GENERATION

'Green Energy Auditing for a Low Carbon Economy'

Simplified Energy Audit Methodology

Project Partners

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1. INTRODUCTION

The building energy audit seeks to analyse the energy consumptions produced by a building with the aim of proposing measures to reduce them, as well as the related emissions and the economic cost of the energy used. A decrease in the final energy consumption does not always either entail the reduction of primary energy consumptions or economic saving.

The energy audit is carried out, in the most complete case, in the following phases:

1. To analyse the constructive and use characteristics of the building, in order to determine the real demand.

2. To determine the performance of the **HVAC** systems installed, in order to estimate the consumptions which satisfy the real demand of the building.

3. To evaluate the possibility of reducing the real demand of the building.

4. To evaluate possible measures to reduce the systems consumption.

5. To evaluate and propose a list of measures prioritised according to the previous analysis, calculating the joint effect and its profitability, both in terms of reduction of the energy (primary and final) consumption and in economic terms.

In the energy audit different levels of detail are established according to the means used to address each of the previous points. Obviously, a major degree of detail entails more time for the analysis, better means and major costs. In the practice, it will be necessary to use a proper combination of the data obtained in situ with building performance models.

The models should:

- Have enough precision to reproduce the monthly consumption.

- Have enough precision to evaluate the interest of the saving measures proposed.

- Be able to evaluate the influence of the variables not measured in the consumption.

Then, the previous points will be briefly developed with special impact in the air conditioning consumption, since they are the most complex in their treatment. Furthermore, the proposed option is specified for the simplified energy audits in public buildings.

1.1. Determining the real demand

The thermal demand of a building is consequence of the heat and water flows which are produced among the air of the room to be conditioned, the external environment (external dry and humid temperature, solar radiation, speed and wind direction) and the internal flows (occupants, lighting and equipments). The thermal exchanges with the outside are the transmission (provoked by the difference of temperature), the solar gains (both by transparent and opaque surfaces) and the infiltrations. It is to be highlighted that the air conditioning demand relies on, apart from the imposed external conditions, on the internal conditions required in the space; it specially relies on the temperature and humidity set points and the level of renovation of the air.

In order to compare the current and future situations (once the saving measures are applied), it is necessary to suppose that the comfort of the occupants is achieved in both situations. Prior to any proposal of saving measure, it should be checked that the comfort conditions in the starting situation are achieved. For instance, it is not rare to find buildings where there is no ventilation. In these cases, the consumptions may be inferior to the theoretical at the expense of no respecting the standard. Even the lower level of audit should analyse the comfort degree of the occupants.

The real demand of air conditioning of the building cannot be measured in an easy way. In the best of the cases, there would be necessary to make independent the heat flows produced for determining if its reduction is possible. This is a very difficult and expensive task. However, the lighting and equipment demand can be estimated more easily according to the working schedule and the installed power, since the performance of the systems are constant and the relation between demand and consumption is direct.

In a simplified level of audit, as it is proposed in this project in which the real demand is not available, it cannot be distinguished, according to the data measured, which part of the consumption comes from the demand and which from the systems performance. There is only information about the final variable, that is, the systems consumption. For instance, there are some public buildings with a high level of consumption where the cause it is difficult to determine. It could be due to a high demand, for example, an excessive level of infiltration, or to a poor efficiency of the systems. In order to identify the cause, it would be necessary to measure the performance of the air conditioning system during a period of time representative enough, or to carry out a trial for measuring the level of infiltration. Both solutions are possible, however they entail a deeper level of audit

than the energy audits which are usually carried out in public buildings and proposed in this project
On the other hand, it is important to estimate the real demand of the building apart from the systems consumption for two reasons:

1. If the real and theoretical demands are set apart, there is a potential reduction of the consumption from the reduction of the demand.

2. If the real demand is known, the outputs of the systems can be evaluated from the real demand and the consumptions measured.

In order to estimate the air conditioning demand, models of a different degree of detail can be used:

- Demand Index numbers, based on a high number of simulations of similar buildings. It is necessary that a wide enough database (which does not exist in this case) is available. One of its objectives is precisely to establish these index numbers.

- Simulation models. There is a wide range, from methods in a monthly basis based on degree day, to more or less detailed balance methods (EN ISO 13790:2008, or programmes like EnergyPlus, TRNSYS, etc.). The use of detailed models demands an appropriate level of knowledge of the constructive and operational data.

The degree of detail of the model will condition the latter level of analysis, since it will allow to analyze in depth the possible saving measures. For instance, it is possible to obtain a model of black box which reproduces the consumptions only from monthly averages of the climatic variables. There are numerous techniques to obtain these models: neural networks, regression models, etc. However this kind of model is not useful to evaluate the influence of the physical variables (degree of insulation, level of infiltrations, etc.) in the demand.

In the level of audit proposed in this document, the measurement of the demand is ruled out, that is why it is necessary the use of models. In particular, it is proposed the realization of an hourly simulation based on a balance method (see **ASHRAE Fundamentals 2005**).

The proposed procedure calculates the theoretical demand from a model. As much higher it is the level of ignorance of the building then as much higher it will be the uncertainty of the estimated value of the demand. In practice, the parameters required in the simulation are adjusted as much as possible from the data collected in the visit to the building.

1.2. Determining the real consumptions

As it is difficult to determine the demand in a first level of audit, the consumptions are obtained from the analysis of the electrical and fuel invoicing data. In more detailed levels of audit, it is required the measurement, during an enough period of time, of the necessary variables which allow to carry out the energy balances of the equipments: flows, temperatures, valves positions etc. The outputs depend on the operational conditions (condensation and evaporation temperatures, flows, etc.) and on the load fraction demanded in every moment.

From the analysis of a high number of buildings during an enough period of time (at least two years) the Energy Use Index (**EUI**) are elaborated, which provides the annual consumption per surface unit (kWh/m^2) of the air conditioning systems (visit, for instance, http://buildingsdatabook.eren.doe.gov/ of the US government, or the British http://www.ukace.org). The index depends on the climate and on the type of building. In Spain, there are no similar indexes to be used rigorously, it is even doubtful the validity of the application of index numbers in particular cases. The most of the studies which have analysed its validity conclude that the energy consumption can be predicted in a precise way in average values. For instance, the indexes can be used for the dimensioning of the district heating and cooling systems, where the added demand of a good number of buildings have to be calculated, but they do not work in the analysis of particular cases (see, for example, J.R. Stein and A. Meier, **Accuracy of home energy rating Systems**, Energy, 25, pages. 339-354, 2000). On the other hand, the EUI combine the two causes which determine the consumption: the demand and the efficiency of the systems. We have not considered just EUI for several reasons:

- They do not identify the causes of a high consumption and, therefore, they are not useful for the diagnosis.
- They only are useful to point out which buildings have abnormal consumptions in order to carry out a more detailed study.
- They are not reliable enough since they depend on many variables which are supposed to be homogeneous in the type of building for which they have been obtained: compactness of the building, profiles of use, etc.

