UNIVERSIDAD DE CÓRDOBA

INSTITUTO DE ESTUDIOS DE POSTGRADO
MASTER EN ENERGÍAS RENOVABLES DISTRIBUIDAS

CREATION OF A SOFTWARE APPLICATION FOR THE ANALYSIS OF SHADOWS, IRRADIANCE AND DAILY RADIATION IN URBAN ENVIRONMENTS: SOLAR RADIATION CONTOUR MAPS ON FAÇADES OF BUILDINGS

ÁLVARO MÁRQUEZ GARCÍA

Trabajo para optar al
Máster en Energías Renovables Distribuidas

Profesor/es Tutor/es:
PROF. DR. RAFAEL LÓPEZ LUQUE
PROF. DRA. MARTA VARO MARTÍNEZ

Córdoba, (Junio, 2013)

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Proyecto presentado a la Comisión integrada por los profesores:

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D. Rafael López Luque, Profesor Titular del Departamento de Física Aplicada de la Universidad de Córdoba y Dña. Marta Varo Martínez, Profesora Contratada Doctora del Departamento de Física Aplicada de la Universidad de Córdoba, autorizan a D. Álvaro Márquez García, con DNI 30970116-H a presentar el trabajo titulado CREATION OF A SOFTWARE APPLICATION FOR THE ANALYSIS OF SHADOWS, IRRADIANCE AND DAILY RADIATION IN URBAN ENVIRONMENTS: SOLAR RADIATION CONTOUR MAPS ON FAÇADES OF BUILDINGS, como Trabajo Fin de Máster del Programa Oficial de Energías Renovables Distribuidas de la Universidad de Córdoba.

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Que el Trabajo de Fin de Máster titulado CREATION OF A SOFTWARE APPLICATION FOR THE ANALYSIS OF SHADOWS, IRRADIANCE AND DAILY RADIATION IN URBAN ENVIRONMENTS: SOLAR RADIATION CONTOUR MAPS ON FAÇADES OF BUILDINGS, ha sido realizado por Álvaro Márquez García, bajo su dirección, para la obtención del título de Máster Universitario en Energías Renovables Distribuidas por la Universidad de Córdoba, es un trabajo original e inédito y reúne los requisitos necesarios para su exposición y defensa.

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ENCUESTA P-2.I

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DEDICATION

A mi familia y amigos

ACKNOWLEDGEMENTS

Me gustaría mostrar mi agradecimiento y gratitud a aquellas personas que han contribuido a la realización de este Trabajo Fin de Máster, especialmente a Rafael López por su inestimable apoyo en la programación informática desarrollada y a Marta Varo por su ayuda en la redacción en inglés de este proyecto.

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RESUMEN

Durante los últimos años se ha puesto de manifiesto la necesidad de trasladar los puntos de generación eléctrica a las zonas de consumo. Con ello se optimizaría la infraestructura necesaria para el transporte de la energía y como consecuencia, se produciría una reducción de las pérdidas durante la fase de transporte. En este contexto, la energía solar se impone como el recurso limpio con mayor capacidad de aprovechamiento en los entornos urbanos. La generación distribuida requiere de herramientas informáticas fiables para la elección de los emplazamientos más idóneos para la instalación de sistemas fotovoltaicos y solares térmicos en los elementos urbanos de mayor superficie, las fachadas. Sin embargo, la falta de espacio disponible con que cuenta un propietario en su fachada, hace necesario el conocimiento preciso de la energía disponible. Por ello, en este trabajo de investigación se pretenden estimar las magnitudes necesarias para conocer la viabilidad de este tipo de instalaciones sobre fachadas, creando una herramienta informática capaz de proporcionar mapas de contorno de radiación solar sobre fachadas de edificios en entorno urbanos.

