Ener-Habitat: Wall/Roof Envelope Thermal Performance Simulator

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ABSTRACT: The envelope of a building is an important factor for its thermal behavior. The selection of an adequate wall/roof configuration in climates with large temperature oscillation during one day and high solar radiation requires a time- dependent heat transfer analysis. To help architects and other building designers to choose a suitable wall or roof configuration for Mexican climates a wall/roof envelope thermal performance simulator, named Ener-Habitat, is under development. In this work, this simulator and its mathematical model are presented. The simulator allows comparing the thermal performance of wall/roof configurations either in air-conditioned or in non-air-conditioned rooms. Ener-Habitat solves the periodic time-dependent heat transfer equation for multilayered wall/roofs, with constant film coefficients on exterior and interior sides, for the typical day of a month. The simulator uses climatic data from a database for the most important Mexican cities. The simulation can be performed for a selected month or for the twelve months of the year. Ener-Habitat gives the energy transferred to the indoor through a unit area of the wall/roof for the non-air-conditioned situation. For the air-conditioned situation, Ener-Habitat gives the energy consumed by the air-conditioned system due to a unit area of the wall/roof.

Keywords: building, envelope, thermal, performance

INTRODUCTION

In Mexico, there are a variety of climates; nevertheless, more than 70% of the country corresponds to hot climates [1]. In these regions, the buildings must use some kind of technology to keep indoor temperature within comfort conditions. The National Energy Balance [2] presents that almost 20% of consumed energy corresponds to residential and commercial sectors. The 89% of this energy was produced from hydrocarbons, with the consequent environmental impact.

Among the technologies for keeping indoor temperature within comfort conditions are the passive systems; these required none or little energy to achieve hygrothermal comfort inside a building. These systems reduce or eliminate the use of conventional systems, achieving an important energy saving. They are generally known as passive systems to specific constructive elements such as solar chimneys, ventilation towers, Trombe walls, ceilings coat, proper use of vegetation, shading elements, etc., however the passive system that could prove more important is the same envelope of the building. This includes the building orientation, the proportion of window area and the configurations and materials of the walls and roofs of the envelope.

The Mexican sector of construction in recent years has shown little, but increasing, interest towards energy saving. The National Agency for Standardization and Certification of Construction and Building proposed a rule [3] with the aim to reduce the energy consumption in buildings with air conditioning. This standard, as well as the Mexican official standards NOM-008-ENER-2001 NOM-ENER-020-2011, for energy efficiency in buildings, envelopes of non-residential buildings and residential buildings, respectively [4,5] use methods based on an steady-state heat transfer analysis. Thus, they take into account the thermal resistance of the envelope elements, but do not take into account their thermal storage capacity. These methods are useful to estimate the needs of heating in winter for countries in the temperate or polar areas where the temperature oscillation during one day and solar radiation are small [6]. When the temperature oscillation during one day is large and the solar radiation is high, the wall/roof heat storage capacity is very important. In these cases, a method based on an analysis of time dependent heat transfer must be used. It has been demonstrated that when the daily temperature oscillation and the solar radiation are important, a wall/roof built with materials with a suitable combination of the values of conductivity, density and specific heat can have better thermal performance than other with lower thermal resistance, especially when used in non-air-conditioned buildings [7].

Along the year, solar radiation and daily temperature oscillation are significant in most parts of Mexico [8], thus to evaluate the thermal performance of envelope walls/roofs in Mexico a method based on an analysis of time-dependent heat transfer must be used. This analysis can be done through programs like Energy Plus and TRNSYS, however require specialized users with knowledge in heat transfer. To help architects and other building designers to choose a suitable wall or roof configuration for Mexican climates a wall/roof envelope thermal performance simulator, named Ener-Habitat, is under development. The simulator allows comparing the thermal performance of wall/roof configurations either in air-conditioned or in non air-conditioned rooms. The present version of the simulator evaluates roof configurations composed by homogeneous layers and is in Spanish. In this work, this simulator and its mathematical model are presented.

MATHEMATICAL MODEL

To calculate the heat transfer through a wall/roof composed of N layers of homogeneous materials, with a total thickness L, for each *j-th* layer, the one-dimensional time-dependent heat conduction equation is used

$$\frac{\partial T_j}{\partial t} - \alpha_j \frac{\partial^2 T_j}{\partial x^2} = 0. \tag{1}$$

This equation describes the variation of the temperature inside the *j-th* layer, T_j, as a function of time, t, and the position x. The coefficient α_j is the thermal diffusivity of the material of the *j-th* layer and is defined as the ration between the thermal conductivity k and the thermal capacity of material $C_j = \rho_j c_j$, where, ρ_j is the density and c_j is the specific heat capacity.