In the methodology proposed, it has been proposed to breakdown the added consumptions obtained through the electrical and fuel invoicing from criteria like the installed power, the occupational profiles, the consumption variability during the year, the facilities maintenance status, etc.

1.3. Measures to reduce the demand of the building

The estimation of initial demand is carried out through a model which includes parameters deduced from the building inspection. Much other parameters should be settled from plans, surveys, etc., without direct confirmation. The model is adjusted in order to approach as much as possible the calculated consumption and the collected invoicing data. In practice, approximations of around ±10% are achieved.

In the proposed approximation for public buildings, the demand and the systems consumption are not coupled. Firstly, it is calculated the demand and, then, the consumption. It is said that it is a calculation guided by the demand.

Once the thermal model of the building is gauged, the demand saving achieved can be evaluated with the different measurements. The more detailed the model is, the more analysis possibilities there will be in this phase of the audit. The model should be able to evaluate the following measurements:

- Modification of the set point temperatures
- Modification of the schedules of use
- Improvement in the insulation level
- Influence of the colour and solar protections
- Modification of the glazing
- Influence of the level of infiltrations

1.4. Measures to reduce the systems consumption

As in the case of the saving measures in demand, once adjusted the model of calculation of consumption, the saving measures will be able to be evaluated from the modification in the model of the parameters affected by the measures. In particular:

- Incorporation of free cooling and heat recovery
- Modification of the set points
- Modification of system: cool/heat production systems, transport system, terminal units, etc.

As in the case of demand reduction measures, the more detailed the model of air conditioning system is, the more possibilities there will be in this phase of the audit.

In the proposed procedure, the systems are modelled from the curves which take into account the production and condensation temperatures (in summer), and the part load ratio. There is no detailed model of the transport system nor the terminal units, because, in most of the cases, it is about direct expansion systems with a little network of pipes.

1.5. Prioritised list of measures

The saving achieved by each measure alone cannot be added in order to obtain the joint saving. The saving measures interact with one another, that is why it is necessary to introduce the combination of selected measures in the model of calculation of consumption.

On the other hand, an economic evaluation which allows to decide which measures present acceptable return periods for the property will be necessary.

2. OBJECTIVE

The objective of this project is to define the methodology, related to the energy audits, which is able to collect and calculate the consumptions measured the calculated theoretical consumptions and the saving measures proposed for each of them. All this under a simplified procedure able to minimize the human and equipments resources.

3. METHODOLOGY

In order to fulfil the previous objective, there will be available:

a) Registered electricity and fuel consumption data. It belongs to the invoicing of the marketers of each energy resource used in the building.

b) A tool of hourly thermal simulation which allows to calculate the thermal demand and the consumption of the air conditioning systems during a year.

The methodology proposed is based on the following aspects:

a) To breakdown the consumptions registered in order to identify the ones which belong to the air conditioning, the household hot water, the lighting and to other uses.

b) To calculate the air conditioning consumption every public building should have. For this calculation, the data collected in the inventories are entered in the tool.

c) To compare the calculated and the measured consumptions.

d) To propose and evaluate the saving achieved with consumption reduction measures. The measures will affect the envelope (for instance, improvement of the insulation, shading, change of glasses, etc.) and the systems.

3.1. Consumption breakdown

With the aim of obtaining the electric consumption of HVAC systems, it is proposed to breakdown the consumptions registered in the lighting invoices, equipments and air conditioning. The procedure proposed for Andalusia is the following:

a) From the invoices of one or two completed years, the average electric consumptions for every month of the year and for every building are obtained.

b) In a first step, the minimum of the curve, which matches with intermediate periods of the year (spring or autumn), is associated with the electric consumption in lighting and equipments. Supposing that in intermediate periods of the year the air conditioning consumption is nil. The rest of the electric consumption is associated to the air conditioning.

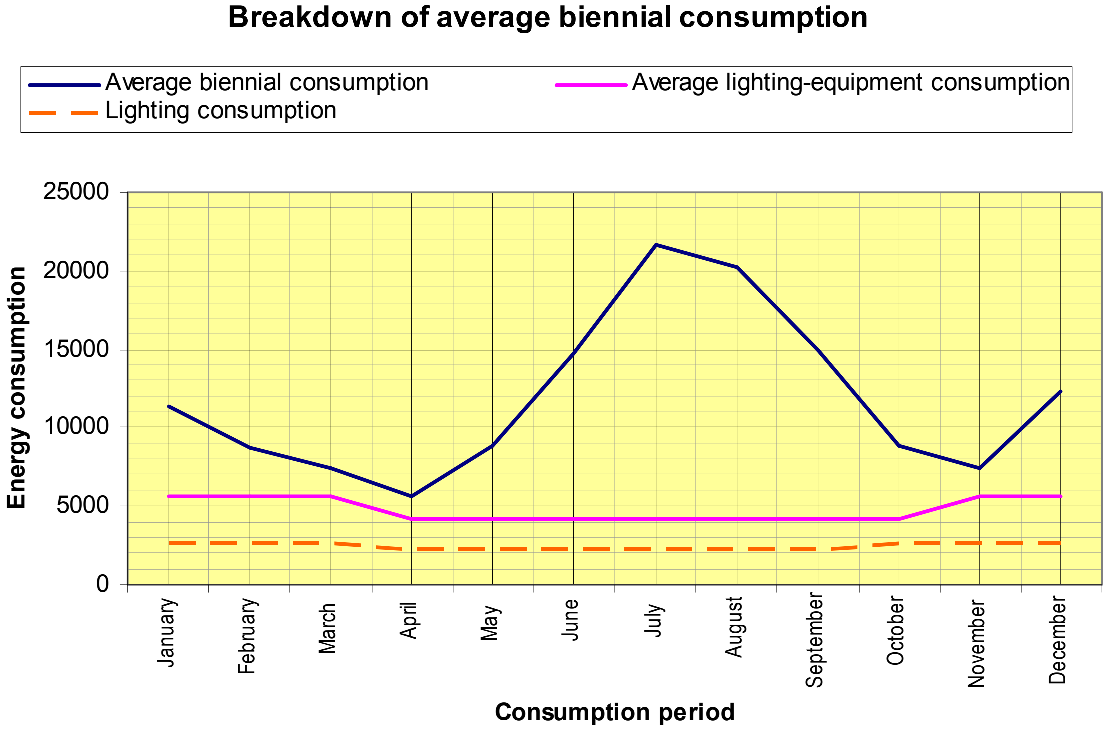
c) The monthly lighting consumption is calculated according to the installed power data and the hours of use of the buildings.

d) This way, the equipments consumptions are obtained by deducting the lighting consumption calculated from the lighting and equipments consumptions (the ones associated with the minimum of the curve).

