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Evaluation of thermal behavior for an asymmetric greenhouse by means of dynamic simulations

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Abstract
In this paper is presented the design of an asymmetric greenhouse, with a simulation and evaluation of its microclimate by means of DesignBuilder®. Climatic and geographical conditions of the greenhouse location are processed with DesignBuilder®, which also allows to include the geometrical characteristics of the enclosure and its roofing, the properties of its building materials and a description of the climate control system. Three configurations of this asymmetric greenhouse are evaluated in order to analyze and compare their internal gains.

Keywords: asymmetric greenhouse, climate control, dynamic simulation, microclimate.

Evaluación del comportamiento térmico de un invernadero asimétrico mediante simulaciones dinámicas

Resumen
En este trabajo se lleva a cabo el diseño, simulación y evaluación del comportamiento del microclima de un invernadero asimétrico mediante el software DesignBuilder®, incorporando las condiciones climáticas y geográficas del lugar donde se pretende instalar el invernadero, sus características geométricas y las propiedades de los materiales del recinto y su techado, así como del sistema de control de climatización. Se evaluaron tres diferentes configuraciones para la envolvente del invernadero para comparar el comportamiento de sus ganancias internas.

Palabras clave: *control de climatización, invernadero asimétrico, microclima, simulación dinámica*.

1. Introduction

An advantage of farming based on greenhouses is that it makes possible to supervise closely every factor related with crop behavior [1], even in zones with low quality soils if a hydroponic technique is used [2]. Additionally, inner temperature, ambient humidity and soil humidity can be sensed in an automatic way, to send all this data to a control system that modifies the internal conditions of the greenhouse. This represents an advantage in respect to open field cultivation, since the damage on crops due to plagues is minimized [3].

Accordingly to IDAE (Instituto para la Diversificación y Ahorro de Energía, Spain),the study on energy efficiency of the greenhouses is vital for country development, as it could be a great support for natural resources conservation and the reduction on the emission of greenhouse gases, generating big savings on energy consumption in parallel.

The thermal performance of a greenhouse depends basically on climate conditions, structural shape, orientation and its building materials [4]. The analysis of thermal performance is a complex task, so a software for developing dynamic simulations is needed, such as DesignBuilder [5], [6], EnergyPlus [7] or Ecotect Analysis [8].

In recent years, computational fluid dynamics has been used to develop numerical models that improve the understanding of the variables interaction that make up climate inside greenhouses. In addition, the development of

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more powerful software and hardware has been a key to the generation of improved results in the past five years [9].

An understanding of energy behavior is important in order to design efficient greenhouses that include climate system automation; for example, there is an Energy Audit protocol for greenhouses based on energy balance by a mathematical model for heat transfer phenomena, that serves to analyze the nature of the thermal and energetic behavior in terms of its interacting variables, as solar radiation, construction materials, and active cooling systems [10].

In this paper, the thermal behavior of three kinds of greenhouses is studied. Each enclosure is built using different covers with passive climate control systems, applying similar criteria to those used for buildings design in order to decrease the necessity of systems for heating or cooling, which require a huge amounts of energy. The organization of this work is as follows: Section II gives a theoretical framework about earth's movement and thermal phenomena in greenhouses. Section III contains an explanation about the asymmetric greenhouses design, while simulation parameters are considered in Section IV. Finally, results and conclusions are included in Section V.

2. Theoretical framework

Different techniques and technologies are applied to crop production in greenhouses, to modify the regular cycles of cultivation and increase the product quality and the number of harvesting periods, in order to improve the sale conditions [11]. This is possible by means of automated systems for irrigation and controls for temperature and relative humidity, to help farmers to optimize their productive resources, diminishing water consumption and electric energy demand in order to lower production costs [12].

The use of production systems with greenhouses in Mexico is extended to 24 of his 32 states. However, approximately 75% of this production is concentrated in just five entities: Sinaloa, North Baja California, South Baja California, Sonora and Jalisco [13], with tomato as main crop [14]. Applied technologies include irrigation, automatic ventilation, water heating, thermal screens, automatic control and hydroponics. Most Mexican regions have optimal conditions for greenhouse production, because of long duration of days and enough intensity of winter's solar energy [15].

The earth rotates around her polar axis and an angular change is produced between the equatorial plane and the lines passing through earth center and sun center, causing a solar declination (Fig. 1).