By continuity of the heat transfer at the layers joints

$$-k_j \left.\frac{dT}{dx}\right|_{j,j+1} = -k_{j+1} \left.\frac{dT}{dx}\right|_{j,j+1}, \tag{2}$$

at the exterior surface

$$-k_1 \left.\frac{dT}{dx}\right|_{wo} = ho(Tsa - Two), \tag{3}$$

and at the interior surface

$$-k_N \left.\frac{dT}{dx}\right|_{wi} = hi(Twi - Ti). \tag{4}$$

Where Tsa and Two are the solar-air and the wall/roof external surface temperatures, Ti and Twi are indoor and interior surface temperatures, ho and hi are the exterior and the interior film coefficients. The solar-air temperature is given by [9]

$$Tsa = To + \frac{AI}{ho} + RF, \tag{5}$$

where To is the temperature of the outdoor air, I the solar radiation, A the solar absorptivity of the exterior surface, and RF the infrared radiation factor.

For the case where air conditioning is used, the temperature of the air inside is kept constant to the comfort temperature [10]

$$Ti = Tc. \tag{6a}$$

In the case where air conditioning is not used, the indoor temperature of the air is calculated from the heat transferred through the wall/roof

$$d\rho_a c_a \left(\frac{\partial Ti}{\partial t}\right) = hi(Twi - Ti) \tag{6b}$$

where ρ_a and c_a are the density and the specific heat of air. It is assumed there is a distance d from the interior surface where there is no heat transfer, i.e. an adiabatic condition.

The simulator solves the time-dependent heat transfer equation (1), with the boundary conditions (2-6), during a typical day of a month under periodic conditions. It considers constant the film coefficients ho and hi. The values of these coefficients are taken from the Mexican official standards NOM-008-ENER-2001 and NOM-ENER-020-2011 [4,5].

The typical day for each month was constructed by averaging the daily corresponding values of the maximum solar radiation, the maximum and minimum outdoor temperatures and the time when these occur, which are the required data for the outdoor conditions model [11]. These values are taken from the typical year for a place obtained from Meteonorm [12]. A climatic database with the twelve monthly typical days for the most important Mexican cities was generated, and is used by the simulator.

The objective of the simulator is to compare the thermal performance of walls/roofs configurations, thus it is required to define a parameter for this purpose. When evaluating a wall/roof for the non-air-conditioned situation, the parameter is the energy transferred to the indoor through a unit area of the wall/roof during a day, Q,

$$Q = \sum_n \frac{hi(Ti - Twi)_n}{\Delta t} \quad if \quad Ti > Twi, \tag{7}$$

where the summatory is taken during a day, and Δt is the time step for the numerical solution. While evaluating the wall/roof for the air-conditioned situation, the parameter is the total thermal energy consumed by the air-conditioned system due to a unit area of the wall/roof, E,

$$E = E_h + E_c, \tag{8}$$

where E_h and E_c are the energy consumed for heating and the one for cooling, respectively and are given by

$$E_h = \sum_n \frac{hi(Tc - Twi)_n}{\Delta t} \quad if \quad Twi < Tc \tag{9}$$

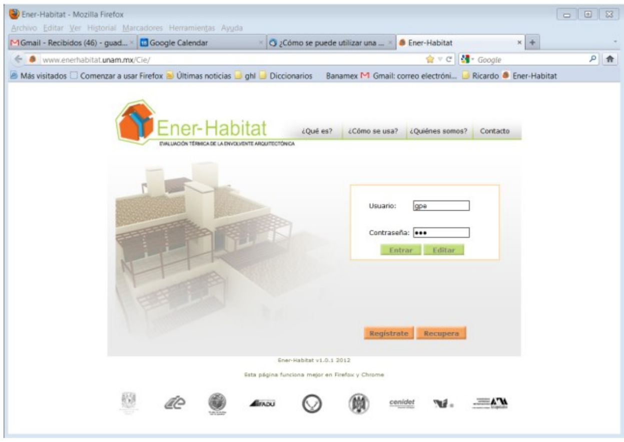
and

$$E_c = \sum_n \frac{hi(Twi - Tc)_n}{\Delta t} \quad if \quad Twi > Tc. \tag{10}$$

USE OF THE SIMULATOR

The philosophy of the simulator is to be as simple as possible and not require the user to be an expert on heat transfer. The simulator is available via Internet for free, though the webpage http://www.enerhabitat.unam.mx (Fig. 1). So to access, it is only required a browser (Firefox and Chrome are recommended) and an internet connection. To use it, it is necessary to carry out an initial registration process.