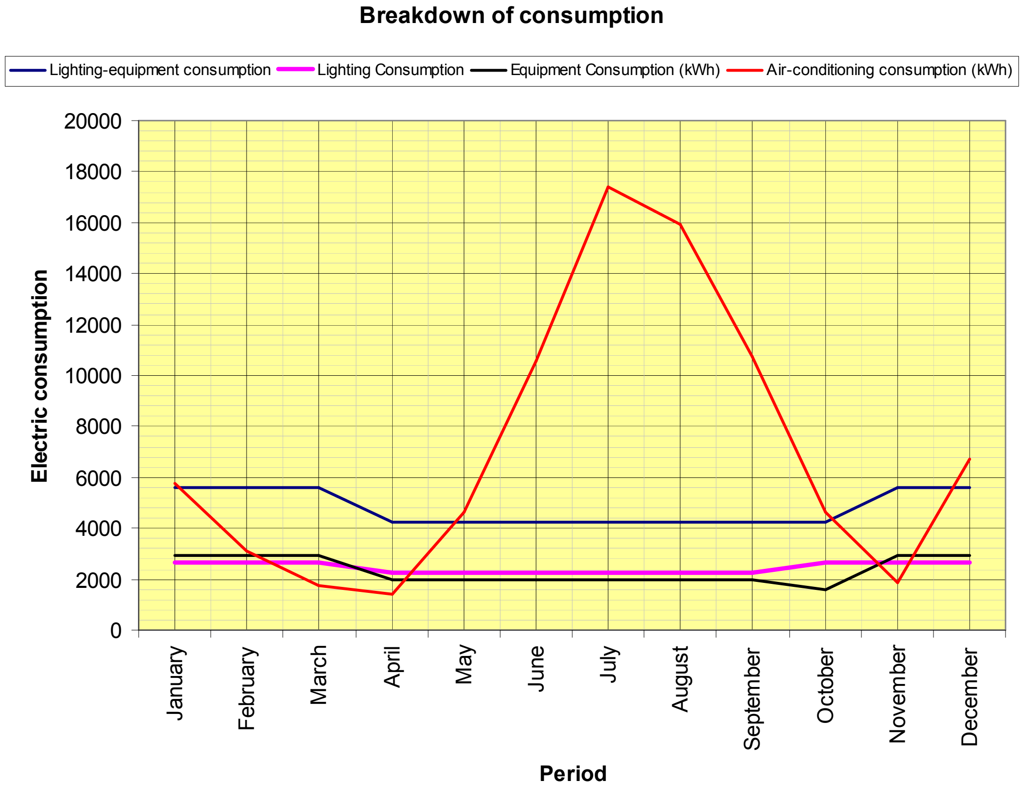
e) Then, the lighting and equipments consumptions have to be adjusted approximately to the minimum of the curve by means of iterations until the percentages of consumptions are reasonable according to the characteristics of the building to study.

f) Besides, monthly factors which increase or decrease the lighting and equipments consumptions are used, according to the time of the year.

Next, two graphics which instruct the method are shown:



Graphic 1: Consumptions breakdown



Graphic 2: Biannual average consumption breakdown

3.2. Simulation tools. Default values

The tool used is based on a heat balance method for the calculation of the demand and the use of normalized curves based on models of air conditioning systems.

As it is about a one zone model, it is crucial to divide the building into thermal zones, which does not mean that they should be adjoining (administration, offices, common areas) according to the activities developed in them, the type of system…

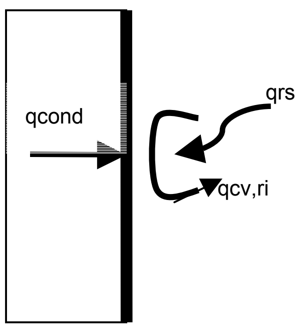
3.2.1. Calculation of the demand

The heat balance method used in order to calculate heating and cooling demand consists of raising:

- One heat balance equation in the inside face of each zone surface
- One heat balance equation in the air of the zone

The inside-face heat balance for each surface will be:

$$q_{cond} + q_{cv,rl} + q_{rs} = 0$$



in which:

q_{cond} = Conductive flux through the wall (inside face) [W/m^2]
$q_{cv,rl}$ = Convective heat flux to zone air and long-wave radiation flux [W/m^2]
q_{rs} = Transmitted solar radiative flux absorbed at surface

Calculated conductive flux will be explained below in this document.
Convective-radiant flux is modeled as follows:

$$q_{cv,rl} = h_{cv,rl}(T_r - T_{si})$$

in which:

T_r = Zone air temperature [ºC]
T_{si} = Temperature of the inside face of the surface [ºC]
$h_{cv,rl}$ = Convective-radiant coefficient (2005 ASHRAE Handbook Table 1 p 25.2) [W/m^{2}K]

In the case of transmitted solar radiative flux, all the radiation that enters in the zone is considered to be absorbed by the floor. This way, in the floor case:

$$q_{rs} = \frac{\sum Q_{dir,i} + Q_{dif,i}}{A_{floor}}$$

in which:

i = Number of windows
$Q_{dir,I}$ = Gain due to direct radiation [W], as it is explained later it is modeling according to the next equation: $Q_{dir} = A_{sol} E_{dir} \cdot SHGC(\theta) \cdot IAC$
$Q_{dif,I}$ = Gain due to diffuse radiation [W], it is defined as $Q_{dif} = A\,(E_{dif} + E_{ref}) \cdot SHGC_D \cdot IAC$
A_{floor} = Floor area [m^2]

The air heat balance will be:

$$Q_{g.\mathrm{int}} + Q_{\mathrm{inf}/vent} + Q_{conv,\mathrm{su}rf} + Q_{sys} = \rho c_v V \frac{dT}{dt}$$

Taking into account that the term $\rho c_v V \frac{dT}{dt}$ is zero when the zone is conditioning, this equation will be:

$$Q_{g.\mathrm{int}} + Q_{\mathrm{inf}/vent} + Q_{conv,\mathrm{su}rf} + Q_{sys} = 0$$

in which:

$Q_{g.\mathrm{int}}$ = Convective gains due to internal gains of lighting, people, and equipment
$Q_{\mathrm{inf}/vent}$ = Convective gain due to infiltration and ventilation
$Q_{conv,\mathrm{su}rf}$ = Convective exchange between the inside face of each surface and the zone air. For each surface:

$$Q_{conv,\mathrm{su}rfi} = A_i \cdot h_{cvrl,i} \cdot (T_r - T_{si})$$

in which:

T_r = Air zone temperature [ºC]
T_{si} = Temperature of the inside face [ºC]
h_{cvi} = Convective-radiant coefficient [W/m^2 K]

A_i = Surface area [m^2]
Q_{sys} = Load [W]

Once all the equations are haven, in each hour, surface temperatures (T_{si}) and load (Q_{sys}) are the unknown variables as zone temperature is cooling or heating set-point when zone is conditioning. The problem is worked out by obtaining surface temperatures from surface heat balances and load from air heat balance.