This phenomenon is magnified during the solstices because in summer there is a 23.5° solar declination that produces long days, while in winter the angular magnitude is the same but in the opposite direction, i.e. -23.5°, causing short days. However, during vernal and autumnal equinoxes the solar declination is zero because the sun is over the celestial equator, which implies that day and night have the same number of hours.

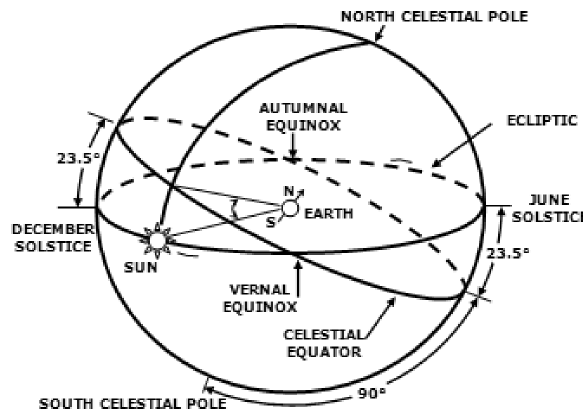

Figure 1. Sun's apparent motion.
Source: Adapted from Strobel, N., 2013. [16]

The geographic location of the greenhouse also affects its design, since sunlight is perpendicular to equator but deviates accordingly to the location on North or South due to earth curvature. So, the first parameter for designing the solar collection surface is the latitude (L), which is the angle between the equatorial line and the meridian where the installation site is located.

2.1. Thermal phenomena in greenhouses

The envelope and the internal elements of a greenhouse affect the difference between the inner and outer climates, producing an energetic interchange that defines its thermal and environmental behavior [17]. For this reason, the inner microclimate needs to be regulated in order to obtain optimal conditions for crops growth.

The relation between the inner and outer maximum temperatures is obtained by an adequate selection of materials for walls, floor and roof, especially considering their thickness. However, mechanical systems for heating or cooling are required when the external climate conditions do not allow optimal inner conditions. The passive design helps to minimize the use of these mechanical systems and to diminish the energy required for its operation [18].

The glazing system is the simplest and most economical passive design. The strategy is based on an adequate positioning of the glazing in order to have a maximum solar radiation in winter and a minimum solar radiation in summer, so greenhouse geometry is an important aspect. The geometry parameters of the enclosure for an adequate operation include length, width and height [18].

2.2. Computational fluid dynamics and the measuring of greenhouses variables

In the last decade, the use of numerical methods such as the Computational Fluid Dynamics (CFD) which is based on Navier-Stokes equations, has proved to be a good tool for developing models in order to understand relationships among the interacting variables in the behavior of climate for a greenhouse [9].

Simulations are used frequently to predict the behavior of the greenhouses; several studies used computational dynamics analysis to investigate the climatic conditions inside them. These computational tools increase the degree of realism by simulating insect-proof environments (among other 3D models) and analyzing their effect on crops, considering it as a porous medium. The results have improved our understanding of the phenomenon in a greenhouse.

The computational dynamics produces a model for simulating night-time climate and condensation in the greenhouse. The model was applied to a enclosure with a four-span plastic cover. The condensation film was simulated by adding a user defined function (UDF) to the commercial CFD software. The results showed the importance of heat transfer losses by radiation, particularly for low values of soil heat flux (SHF); they also showed the roof was the coolest surface in the greenhouse, and therefore it is the condenser and sink for the water vapor produced by the crop. The CFD condensation model is intended to be used for the design of strategies for humidity control, particularly in unheated greenhouses [19].

There are numerical simulations for the distribution of climate parameters within a tomato greenhouse ventilated by tunnel, with variable outside conditions. The boundary climatic conditions were determined by experimental measurements, and the sun position was calculated for every time interval considered. Results are presented for spring equinox and summer solstice; these results highlight the combined influence of sun position, wind direction and the greenhouse microclimate. In this work, the possibility of using this methodology as conceptual tool for designers or in association with a control climate model for farmers is discussed [20].

As mentioned before, another important item is the study and measure of the variables interacting on a greenhouse. Advanced systems monitor these variables using wireless sensor networks that consider humidity, temperature, light, and volumetric water content in the soil. These systems are flexible enough to be adapted to any greenhouse; since they are based on wireless technology, their nodes can establish links automatically, and have implemented functions for saving energy which extend the life of batteries up to a crop year without maintenance [21].