Palabras clave: entornos urbanos, fachadas, radiación solar, sombras

ABSTRACT

In recent years, the necessity of relocating the electricity generation centrals closer to the final consumption areas has been detected. Thus, optimizing the infrastructure required, and consequently minimizing the energy losses on the transportation phase has been established as drivers of the sector development. In this context, solar energy emerges as the most environmental friendly and appealing resource, in addition to its suitability in urban areas. The distributed generation requires of reliable IT tools for the selection of best locations when it comes to the photovoltaic and solar thermal systems on the largest urban elements, namely façades. However, the lack of available space makes advisable for the house owner to accurately measure the existing energy. For that reason, this research project intends to establish the key performance indicators so as to determine the system viability for this particular purpose, then a software tool able to provide solar radiation contour maps on façades of buildings in urban environments has been developed.

Key words: urban environments, façades, solar radiation, shadows

1. INTRODUCTION

The current situation of economy, environment and society is suffering a progressive change toward a new model based on the management optimization of the energetic resources, in which all the social actors (governments, companies and citizens) must participate.

Most of the countries of the world have changed their energetic policies in the last years on account of global warming and the general decrease of the amount of the available traditional energy sources (coal and oil) together with the increase of their prices.

Specifically, the European Union has worked harder in this direction than the rest of the states due to his important dependence on the supply of gas and oil from Asia and Africa. For that reason, the future viability of the European energetic system will depend on the correct establishment of the energetic efficiency policies and the use of renewable energies.

The well-known European parliament directive 20/20/20 establishes the following targets:

- A reduction of 20% in EU greenhouse gas emissions from the 1990 levels
- A raise of the share of EU energy consumption produced from renewable resources up to 20%
- An improvement of 20% in the EU energy efficiency

Thus, the 20-20-20 targets represent an integrated regulation that aims to combat against climate change, to increase the EU energy security and to strengthen its competitiveness.

1.1 Solar radiation maps on façades in the context of RD 1699/2011

The RD 1699/2011 is the draft of the future regulation that will establish the conditions for the implementation of the net metering in the electrical installation in buildings in Spain. With this policy, general users, and particularly, household consumers, could use the electricity generated by their own installations, giving the rest to the provider company and taking its electricity when they are not able to produce it.

Thus, most of the users could place photovoltaic panels on a piece of their façades, being able to produce their own energy. For that reason, it is interesting to know how much electricity could provide these panels and, for that, an economic study would be required.

In that sense, solar radiation maps turn into an useful tool since, with them, owners will have better information to evaluate the viability invest necessary for the net metering system.

1.2 Applicability of the solar radiation maps on façades

The creation of a method for calculating solar radiation maps on façades presents a wide applicability for supporting the decisions of the different agents involved, housing owners, urban planners and daylighting specialists.

The rate of solar irradiance on buildings has always been an important factor for the purchase of a home since with information about the solar irradiance on a window of a house, it is easy to calculate the natural illumination that the sun provides inside the room. However, none estimation is done for this purpose. Knowing the level of this rate, any potential buyer can analyze if the house satisfies his expectations. In addition, it also can facilitate the analysis of different strategies of the passive energetic systems to reduce the loads of the buildings during the year.

The installation of photovoltaic panels and solar thermal collectors takes every day more importance. Besides the roofs, the façades of buildings represent big surfaces with great rates of radiation so that they can be used to install these kinds of systems for producing electricity and hot water. Solar radiation maps could be very useful for that purpose.

On the other hand, radiation maps on façades can also be used by urban planning designers. Solar Rights is an old concept that has been studied many times, during the last decades. The most important elements of the urban environments, such as squares, avenues, gardens etc must collect some features for guaranteeing the minimum values of habitability to be used for citizens. For that reason, this application tool can help urban designer to improve the future growth of the cities.

Moreover, the *Codigo Tecnico de la Edificacion* (CTE) develops in detail how to get the targets for the 20/20/20 European directive. This one represents a compulsory regulation for the recently constructed buildings. The section “Save Energy” of the Basic Document HE-4 establishes the minimum contributions of energy from renewable energies, having the solar radiation an important consideration.

