indoor environments with mechanical ventilation systems, adequate levels are between -3 (very cold) and +3 (very hot). A zero (0) value corresponds to a neutral thermal sensation, and +3 translates as too hot.

For energy efficiency, the same scenarios are simulated with the building in mechanical mode (with the air conditioners on all day). In this case, the electricity consumption only for air conditioning and internal solar gains are analyzed, which turned out to represent the highest external thermal gains.

III. RESULTS ANALYSIS AND DISCUSSION

This section presents the results of the simulations under different arborization scenarios, including the scenario without trees.

A. *Thermal comfort assessment in passive mode*

In Fig. 7, the monthly average indoor operating temperature levels of the entire building are observed for each of the arborization scenarios. As expected, the highest values are found for the scenario without trees (Fi0, dark blue color). However, it is observed that no scenario presents interior conditions within the temperature comfort ranges. This indicates that the building would not be able to operate in passive mode satisfactorily. This can be explained through internal gains due to equipment (Fig. 8).

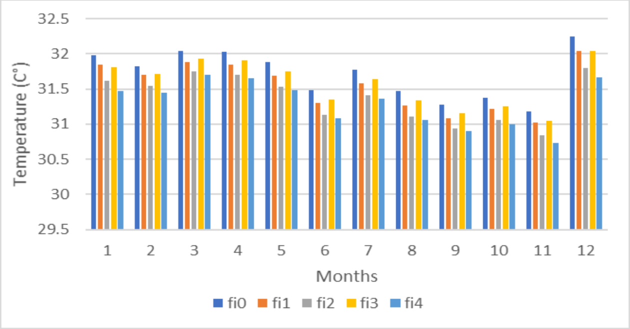


Fig. 7 Monthly average operative temperature for each arborization scenario.

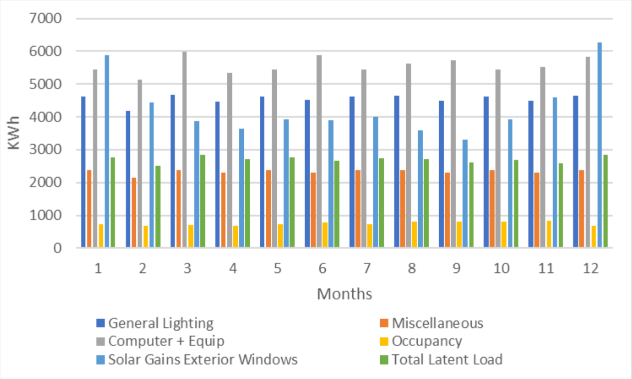


Fig. 8 Internal gains for the scenario Fi0.

Similarly, in Fig. 9, the monthly average indoor relative humidity levels of the entire building are observed for each arborization scenario. The highest levels of relative humidity are found during the rainy season months, as expected. Contrary to temperature levels, relative humidity levels for the first months of the year are within comfort ranges. It is possible to notice that the relative humidity values do not contemplate significant differences between the different scenarios. In passive mode, with natural ventilation activated all day, this behavior of humidity between the different scenarios is fully expected, mainly because the effect of evapotranspiration was not considered in the simulations.

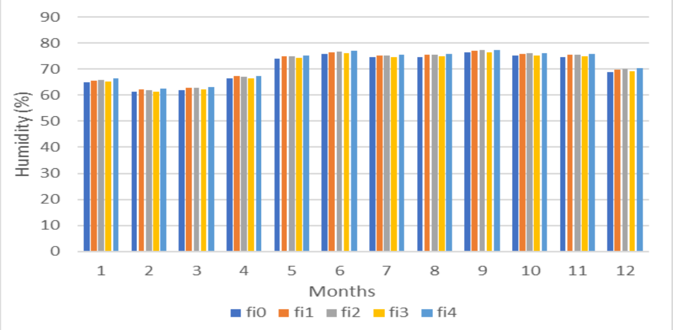


Fig. 9 Monthly average relative humidity for each arborization scenario.

In Fig. 10, the monthly average levels of the PMV comfort indicator are observed for each scenario. As for the relative humidity levels, the PMV values do not significantly differ between the scenarios, where the highest values correspond to the scenario without trees. The above classifies as "warm" and almost "very hot" for the indoor environment. Which again affirms the unsatisfactory operation of the building in passive mode as indicated by the temperature.

According to monthly averages, the evaluation of the performance in terms of thermal comfort under each arborization scenario shows that this building does not achieve comfortable interior conditions at any time of the year. However, the interior conditions seem to be dominated by the internal gains, as shown in Fig 8. Moreover, the and the greater the number of trees, the better the comfort performance (Fi4 scenario, in Figs 7, 9, 10).

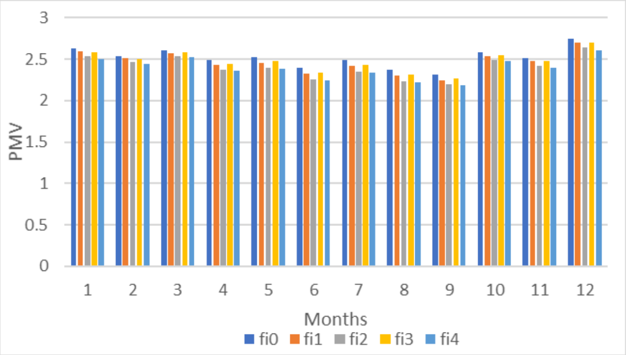


Fig. 10 Monthly PMV values for each arborization scenario.