After accessing the tool, the user must choose from a list provided the place where the roof will be evaluated; select the period of evaluation: one month in specific or throughout the year; choose the condition for the evaluation: either in air-conditioned or in non air-conditioned room; and must define the number of configurations to assess from two to five.



Usuario: gpe
Contraseña: •••

Figure 1: Simulator webpage http://www.enerhabitat.unam.mx.

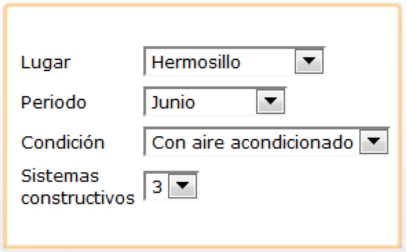
In the next step, for each configuration, the user must define the number of layers, up to seven. The layers are numerated beginning with the most exterior one. Then the characteristics of each layer must be given, beginning with the layer thickness. The layer material can be selected from a given database (BD), but also the user has the possibility to create a database.

In the simulator database, the name material is accompanied of the thermal properties of the material: thermal conductivity, density, and specific heat, all in the International Unit System (IUS). The database of materials provided by simulator (BD) contain the most used in Mexico building materials, their thermal properties values were taken from ASHRAE [9], since Mexican manufacturers do not report these values. The user is the only one that has access to his/her own materials database. To add a material to the user database, a name and the three thermal properties in the IUS must be given. For layer 1, additionally the solar absortivity must be given.

Once all the layers of all the configurations have been defined, the simulator performs numeric calculations to solve the periodic time-dependent heat transfer equation, along with the appropriate boundary conditions, and then it shows the results.

EXAMPLE: THREE ROOF CONFIGURATIONS EVALUATION FOR AIR CONDITIONING CONDITION

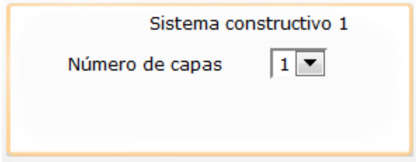
Selection of the place, the period, the condition of air conditioning, and the number of roof configurations. In Fig. 2, the selected variables for the example are presented.



Lugar: Hermosillo
Periodo: Junio
Condición: Con aire acondicionado
Sistemas constructivos: 3

Figure 2: Selection of place (lugar), the period (periodo), the condition of air conditioning (condición), and the number of configurations (sistemas constructivos) to evaluate.

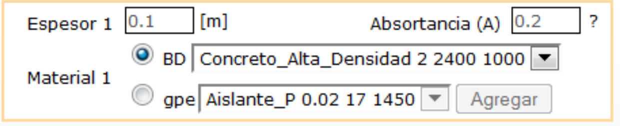
Selection of the number of layers for configuration 1 (Fig. 3).



Sistema constructivo 1
Número de capas: 1

Figure 3: Selection of the number of layers for configuration 1.

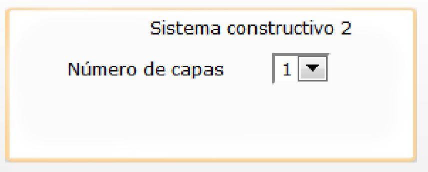
Definition of layer 1 characteristics for configuration 1 (Fig. 4).



Espesor 1: 0.1 [m]
Absortancia (A): 0.2
Material 1: ● BD Concreto_Alta_Densidad 2 2400 1000
○ gpe Aislante_P 0.02 17 1450

Figure 4: Definition of layer 1 characteristics of configuration 1, thickness (espesor) of 0.1 m, absortivity (absortancia) of 0.2, and material from the simulator database (BD): high density concrete (concreto alta densidad).

Selection of the number of layers for configuration 2 (Fig. 5).

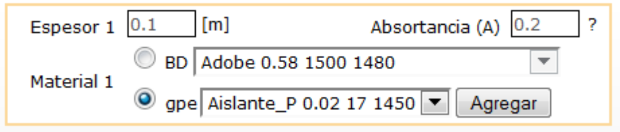


Sistema constructivo 2

Número de capas: 1

Figure 5: Selection of the number of layers for configuration 2.

Definition of layer 1 characteristics for configuration 2 (Fig. 6).