Following, the equations used to calculate the different gains will be shown.

Gain through the external walls, roof and floor

In order to calculate these gains it has been used the transfer functions method, through which some response factors for the heat flow, the external and internal temperatures are obtained according to the wall characteristics. The necessary characteristics to enter for each wall layer are: density, specific heat, conductivity and thickness.

So, the heat flow for a certain time instant t will be calculated according to the following equations:

$$SumaT_{ext,t} = A_0 \cdot T_{ext,t} + A_1.T_{ext,t-1} + A_2.T_{ext,t-2} + A_3.T_{ext,t-3} + \ldots + A_n.T_{ext,t-n}$$
$$SumaT_{\text{int},t} = B_0 \cdot T_{\text{int},t} + B_1.T_{\text{int},t-1} + B_2.T_{\text{int},t-2} + B_3.T_{\text{int},t-3} + \ldots + A_n.T_{\text{int},t-n}$$
$$Sumq_t = C_1.q_{t-1} + C_2.q_{t-2} + C_3.q_{t-3} + \ldots + C_n.q_{t-n}$$
$$q_t = Sumaq_t + SumaT_{\text{int},t} + SumaT_{ext,t}$$

in which:

$T_{ext,t}$ = ”Outside” temperature wall at time t [ºC]
$T_{\text{int},t}$ = Temperature in the inside face of the wall at time t [ºC]
q_t = Heat flow in the internal for the instant t [W/m^2]
$A_0,\ldots A_n$ = Response factors for the external temperature (sol-air temperature)
$B_0,\ldots B_n$ = Response factors for the internal temperature
$C_1,\ldots C_n$ = Response factors for the heat flow

Since the heat flow is an external surface, it is calculated as:

$$q = \alpha \cdot E_t + h_0.(T_0 - T_s) - \varepsilon \Delta R$$

in which:

q = heat flow through the surface [W/m^2]
α = surface solar absorptivity
E_t = Incident solar radiation on the surface [W/m^{2}K]
h_0 = Outside heat transfer coefficient (convection and long wave radiation) [W/m^{2}K]
T_0 = External air temperature [ºC]

T_s = Surface temperature (inside face) [ºC]
ε = hemispherical emittance of the surface
ΔR = Difference between the long-wave radiation incident on surface from the sky and surroundings, and the radiation emitted by the blackbody at the outside air temperature [W/m^2]

And assuming that it can also be expressed in terms of sol-air temperature

$$q = h_0 \cdot (T_{sol-aire} - T_s)$$

in which:

$$T_{sol-aire} = T_0 + \frac{\alpha \cdot E_t}{h_0} - \frac{\varepsilon \Delta R}{h_0}$$

the temperature in the external air of the wall used in the ZTRAN-method (T_{ext}) matches with the sol-air temperature ($T_{sol\text{-}air}$) and it is calculated according to the previous equation. The internal temperature (T_{int}) is the one of the interior face of the wall. And the thermal resistances of the external air will be taken into account.

The term $\frac{\alpha}{h_0}$ α/h has a value of 0.026 for light colour surfaces, of 0.041 for average colour surfaces and of 0.052 for dark surfaces.

For horizontal surfaces ΔR is approximately 63 W/m^2, ε = 1 and h0=17 W/m^{2}K. That is, $\frac{\varepsilon \Delta R}{h_0} \approx$ 4K

For vertical surfaces, it is assumed that $\varepsilon \, \Delta R$ = 0

The external air temperature for each hour of the year (T_0) is introduced as data.

The software calculates the total incident radiation (Et) on every surface according to the orientation and the inclination from the data of direct and diffuse radiation input on horizontal area obtained through the aforementioned programme (see Solar Engineering of Thermal Processes, Duffie y Beckman Wiley 2006).

The types of walls used will be detailed later in this document.

<u>Gain through the windows</u>

It has three components: gain due to the direct radiation, gain due to the diffuse radiation and transmission (due to the outside-inside temperature difference).

Direct radiation

It is calculated according to the following equation:

$$Q_{dir} = A_{sol}E_{dir} \cdot SHGC(\theta) \cdot IAC$$

in which:

A_{sol} = Area of the window which gets sunlight [m^2]
E_{dir} = Direct radiation on the window [W/m^2]
$SHGC(\theta)$ = Solar heat gain coefficient according to the angle of incidence (θ) of the solar radiation on the window
IAC = Solar attenuation coefficient due to solar protections

The tool calculates the incident solar radiation (Edir) for each hour of the year on every window according to its orientation and inclination from the data of direct radiation input on horizontal area (see Solar Engineering of Thermal Processes, Duffie y Beckman, Wiley 2006).

For each type of glass used in the tool, such coefficients have been obtained through the Window 5 programme. So, the programme calculates the angle of incidence of the solar radiation on the window and, according to the type of glass, it selects a coefficient of solar gain. Later, in this document, the glasses and coefficients of solar gain used in the programme will be specified.

The solar attenuation coefficient (IAC) collects the attenuation effect of the solar radiation provoked by both, the internal solar protections and the external and intermediate. And they have been extracted from the tables 18,19 and 20 of the chapter 31 of ASHRAE Fundamentals 2005.

In order to calculate the area of the window which gets the sunlight, it has been taken into account the shadows provoked both by the external shading and the external obstacles (buildings, trees…).

Diffuse radiation

$$Q_{dif} = A\ (E_{dif} + E_{ref}) \cdot SHGC_D \cdot IAC$$

A = Area of the window [m^2]
E_{dif} = Diffuse solar radiation which comes into contact with the window [W/m^2]
E_{ref} = Solar radiation reflected radiation, by the ground, which impinges the window [W/m^2]
$SHGC_D$ = Diffuse solar heat gain coefficient

The area of the window is an input data. The diffuse radiation over the window is calculated by the programme from to the input data of hourly diffuse radiation according to the model of Perez et al. (See Solar Engineering of Thermal Processes, Duffie y Beckman). According to such model, the reflected radiation, by the ground, which comes into contact with the window is calculated:

$$E_{ref} = I \cdot \rho_g (\frac{1-\cos\beta}{2})$$

in which

I = sum of the direct and diffuse radiation on a horizontal surface [W/m^2]
ρ_g = albedo, is considered 0.4
β = surface inclination angle

The coefficient of diffuse solar gain depends on the characteristics of the glass and it has been also calculated by Window 5.