B. *Energy performance in active mode*

In Figs. 11 and 12, the solar gains through the exterior windows and the electrical consumption due to air conditioning are presented. These results are analyzed together to explain the behavior encountered.

In Fig. 11, it is possible to observe the enormous difference between the scenario without trees and the other scenarios, indicating that the block or shadow effect associated with the arborization can reduce heat gains. It is also possible to observe that a difference between each scenario with trees. The Fi2 (gray color) and Fi4 (light blue color) scenarios present values close to each other. This may indicate that a significant positive effect is not necessarily reached by adding a substantial number of trees, four trees in Fi 2 and 16 trees in Fi 4, considering the consumption levels in these scenarios. However, the Fi3 distribution is the most unfavorable, but a significant reduction is still observed with respect to the scenario without trees.

In this way, it can be inferred that the Fi1 scenario corresponds to an adequate distribution in terms of a commitment of fewer trees with significant effects (approximately on an annual average) (Figs. 11 and 12).

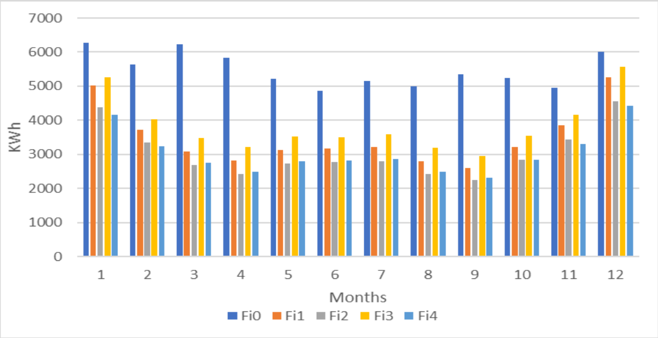


Fig. 11 Monthly average solar gains for each arborization scenario.

Similarly, a significant reduction in electricity consumption is observed due to air conditioning (Fig. 12). These reductions are dominated by trees' presence, influencing solar gains because internal gains are the same for all scenarios.

In this case, the Fi2 (gray color) and Fi3 (yellow color) scenarios present similar values throughout all the months, even if the number of trees differs significantly (two trees in front of each facade with windows).

This indicates that the electrical consumption for air conditioning is more affected (or reduced) by the trees that are at the corners of the building (Fi3) than by the trees that are directly in front of the facades with windows (Fi1), but the greatest reduction is achieved when trees are placed both in front of the facades and in the corners (scenario Fi2). The above analysis indicates that Fi2 is the most energy-efficient scenario.

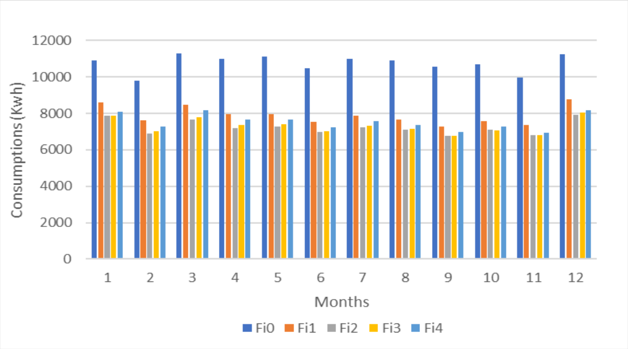


Fig. 12 monthly average electrical consumption for air conditioner.

As in other studies in the literature, it has been shown that the inclusion of trees in the microclimate of a building has a significant and positive influence on the performance of both thermal comfort and electricity consumption. As in [12], the addition of trees in barrier mode (Fig. 1) provides notable benefits, which are evidenced in a similar way to our Fi 2 scenario (Fig. 5 (b)). The aforementioned, supported by simulation results, indicates that a tree planting configured as a barrier to prevailing winds (in front of the facades with windows) allows obtaining the best results.

Moreover, knowing that one of the benefits of trees is to reduce the speed with which the air makes contact with the building, if we combine this with the effect of evapotranspiration (not simulated in this case), the long row of trees (scenario Fi2) reduces the contact area between the building and the heat emitting sources. Thus, the heat gain ratio is directly decreased, which may lower the indoor temperature, resulting in the reduction of air conditioning having to work less and consume less electricity.

IV. CONCLUSION

To study the influence arborization has on buildings thermal comfort and energy consumption, the thermal behavior of a 3D model dwelling was built and tested under different arborization scenarios. The purpose of the simulations in the different scenarios was first to prove that the trees have a positive thermal effect on the environment where they are planted. Secondly, to demonstrate that planting the trees with different configurations or positions also influences their effect on the environment and the surrounding buildings.

After analyzing the proposed scenarios given that solar gains are one of the forms of heat that most affects buildings and trees, blocking part of this radiation from the sun, they reduce this factor in addition to reducing the speed of the wind that this by having a higher temperature than the building envelope, it gives heat to it, also increasing the humidity of the environment, which directly reduces the temperature of the surroundings of the trees, it is concluded that trees are an efficient way to reduce electricity consumption required by air conditioning equipment to reach comfort or user-friendly conditions within the regulated control volume.

By arborizing correctly, not only considering the attractiveness of the tree but also taking advantage of all the benefits that they provide both social and regulating the micro and macro climate, combining the characteristics of the landscape, ones helped presented, materialize the bases of an efficient method, capable of optimizing the consumption of the building, and of improving its surroundings.

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