3. Asymmetric greenhouse design

The construction virtual site is near Mexico City, due to the low solar-radiation produced by cloudiness, the high pollution rate and the predominant low temperatures [22]. In order to increase the solar radiation received, the greenhouse is designed with a larger area on the roof side facing south, with an orientation that is parallel to sun's apparent movement, i.e. east to west. The slope on this south face produces minimal variations of the solar energy collected during the year. The slope angle (β_z) is defined by means of the difference between the latitude (L) of the location site and the solar declination (d), i.e. $\beta_z = L - d$.

Taking into account that latitude of Mexico City is 19° and that in equinoxes the solar declination is zero, the resultant slope angle is 19°, as shown in Fig. 2.

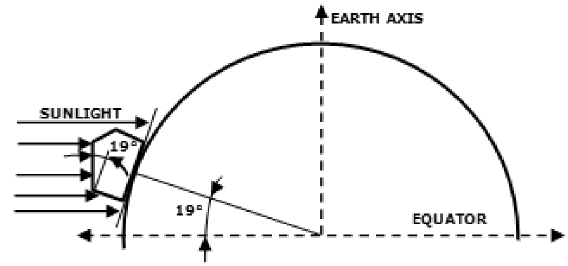

Figure 2. Cover's angle for equinoxes.
Source: Own elaboration

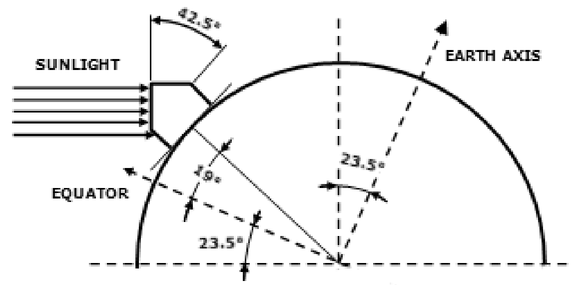

Figure 3. Cover's angle for winter.
Source: Own elaboration

In the north hemisphere exists a solar declination of approximately -23.5° during the solstices, as shown in Fig. 3, which produces a slope angle $\beta_z = 42.5°$.

The ideal slope for the cover can be calculated from this adjustment, to receive the solar radiation perpendicularly at noon. Since in equinoxes the angle is 19° and in solstices it is approximately 43°, the selection of an angle between this two values is needed. For simulation purposes the slope angle selected is 26°, because an angle near to 43° could produce instability in the greenhouse structure under strong winds.

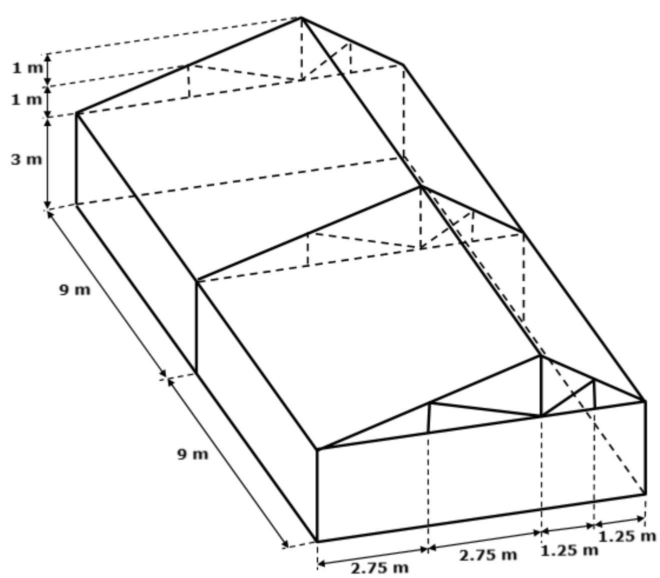

Figure 4. Final design of asymmetric greenhouse.
Source: Own elaboration

Fig. 4 shows the designed asymmetric greenhouse. The enclosure has a bamboo structure with two modules of 9 m x 8 m, a lateral height of 3 m and 5 m in the ridge, with 144 m^2 of total area and a total volume of 576 m^3. The dimensions were selected taking as a base the maximum longitude of the bamboo beams, which is 12 m.