Transmission gain

$$Q_{cond} = U \cdot A\ (T_0 - T_{\text{int}})$$

in which:

U = coefficient of heat transfer of the window [W/m^{2}K]
A = Area of the window [m^2]
T_0 = External air temperature [ºC]
T_{int} = Temperature in the interior face of the window [ºC]

Both the area of the window and the external air temperature are input data. The coefficient of heat transfer depends on the characteristics of the glass and it has been calculated with the Window 5 programme for the different types used in the tool. The internal air temperature is the one of the zone and it is corresponding to the set point temperature.

<u>Gain through internal surfaces</u>

In this section are included the gains through any opaque surface whose heat flow will be calculated supposing a boundary condition. This would be the case of adjacent surfaces with not air conditioned areas, of areas in contact with the ground…

The equation which models this gain is:

$$Q_{\text{sup,int}} = U \cdot A \cdot (T_{cc} - T_{surf,\text{int}})$$

and

$$T_{cc} = \lambda \cdot T_0 + (1-\lambda) T_{zona}$$

in which:

U = Overall heat transfer coefficient [W/m^{2}K]
A = Area of the surface [m^2]
T_{cc} = Temperature according to the boundary condition [ºC]
$T_{surf,\mathrm{int}}$ = Temperature of the interior face of the surface, [ºC]
T_0 = External air temperature [ºC]
λ = Constant of boundary condition, entered as data

<u>Internal gains</u>

Three types of internal gains are distinguished: people, lighting and equipments.
People

The gain due to the people is calculated according to the following equation:

$$Q_{pers} = N_{pers} \cdot q_{act} \cdot Perf_{ocup}$$

Q_{pers} = Internal gain of people [W]
N_{pers} = Number of people
q_{act} = Gain per person [W/pers]
$Perf_{ocup}$ = Schedule of occupancy,

From this gain a part is sensible and the other is latent:

$$Q_{pers,L} = N_{pers} \cdot q_{act} \cdot Perf_{ocup} \cdot P_{ocup,L}$$
$$Q_{pers,s} = N_{pers} \cdot q_{act} \cdot Perf_{ocup} \cdot P_{ocup,s}$$

$P_{ocup,L}$ = Latent percentage of the gain of people
$P_{ocup,S}$ = Sensible percentage of the gain of people

In the tool, the gain per person (q_{act}) and the percentages of sensible, latent gain are input data which depend on the type of activity carried out by the people. The number of people and the schedule are also data. The reference tables used for the energy audits are the ones from *ASHRAE Fundamentals 2005*.

Lighting

$$Q_{ilum} = Q_{ilum,inst} \cdot Perf_{ilum}$$

in which:

$Q_{ilum,inst}$ = Installed power for lighting [W]
$Perf_{ilum}$ = Lighting profile,

From this gain a part is sensible and the other is latent:

$$Q_{ilum,L} = Q_{ilum,inst} \cdot Perf_{ilum} \cdot P_{ilum,L}$$
$$Q_{ilum,s} = Q_{ilum,inst} \cdot Perf_{ilum} \cdot P_{ilum,s}$$

in which:

$P_{ilum,L}$ = Latent percentage of lighting gain
$P_{ilum,s}$ = Sensible percentage of lighting gain

In the tool, the installed power ($q_{ilum,inst}$), the lighting profile and the percentages of sensible, latent gain, which depend on the types of lighting installed, are input data. The lighting profile is also a data. The reference tables used for the energy audits are the ones from EnergyPlus (see EnergyPlus Documentation).

Equipments

$$Q_{equip} = Q_{equip,inst} \cdot Perf_{equip}$$

in which:

$Q_{equip,inst}$ = Installed power in equipments [W]
$Perf_{equip}$ = Equipment schedule,

from this gain a part is convective and the other is radiant:

$$Q_{equip,L} = Q_{equip,inst} \cdot Perf_{equip} \cdot P_{equip,L}$$
$$Q_{equip,s} = Q_{equip,inst} \cdot Perf_{equip} \cdot P_{equip,s}$$

in which:

$P_{equip,L}$ = Latent percentage of the equipments gain
$P_{equip,s}$ = Sensible percentage of the equipments gain

In the programme, the installed power ($q_{equip,inst}$), the lighting profile and the percentages of sensible, latent gain, which depend on the types of equipments, are input data. The equipments profile is also a data. The reference tables used for the energy audits are the ones from *ASHRAE Handbook of Fundamentals 2009*.

Infiltration and Ventilation

The equations used to calculate the sensible part of both gains are:

$$Q_{inf/vent,s} = Perf_{\inf/vent} \cdot \dot{v}_{\inf/vent} \cdot \rho \cdot Cp \cdot (T_0 - T_{zona})$$

in which:

$\dot{v}_{\inf/vent}$ =Infiltration or ventilation flow [m^3/s]
$Perf_{\inf/vent}$ = Infiltration or ventilation profile
$Q_{inf/vent,s}$ =Gain due to the infiltration or ventilation [W]
ρ =Air density [kg/m^3]
Cp =Air specific heat [J/kgK]
T_0 =External air temperature [ºC]
T_{zona} =Temperature of the air zone [ºC],

In the programme, the profile, the flow and the external air temperature are entered as data. The air density is 1.16 kg/m^3, the specific heat 1024 J/kg·K and the temperature of the zone matches with the set point temperature.

It is to be highlighted that all this gain becomes a load in an instantaneous way.

3.2.2. Calculation of the systems consumption

Once the demand has been calculated, and by using it, the systems consumption which depend both on the type (cooler, boiler…) and on their characteristics (capacity, COP…) has to be calculated. This section will described how the consumption for each type of system implemented by the programme has been calculated.

The air conditioning equipments introduced in the tool are:

For cooling:

a) Direct expansion heat pump
b) Chiller machines condensed by air or water

For heating:

a) Direct expansion heat pump
b) Boiler of high, medium or low temperature

Once the type of system for cooling and heating have been chosen, the input data are practically the same for all of them.

a) Nominal capacity [W]
b) Nominal COP [W]
c) System profile

Besides, the programme includes the possibility of using free cooling in the systems. This will be explained later.

On the other hand, it is important to take into account that in this level of audits, the nominal value both for cooling and heating has been adapted to take into account the type of the systems and the conservation.