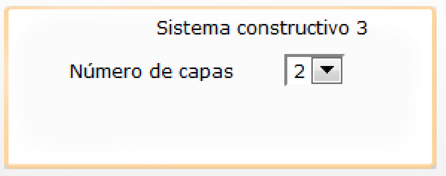
Espesor 1: 0.1 [m]

Absortancia (A): 0.2

Material 1:
- ○ BD: Adobe 0.58 1500 1480
- ● gpe: Aislante_P 0.02 17 1450

Figure 6: Definition of layer 1 characteristics of configuration 2, thickness (espesor) of 0.1 m, absortivity (absortancias) of 0.2, and material from the user database (gpe): insulating P (Aislante P).

Selection of the number of layers for configuration 3 (Fig. 7).

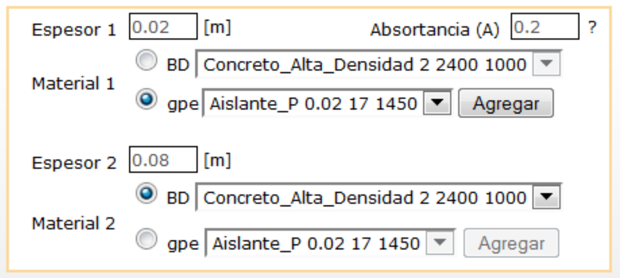


Sistema constructivo 3

Número de capas: 2

Figure 7: Selection of the number of layers for configuration 3.

Definition of layers 1 and 2 characteristics for configuration 3 (Fig. 8).



Espesor 1: 0.02 [m]

Absortancia (A): 0.2

Material 1:
- ○ BD: Concreto_Alta_Densidad 2 2400 1000
- ● gpe: Aislante_P 0.02 17 1450

Espesor 2: 0.08 [m]

Material 2:
- ● BD: Concreto_Alta_Densidad 2 2400 1000
- ○ gpe: Aislante_P 0.02 17 1450

Figure 8: Definition of layers characteristics of configuration 3, thickness (espesor) of, absortivity (absortancia) , and material. For layer 1 : 0.02m, A=0.2, material from the user database (gpe): insulating P (Aislante P). For layer 2: 0.08m and material from the simulator database (BD): high density concrete (concreto alta densidad).

Once defined the three roofs configurations, the simulator presents a results page. In this page, for the condition of air conditioning and monthly evaluation, the simulator gives three plots, the thermal energy consumed by the air-conditioned system per day by a unit area of the wall/roof, for cooling (enfriamiento), E_c, for heating (calentamiento), E_h, and the total, E, for the simulated configurations. In Fig. 9, the results plot for the total energy per day per unit area for the three roof configurations, is presented. As can be observed, the best configuration for air-conditioned condition, for Hermosillo during June is configuration 2 (S.C. 2).

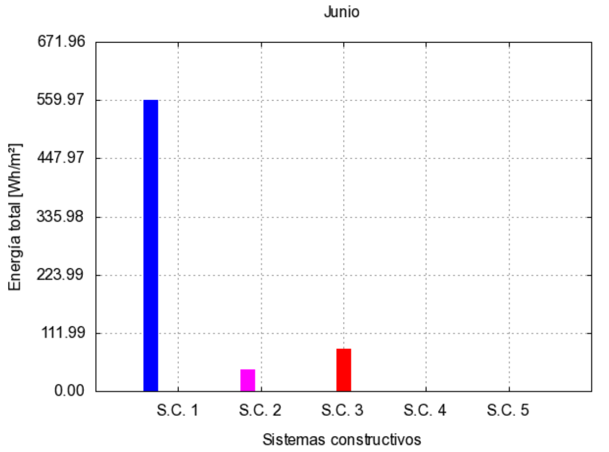
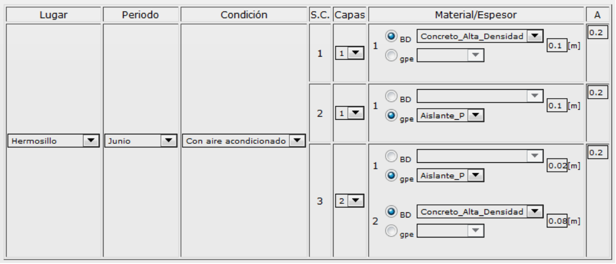


Figure 9: Total energy consumed in a day for the three roof configurations, for Hermosillo in June.

In the lower part of the results page, the simulator presents a table with the simulation conditions, shown in Fig. 10. This table allows changing all the conditions, except the number of configurations.