4. Simulation parameters

In order to carry out dynamic simulations with DesignBuilder is necessary to define important parameters such as climatic data, characteristics of the materials of the cover, and HVAC systems.

4.1. Climate data

The climate data of Mexico City for this work consist of a TMY3 that was made from the 1991 to 2005 database; the climate file is under the designation of the World Meteorological Organization (WMO) and the source format is IWEC (International Weather for Energy Calculations). In Fig. 5, the weather can be seen in the template for DesignBuilder, which is necessary to describe the location of data such as latitude, longitude and altitude above sea level; this climate template is created with the data for every hour.

Fig. 6 shows the template field soil temperatures obtained with the EcotectAnalisys software; this is an important parameter since represents the heat transfer by conduction through soil terrain, and soil temperature varies depending on the year. So it would be a mistake to consider the soil temperature as constant throughout the year; it can be seen that it is coldest during the month of January with 15 ° C, while in July is the hottest, with 18.7 ° C.

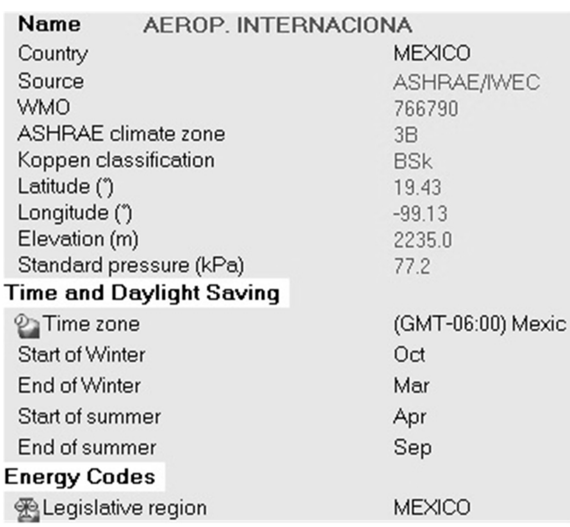

Figure 5. Template climate of Mexico City.
Source: Adapted from U.S. Department of Energy.

4.2. Characteristics of the building materials

Templates and their glazing materials are created to simulate the characteristics of the walls and cover with DesignBuilder. Fig. 7 shows the properties of the glazing

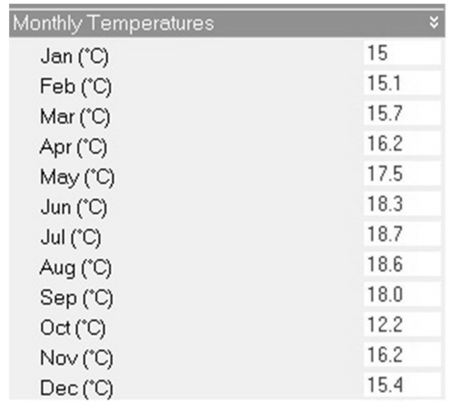

Figure 61. Ground temperatures in DesignBuilder.
Source: Adapted from U.S. Department of Energy.

templates, that were developed for polycarbonate which has a total solar transmission of 0.780, a light transmission of 0.790 and U-value (thermal conductivity) of 3.50 W / m 2-K. In the case of concrete blocks, the template included in the package is used.

4.3. HVAC Systems

HVAC systems are divided into active heating and cooling; the heating system runs on natural gas, with a COP of 0.83 and a flow temperature of 35 ° C, the system is programmed to operate whenever the inner temperature is 22 ° C; the cooling system operates with electric power, has a COP of 1.67 and air drive ranges between 7 ° C and 7.5 ° C, and is scheduled to run whenever the inner temperature reaches 26 ° C.

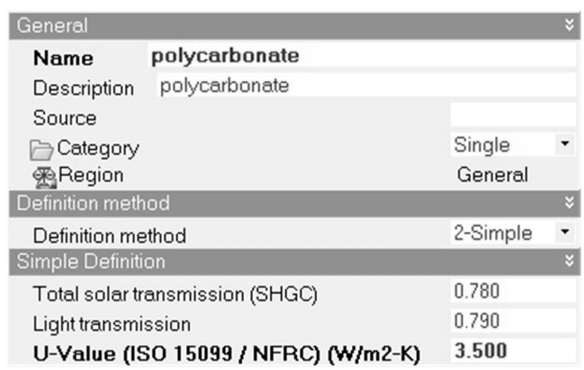

Figure 7. Template glazing.
Source: Adapted from U.S. Department of Energy.