In order to calculate the consumption of this type of machines, it is necessary to calculate the following curves:

a) Curve of the capacity according to the external and internal temperature of the zone: *CurvaModCap=f*(T_0, T_{zona})

b) Curve of the EER (opposite of the COP) according to the external and internal temperature of the zone: *CurvaModEER=f*(T_0, T_{zona})

c) Curve of partial load: *CurvaCargaParcial*=$EIR_{parciall}/EIR_{plenacarga}$, in which PLR is the coefficient of partial load.

A model machine was taken as model and such curves were adjusted from the catalogue data. For the first two cases, it have been adjusted biquadratic curves, and for the last one, a lineal curve. Later, the curves have been normalized by dividing their coefficients between the nominal capacity of the model machine in the first one, and the nominal EER of the machine in the second one.

In order to calculate the consumption, the following equation has been used:

$$P = Cap_{nominal} \cdot CurvaModCap^{*} \cdot EIR_{nom} \cdot CurvaModEIR^{*} \cdot CurvaC\arg aParcial$$

P = Electric power of the machine [W]
$Cap_{nominal}$ = Nominal capacity of the machine [W]
CurvaModCap = Standardized curve of the capacity according to the external and internal temperatures
EIR_{nom} = Rated EER (opposite of the COP) of the machine
CurvaModEIR = Normalized curve of the EER according to the external and internal temperatures
CurvaCargParcial = Curve of partial load

For the curve of partial load it is necessary to calculate the coefficient of partial load (PLR):

$$PLR = \frac{Q_{T,s}}{Cap_{nominal,s}}$$

PLR = Partial load ratio
$Q_{T,s}$ = Total sensible load of the zone [W]
$Cap_{nominal,s}$ = Rated capacity of the machine [W]

Since what it is known, as it is an input data, is the total nominal capacity of the machine, the programme estimates that the 30% of this capacity is latent and the rest is sensible.

This procedure has to be repeated for:

a) Heat pump heat mode. Model machine Daikin RZP71DVI
b) Heat pump cool mode. Model machine Daikin RZP71DVI
c) Cooler refrigerated by air. Model machine Carrier 30RB 182-802
d) Cooler refrigerated by water. Model machine McQuay WSC

Since each case presents different curves.

Boilers

The curves which model the consumption of the boilers are cubics. The independent variable is the partial load ratio (PLR) (see EnergyPlus Documentation).

Next, the equations used in the tool shown:

$$ConsumoCaldera = \frac{Q_T}{COP_{nom} \cdot CurvaPLRCaldera}$$

$$PLR = \frac{Q_T}{Cap_{nom}}$$

in which

$ConsumoCaldera$ = Consumption of the boiler [W]
COP_{nom} = rated COP
$CurvaPLRCaldera$ = Curve of partial load of the boiler
Q_T = Load of the zone [W]
Cap_{nom} = Rated capacity of boiler [W]

3.2.3. Inputs and default values

As it has been said before, the characteristics of each thermal zone of the building should be entered separately in the programme. This section is including different examples about the required input data and the default values to be loaded in data base of our tool, theses values will be complemented with additional information requested to the rest of partners:

Geometrical data of the zones

External surfaces.

Since the zones can be no adjacent, the surfaces are distinguished according to the orientation. Adding the areas of all the surfaces with the same orientation. The options offered by the programme appear in the following table:

Orientations
North
South
East
West
NE
NW
SE
SW

Table 1: List of external surfaces orientations in the simulation tool.

In the case of the four last orientations, the degrees to the East from the North, etc. have to be specified.

From each of the surfaces, the characteristics of the opaque enclosure and the windows have to be specified.

The characteristics of the opaque enclosure which have to entered are:

a) Colour. Each one has an absorptance associated (see section 'calculation of the demand')

Colour of opaque surfaces
Light
Medium
Dark

Table 2: List of colours of the external opaque surfaces in the tool

b) Type of construction. The options are presented in the following tables:

External wall types constructions

Non-insulated cavity wall of ½ feet
Insulated cavity wall of ½ feet
CS Type external wall
Insulated cavity wall of 1 feet

Table 3: List of the types of constructions for the external vertical opaque surfaces.

List of roof constructions
Non-insulated inverted cover
Insulated inverted cover
CS Type
Insulated tile cover

Table 4: List of types of constructions for the roofs

Now, the characteristics of the aforementioned types of constructions are detailed. For this purpose, the properties of each course are shown:

NON-INSULATED CAVITY WALL OF HALF FEET						
Description	**Conductivity** (W/mK)	**Density** (kg/m3)	**Thickness** (m)	**Weight** (kg/m²)	**Strenght** (m²K/W)	**Cp** (kJ/kgK)
Rse					0.04	
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
3.17.1 FLC 1/2 feet LP metric	0.5476	1,020.00	0.115	117.30	0.21	1.000
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
Air - 2cm					0.17	
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
3.17.1 FLC 1/2 feet LP metric	0.5476	1,020.00	0.115	117.30	0.21	1.000
3.07 Plaster floating	0.400	900.00	0.02	18.00	0.05	1.00
Rsi					0.12	
Total properties of the courses						
TOTAL strength (m²K/W)						**0.88**
TOTAL U (W/m²K)						**1.14**

Table 5: Characteristics of the assigned construction of non-insulated cavity wall of half feet

INSULATED CAVITY WALL OF HALF FEET						
Description	**Conductivity** (W/mK)	**Density** (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)	**Strenght** (m^{2}K/W)	**Cp** (kJ/kgK)
Rse					0.04	
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
3.17.1 FLC 1/2 feet LP metric	0.5476	1,020.00	0.115	117.30	0.21	1.000
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
Mineral wool 8 cm	0.04	30.00	0.080	2.40	2.22	1.00
Air - 2cm					0.17	
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
3.17.1 FLC 1/2 feet LP metric	0.5476	1,020.00	0.115	117.30	0.21	1.000
3.07 Plaster floating	0.400	900.00	0.02	18.00	0.05	1.00
Rsi					0.12	
Total properties of the courses						
TOTAL strength						**3.10**
TOTAL U						**0.32**

Table 6: Characteristics of the assigned construction of insulated cavity wall of half feet

CS TYPE EXTERNAL WALL						
Description	**Conductivity** (W/mK)	**Density** (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)	**Strenght** (m^{2}K/W)	**Cp** (kJ/kgK)
Rse					0.04	
Ready-mixed concrete 150 mm (Factory of perforated AL concrete blocks)	0.21	1,000.00	0.150	150.00	0.71	1.00
Water-repellent mortar wash 15 mm (Lime or cement mortar for brickwork and filler or floating)	1.0000	1,600.00	0.015	24.00	0.02	1.000
Polystyrene 30 mm (PS)	0.16	1,050.00	0.030	31.50	0.19	1.30
Air chamber wall 40mm					0.17	
Factory LHS 45 mm	0.500	1,000.00	0.05	45.00	0.09	1.00
Perlite floating 20 mm (AL Mortar)	0.41	1,000.00	0.020	20.00	0.05	1.00
Rsi					0.12	
Total properties of the courses						
TOTAL strength						**1.39**
TOTAL U						**0.72**