Lugar	Periodo	Condición	S.C.	Capas	Material/Espesor	A
Hermosillo	Junio	Con aire acondicionado	1	1	1 ● BD Concreto_Alta_Densidad ○ gpe 0.1 [m]	0.2
			2	1	1 ○ BD ● gpe Aislante_P 0.1 [m]	0.2
			3	2	1 ○ BD ● gpe Aislante_P 0.02 [m] 2 ● BD Concreto_Alta_Densidad ○ gpe 0.08 [m]	0.2

Figure 10: Table with the simulation conditions.

For an annual evaluation, the period (period) option in the initial selection page (Fig. 2) must be selected or change it in the table of results page (Fig. 10). When selecting annual evaluation and air conditioning condition, the results page shows six plots. The first three plots are the thermal energy consumed by the air-conditioned system per year per unit area of the wall/roof, for cooling (enfriamiento), E_c, for heating (calentamiento), E_h, and the total, E, for the simulated configurations. The later one is shown in Fig. 11. The best configuration for air-conditioned condition, for Hermosillo in annual evaluation also is configuration 2 (S.C. 2). The second three plots are the thermal energy consumed by the air-conditioned system per day per unit area of the wall/roof, for cooling (enfriamiento), E_c, for heating (calentamiento), E_h, and the total, E, as function of the month and configuration. The energy consumed for cooling is shown in Fig. 12. For all configurations this energy increases during the summer months.

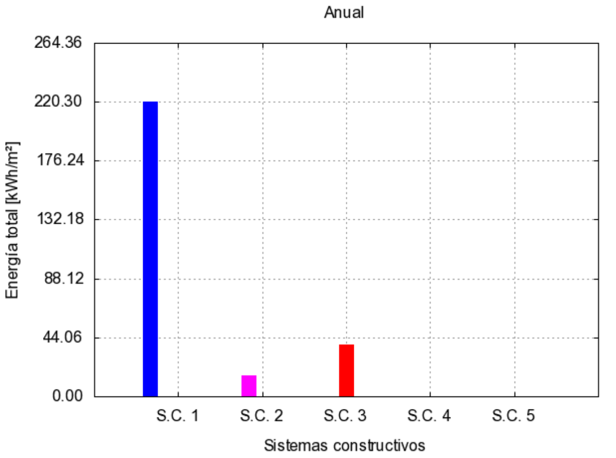


Figure 11: Total energy consumed in a year for the three roof configurations, for Hermosillo.

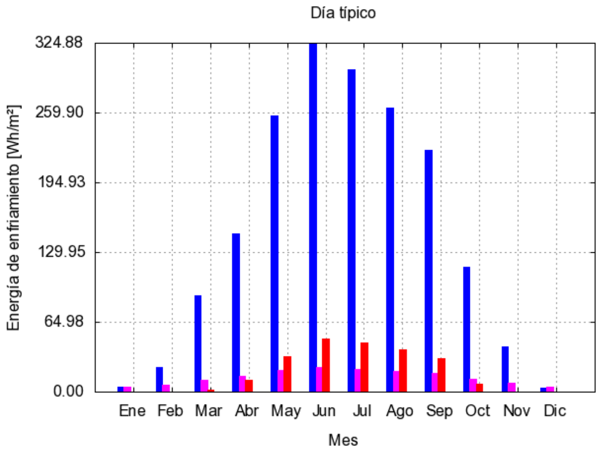


Figure 12: Energy consumed for cooling (enfriamiento) by the air-conditioned system per day per unit area of the wall/roof as function of the month and configuration, for Hermosillo.

EXAMPLE: THREE ROOF CONFIGURATIONS EVALUATION FOR NON-AIR CONDITIONING CONDITION

To evaluate a roof configuration in a room that does not use air conditioning, the option non-air-conditiong (no aire acondicionado) has to be selected in the initial selection page (Fig. 2) or change it in the table of results page (Fig. 10). For the example, selection of the place, the period, and the number of roof configurations are the same of Fig. 2 and the configurations are the same of Figs. 3-8. In the results page, for the condition of non-air conditioning and monthly evaluation, the simulator gives two plots. The first one contains the exterior temperature (temperature ambiente), and the indoor temperature for each one of the simulated configurations (S.C) as function of the time of the day. The corresponding comfort zone is marked within the two green lines. Fig. 13 shows the corresponding plot for the example configurations. As can be observed, for June in Hermosillo, configuration 3 (S.C.3) maintains the indoor temperature inside the comfort zone for almost all the day. The second plot is energy transferred to the indoor through a unit area of the wall/roof during a day, Q. Fig. 14 shows the plot for the example configurations. As can be observed, for non-air conditioning condition, for Hermosillo in June, the best configuration is configuration 3 (S.C. 3).