4.4. Shading System

Among the four types of shading devices provided by DesignBuilder, slatted blinds are chosen because they block the direct radiation and reduce the solar gain; however they allow to pass a portion of the diffuse radiation, which serves to decrease lighting property, as would do a diffusing screen or curtain.

For this case was used a template already defined in the software, called Blind slats with medium reflectivity. Its properties are established as follows: the shading screen distance is 0.05m, a horizontal orientation, the width of the blind slats is 0.0250m, the spacing between slats is 0.0188m, with a 0.0010m thickness, and the tilt angle with respect to glazing is 45 °.

Finally, an indoor air temperature control system (OnIfHighZoneAirTemp) was used; this is activated whenever the temperature of the air inside the area during the previous simulation step exceeds the control value (C or F).

4. 5 Inner-air set point for temperature control

Simulations with DesignBuilder-EnergyPlus generate extensive data on environmental conditions within the enclosure. The set point temperature defines the ideal temperature (i.e. the setting of the heating thermostat) in the range when heating or cooling is required; its interpretation depends on the Temperature control calculation option. For this case the Internal operative temperature was considered; this is calculated by the mean of the internal air and radiant temperatures, where Internal air temperature is the calculated average temperature of the air inside and the Internal radiant temperature of the zone is calculated as if the sensor is in the center of the zone, with no weighting for any particular surface.

5. Results and discussion

The simulations were developed using DesignBuilder® and the weather data archive for Mexico City, obtained from [23]. This archive is based on measurements obtained by weather stations and includes temperature, ambient humidity, solar radiation and wind velocity for each hour of year 2002, which is a representative year of typical weather conditions for the zone.

From the average temperatures for that year it can be noticed that the coldest months were January and December, while the hottest were April and May. The maximum temperature reached was 19.1°C in May and the minimum was 13.6°C in December.

In order to show the behavior of the designed greenhouse, three configurations were developed with polycarbonate as a cover due to its thermal conductance and its common use for building greenhouses [23]. The crop selected as reference was tomato, with an optimal growth temperature during daylight between 21°C and 27°C [24].

The basic configuration (A) for the asymmetric greenhouse, constructed with bamboo, has a polycarbonate envelope both in enclosures as in the roof. The second one (B) has the same structural materials, but also includes a climate control system programmed to maintain the inner temperature between 22°C and 26°C in every time.

Finally, the third configuration (C) has concrete walls 1.5m height on south, east, and west sides, while the north wall is completely of concrete and the remaining structure is constituted by glazing with polycarbonate. For inner weather control this configuration uses active and passive climate control systems.