Table 7: Characteristics of the assigned construction of cs type external wall

INSULATED CAVITY WALL OF ONE FEET						
Description	**Conductivity** (W/mK)	**Density** (kg/m³)	**Thickness** (m)	**Weight** (kg/m²)	**Strenght** (m²K/W)	**Cp** (kJ/kgK)
Rse					0.04	
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
3.17.1 FLC 1 feet LP metric	0.6340	1,000.00	0.240	240.00	0.38	1,150.000
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
Mineral wool 8 cm	0.04	30.00	0.080	2.40	2.22	1.00
Air - 2cm					0.17	
3.05 Lime or cement mortar for brickwork and filler/floating	0.80	1,525.00	0.020	30.50	0.03	1.00
3.17.1 FLC 1 feet LP metric	0.6340	1,000.00	0.240	240.00	0.38	1,150.000
3.07 Plaster floating	0.400	900.00	0.02	18.00	0.05	1.00
Rsi					0.12	
Total properties of the courses						
TOTAL strength						**3.43**
TOTAL U						**0.29**

Table 8: Characteristics of the assigned construction of insulated cavity wall of one feet

CUBIERTA INVERTIDA SIN AISLAMIENTO						
Description	**Conductivity** (W/mK)	**Density** (kg/m³)	**Thickness** (m)	**Weight** (kg/m²)	**Strenght** (m²K/W)	**Cp** (kJ/kgK)
Rse					0.04	
3.01.1 Sand and gravel	2.00	1,950.00	0.020	39.00	0.01	1.05
Bituminous sheet	0.23	1,100.00	0.020	22.00	0.09	1.00
3.05 Light dry mortar	0.410	1,000.00	0.10	100.00	0.24	1.00
Small vault of concrete	0.31	1,168.00	0.310	362.08	1.00	1.05
Rsi					0.16	
Total properties of the courses						
TOTAL strength						**1.54**
TOTAL U						**0.65**

Table 9: Characteristics of the assigned construction of non-insulated inverted cover

INVERTED INSULATED COVER						
Description	**Conductivity** (W/mK)	**Density** (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)	**Strenght** (m^{2}K/W)	**Cp** (kJ/kgK)
Rse					0.04	
3.01.1 Sand and gravel	2.00	1,950.00	0.020	39.00	0.01	1.05
Mineral wool 8 cm	0.0360	30.00	0.080	2.40	2.22	1.000
Bituminous sheet	0.23	1,100.00	0.020	22.00	0.09	1.00
3.05 Light dry mortar	0.410	1,000.00	0.10	100.00	0.24	1.00
Small vault of concrete	0.31	1,168.00	0.310	362.08	1.00	1.05
Rsi					0.16	
Total properties of the courses						
TOTAL strength						**3.76**
TOTAL U						**0.27**

Table 10: Characteristics of the assigned construction of inverted insulated cover

TYPE CS CEILING						
Description	**Conductivity** (W/mK)	**Density** (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)	**Strenght** (m^{2}K/W)	**Cp** (kJ/kgK)
Rse					0.04	
Cover gravel layer 70 mm (Sand and gravel)	2.00	1,700.00	0.070	119.00	0.04	0.91
Polyurethane foam 60 mm PUF	0.0260	24.00	0.060	1.44	2.31	1,590.000
Concrete for slopes formation 150 mm (Concrete AL)	1.1500	1,600.00	0.150	240.00	0.13	1.000
Waffle slab with pieces of concrete beam fill 250 mm	1.920	1,338.00	0.25	334.50	0.13	1.00
Rsi					0.16	
Total properties of the courses						
TOTAL strength						**2.80**
TOTAL U						**0.36**

Table 11: Characteristics of the assigned construction of roof type CS

NON-INSULATED TILE COVER						
Description	**Conductivity** (W/mK)	**Density** (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)	**Strenght** (m^{2}K/W)	**Cp** (kJ/kgK)
Rse					0.04	
3.01.4 Burnt-clay tile	1.00	2,000.00	0.020	40.00	0.02	0.80
3.05 Lime or cement for brickwork and filler/floating	0.8000	1,525.00	0.080	122.00	0.10	1.000
Mineral wool 8 cm	0.0360	30.00	0.080	2.40	2.22	1.000
3.18.1 FU concrete beam fill	1.420	1,240.00	0.30	372.00	0.21	1.00
Rsi					0.16	
Total properties of the courses						
TOTAL strength						**2.75**
TOTAL U						**0.36**

Table 12: Characteristics of the construction of non-insulated tile roof

The characteristics of the semi-transparent external surfaces to be entered are:

a) Surface area (m^2)
b) Window area. The areas of all the windows belonging to that surface will be added.
c) Type of glasses. The options offered by the programme are:

Type of glasses	*U*	**SC**	**SHGC**
Simple-4mm	6.138	0.995	0.866
Simple-6mm	6.062	0.971	0.845
Double-4/6/4mm	3.233	0.884	0.769
Double-6/4/6mm	3.533	0.848	0.738
Other	Enter	Enter	Enter
None	-	-	-

Table 13: Types of glass in the tool and their characteristics

Besides, the programme uses in its calculations the solar heat gain coefficient (SHGC) according to the angle of incidence of the solar radiation for each type of glass (see section 'Calculation of the Demand').

SHGC Angular											
glass/angle	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**Hemi**
Simple-4mm	0.866	0.866	0.865	0.862	0.854	0.834	0.788	0.676	0.424	0	0.789
Simple-6mm	0.845	0.845	0.843	0.84	0.832	0.812	0.766	0.657	0.412	0	0.769
Double-4/6/4mm	0.769	0.769	0.767	0.762	0.75	0.72	0.652	0.508	0.263	0	0.671
Double-6/4/6mm	0.738	0.738	0.736	0.731	0.718	0.689	0.623	0.487	0.253	0	0.643
Other	Enter	Enter	Enter	Enter	Enter	Enter	Enter	Enter	Enter	Enter	Enter
None	0	0	0	0	0	0	0	0	0	0	0

Table 14: Solar heat gain coefficient according to the radiation angle of incidence for the types of glasses of the tool

d) Solar attenuation coefficient according to the type of glass (IAC). (See section 'Calculation of the Demand').

e) Besides, for the windows with overhangs, those should be defined by entering the following data clarified with the figure.