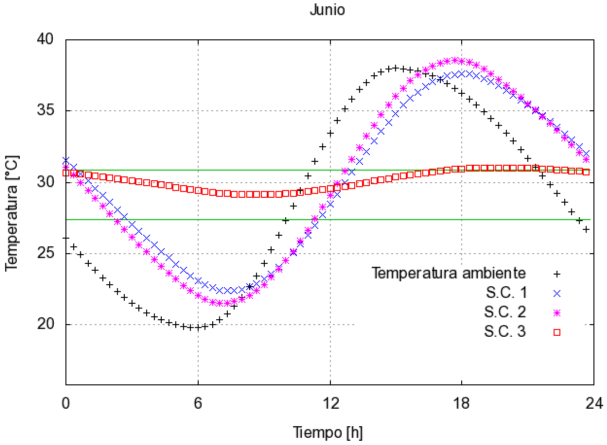


Figure 13: Exterior temperature (temperature ambiente), and the indoor temperature for each one of the simulated configurations (S.C) as function of the time of the day , for Hermosillo in June.

For the condition of non-air conditioning and annual evaluation, the simulator shows two plots in the results page. The first plot is energy transferred to the indoor through a unit area of the roof during a year, Q. Fig. 15 shows the plot for the example configurations. The second plot is the energy transferred to the indoor through a unit area of the roof during a day, for the twelve months and the simulated configurations.

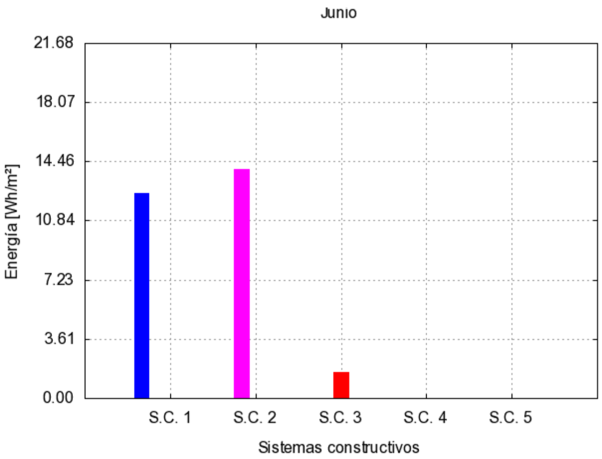


Figure 14: Energy transferred to the indoor through the wall/roof during a day, per unit area, Q, for the three roof configurations, for Hermosillo in June.

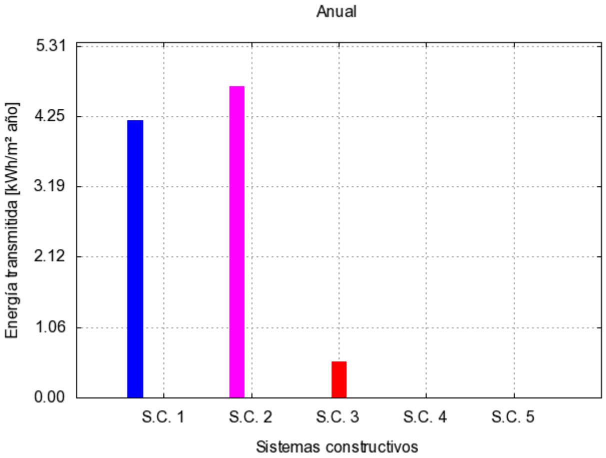


Figure 15: Energy transferred to the indoor through the wall/roof during a year, per unit area, Q, for the three roof configurations, for Hermosillo.

FINAL REMARKS

The present version (1.0.1) of the simulator Ener-Habitat evaluates horizontal roof configurations composed by homogeneous layers. The solar radiation is calculated on a horizontal surface. In the next version, the simulator will calculate also the heat transfer through homogeneous multilayered walls and inclined roofs, by incorporating the calculation of solar radiation on any inclined surface. The authors hope that futures versions of this tool can incorporate the analysis of walls and roofs constructive systems that have non-homogeneous layers, like that of hollow blocks. Also it is expected to incorporate calculations of heat and radiation transfer through windows. The aim of this simulator will remain the simulation of individual components of the building envelope.

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