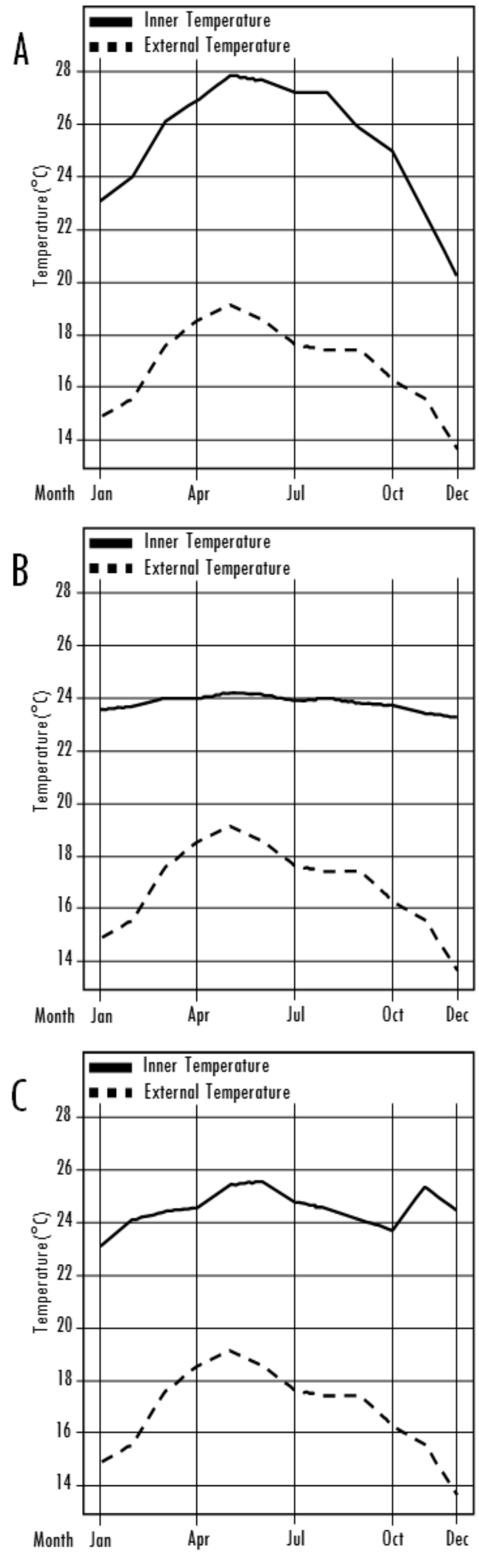

Figure 8. Thermal behavior for the three greenhouse configurations. Source: Own elaboration

The active climate control is a heating system programmed to work when the temperature is under 22°C, only in November and December. From March to October

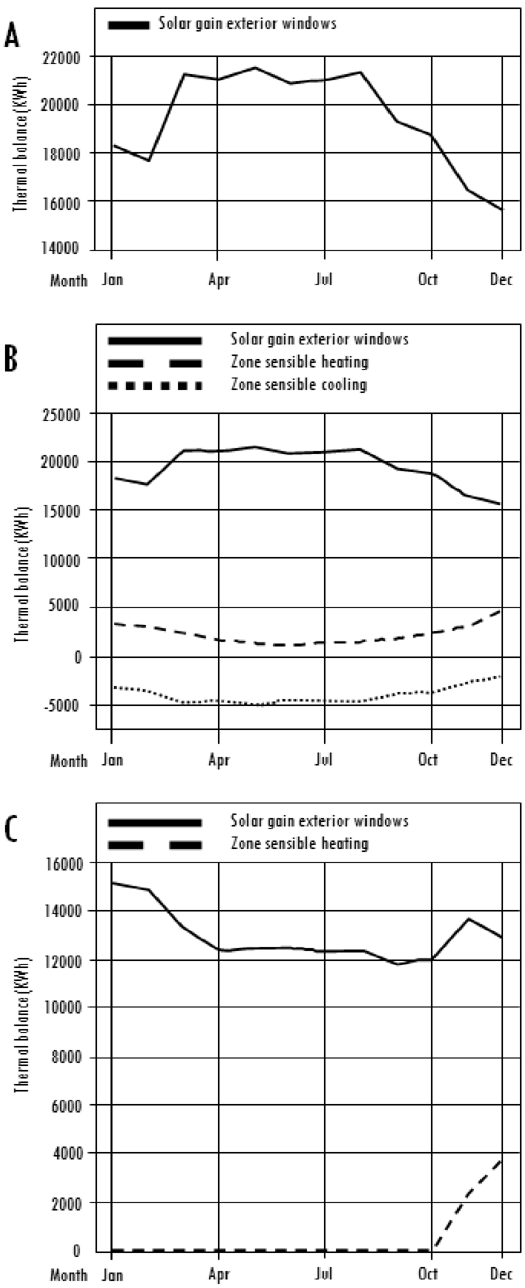

Figure 9. Inner gains for greenhouses A, B and C.
Source: Own elaboration

the passive climate control, consisting of external shading curtains, is activated when the temperature is above 23°C.

The thermal behavior for the three configurations is shown in Fig. 8. In configuration A the temperature oscillates from 20.15°C to 27.81°C, which is out of the optimal limits for crop growth.

The temperature in configuration B oscillates from 23.5°C to 24.11 °C which is between the optimal limits, because the active climate control system operates the whole year. The greenhouse of configuration C has temperature oscillations from 23.09°C to 25.58°C, utilizing active climate control only for two months.

Table 1.
Construction cost for configurations A and B.

Configuration	Area (m^2)	Cost (USD/m^2)	Total (USD)
A	144	20.42	2,940.48
B	144	35.74	5,146.56

Source: Own elaboration

Table 2.
Construction cost for C configuration.