- Number of windows with overhang
- Height of the windows with overhang (m) (W)
- Width of the windows with overhang (m) (H)
- Width of the corbel (m) (Ph)
- Distance between the overhang and the window (m) (Rh)
- Width of the vertical wings (m) (Pv)
- Distance between the wings and the window (m) (Rw)

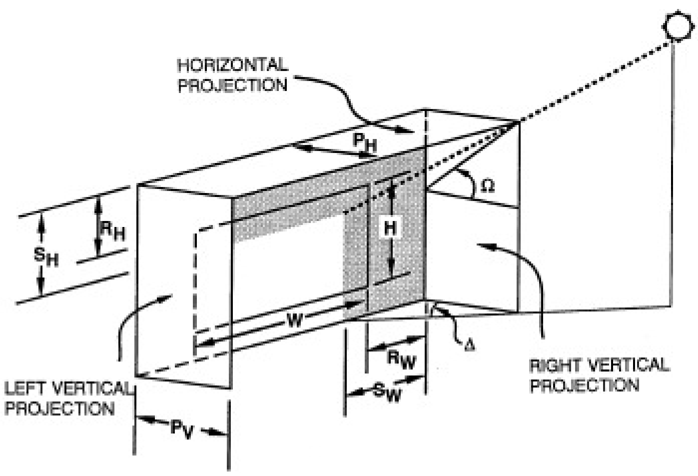


Figure 3: Graphical representation of the corbels and wings of the windows

Internal surfaces

For this kind of surfaces, the area, the heat transfer coefficient (U), and the constant boundary condition have to be entered. (See section 'Calculation of the Demand').

The programme considers the shadows that possible external obstacles (trees, buildings…) may be projected on the external enclosure. That is why; these obstacles have to be defined with the following parameters:

h = Height of the obstacle (m)
S = Distance between the obstacle and the external surface of the zone on which the shadow is projected (m)
H = Height of the zone (m)
d = Distance between obstacle and the end of projection above the ground (m)

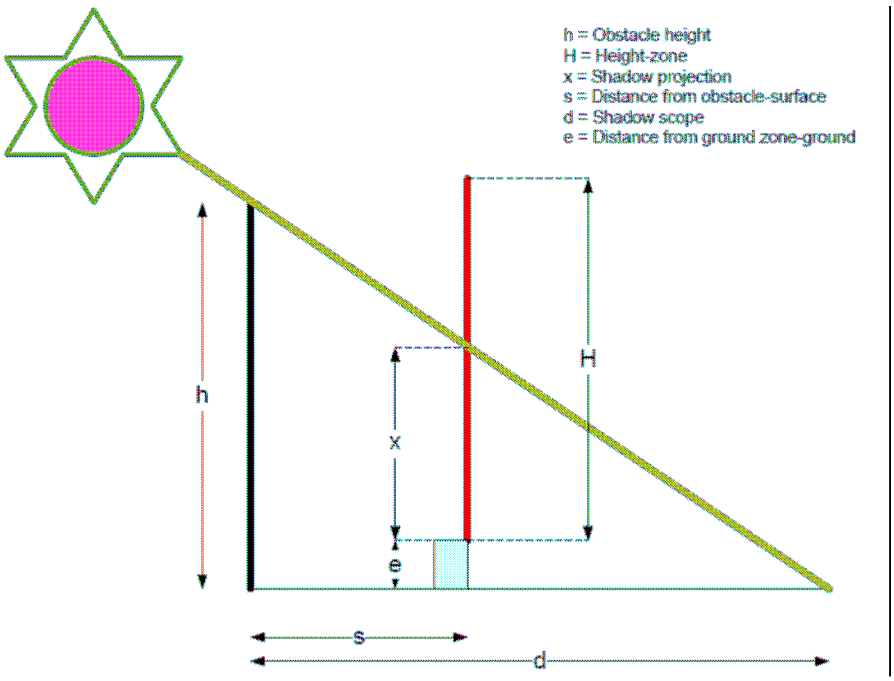


Figure 4: Graphical representation of the external shadows

Internal gains

These input data have been commented in the section 'Calculation of the Demand'.

Infiltration and ventilation

As it has been said before (see section 'Calculation of the Demand'), the infiltration/ventilation flow and the corresponding schedule have to be entered.

It has been considered that a very sealed building has an infiltration of 0.1 ren/h while in the opposite case, it would have an infiltration of 4 ren/h. The flows of the intermediate buildings will be between these two numbers.

System

Regarding the system, the data to entered have been explained in the section 'Calculation of the Systems Consumption'.

Apart from these data about the zone, the programme requires:

a) Hourly data of the external air temperature.
b) Hourly data of the direct and diffuse radiation on the horizontal surface

3.3. Saving measures proposed

Once the air conditioning consumptions have been calculated, the following saving measures have been applied with the same simulation tool:

a) Colour of the external surfaces. All the external surfaces (vertical external walls and roofs) with dark or medium colour have been changed for a lighter colour. This way, their absorptances have been modified.

b) Glasses. The simple glasses (4mm, 6mm…) have been changed for double glasses (4/6/4, 6/4/6…).

c) Shading devices. Internal and external solar protections have been added to those windows which did not have any. For this purpose, the solar attenuation coefficient (IAC) have been changed. With this improvement, a shadow coefficient of 0.264 have been achieved by putting an external opaque blind and an internal Venetians blind. (See *Ashrae Fundamentals 2005*).

d) Reduction of the infiltration. The infiltration level of the zone has been offset to 0.1 air changes per hour which is considered optimum.

e) Free cooling. It is an improvement which affects the system by adding a new machine or by adapting the existing ones.

The programme calculates an optimum flow:

$$\dot{m}_{eg} = \frac{Q_{T,Max}}{C_p \cdot (T_0^* - T_{zona}^*)}$$

$Q_{T,Max}$ = Maximum total demand, chosen among the 8760 hourly demands calculated during the year [W]
T_0^* = External air temperature. It is considered 15 ºC
T_{zona}^* = Air temperature of the zone. It is considered 24 ºC
C_p = Air specific heat. A value of 1024 [J/kgK] is taken

Then, it calculates the contribution of free cooling:

$$Q_{eg} = \dot{m}_{eg} \cdot C_p \cdot (T_0 - T_{zona})$$

T_0 = External air temperature
T_{zona} = Air temperature of the zone
Q_{eg} = Load compensated by the free cooling [W]

Finally, it modifies the load:

$Q^*_T = Q_T - Q_{eg}$
Q^*_T = Modified load [W]
Q_T = Total load calculated [W]

f) Improvement of the COP of the system. It is considered that the optimum COP´s for the heat pump and chiller are 2.5 and 2.7 for cooling and heating, respectively. The COP considered optimum for the boiler is 0.9. The improvement consists of modifying the values of the original COP´s for these ones. It means an improvement (repair or substitution) in the system which implies the production machines, the distribution and/or the terminal units.