Area (m^2)	Cost (USD/m^2)	Total (USD)
144	37.74	5,434.56
No. Blocks	**Cost per unit($)**	**Total ($)**
1535	0.503	772.10

Source: Own elaboration

Table 3.
Operating costs for B configuration

Heating Cost			
Kwh year	MMBtu year	Natural Gas Cost (USD/MMBtu)	Total USD
34,333.72	117.15	3.693	432.635
Cooling Cost			
Kwh year		Cost per Kwh of energy	Total USD
28,130.78		0.105	2,953.732

Source: Own elaboration

Fig. 9 shows the inner gains for the three configurations, these are: the solar gains of exterior windows, the zone of sensitive heating and the zone of sensitive cooling.

The solar gain for the greenhouses A and B is the same, since they both have an envelope built with polycarbonate glazing, which produces gains near to 21500 KWh from March to August. Configuration B requires to extract or supply almost 5000 KWh for reaching the desired temperature. In order to do this, the active climate control systems are functioning in January, February, November and December, which implies a huge demand of electric energy during four months.

Configuration C shows the advantage of the passive climate control using shading curtains, since the solar gains diminish from 21500 KWh to 12500 KWh, implying that a cooling system is not necessary. On the other hand, a heating system is not necessary for January-February, while the use of this system in November-December decreases in approximately 1000 KWh, because of its structure of concrete walls.

Table 1 shows the construction cost for each configuration. The costs are calculated based on the area and the cost per m^2, depending on the type of technology [25,26].

Table 2 shows the number of blocks required for building the configuration C walls, with a total of 1,535 blocks. The cost of solid concrete block is $0.503 USD each piece, and the walls have a cost of $772.10 USD, resulting in total cost of $5,919.14 USD for a C configuration construction.

The operating cost is assessed with DesignBuilder using the fuel consumption per year for each greenhouse topology to determine the cost of an operating year. Fuel prices used correspond to $103.72 USD per kWh of electricity on

Table 4.
Operating costs for C configuration.

Heating Cost			
Kwh year	MMBtu year	Natural Gas Cost (USD/MMBtu)	Total USD
7381	25.18	3.693	92.989
Cooling Cost			
Kwh year		Cost per Kwh of energy	Total ($)
0		0.105	0.00

Source: Own elaboration

downtown area and $ 3,693 USD/ MMBtu. Table 3 and 4 are used for configurations B and C in order to determine the operating costs for each system.

It can be observed from Tables 1 and 2 that the most expensive greenhouse configuration is C, using polycarbonate with both active and passive cooling, for a total of $6,206.66 USD, followed by the type B with polycarbonate and active cooling with a total of $5,146.56 USD. Finally, the greenhouse with only polycarbonate is the cheapest, with a total of $2,940.48 USD.

In terms of operating cost, configuration A is the most economical because does not have a HVAC system installed. Configuration B is the most expensive, with an operating cost of $3,386.36 USD per year, since cooling and heating remain active throughout the year. The C Configuration has an operating cost of $92.98 USD per year, reducing fuel consumption in a 100%, and up to 78% of natural gas consumption.

6. Conclusions

The results obtained shown that an asymmetric greenhouse with concrete enclosure, a polycarbonate cover and shading curtains diminishes the electric energy consumption at the same time that maintains the inner temperature inside the desired limits, with an increment of the thermal efficiency of the greenhouse. This design can be implemented in crop zones similar to the one used in this work, taking into account the correct location of the structure, in order to have the larger solar reception area oriented southwards.

Because of its design, the operating costs for the greenhouses were reduced, with a total quantity of $772.50 USD in concrete blocks and the implementation of passive cooling systems. On the other hand, although the structure is very important the dynamic simulations showed that the solar gains are related mainly to the size of reception area. These results demonstrate the useful of virtual construction of greenhouses using specialized software for analyze the interaction between internal and external weather conditions.

Future work shall consider an increment on the number of natural systems inside a virtual greenhouse, in order to have a much more real simulation. These systems could be: humidity, infiltrations and thermal loads of ground and crop, to mention a few. It is also necessary to build a greenhouse with the designed characteristics to verify the results from the dynamic simulations, comparing them with real measurements.

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