However, as mentioned before, this mandatory rule only refers to newly built houses. The current situation in the housing market, almost paralyzed since 2009, makes that the rate of homes with these new energy systems based on the use of a percentage from renewable sources has not increased as expected.

At this point it is necessary to develop techniques that promote the same philosophy of the CTE but applied to the existing building.

All these applications, as shown in Fig.1, demonstrate that the realization of an open solar radiation map software has an extensive applicability.

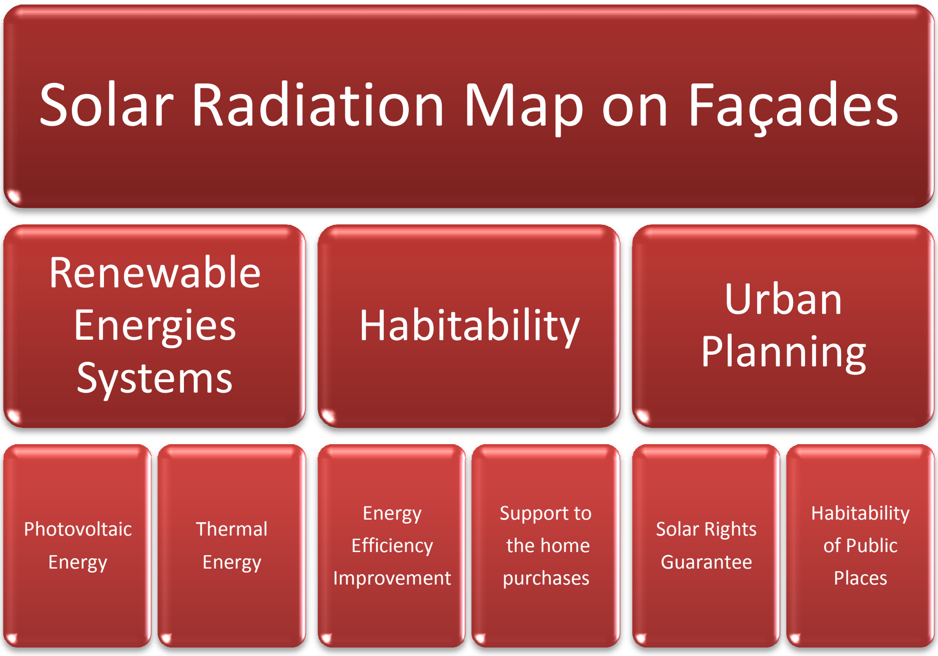

Figure 1: Applications of the solar radiation contour maps on façades

2 AIMS OF THE PROJECT

In this context, the aims of this project can be summarized as follows:

a) Analysis of some solar radiation software for calculating solar irradiance and energy in urban environments.

b) Creation of an open toolbox using the Visual Basic language of Microsoft Excel for estimating the irradiance and solar radiation on façades of buildings.

c) Development of daily radiation contour maps on façades in urban environments.

d) Comparison between the results obtained with commercial software and the open application developed

3 BIBLIOGRAPHIC REVIEW

The researches about solar energy in urban environments, which have been written during the last decades, are numerous. Many scientists have considered that the use of coal and oil for generating electricity should decrease, and, for this reason, it might be a change in the model, going from the use of traditional energy sources to another one, based on the use of the renewable energies available in the cities. In the following chapters a review of the techniques and methods developed for this purpose is exposed.

3.1 Analysis of obstacles using solar charts

Solar charts have been used for resolving several problems which involve the position of the sun for a specific instant. There are different solar charts, depending on the projection chosen. The most used are stereographic and cylindrical projection. These projections represent useful tools for the analysis of obstacles for the study of shadows in urban environments M. Drif et al. [1]. Both of them, stereographic and cylindrical projections, can be used to establish the position of the sun for a specific time and latitude. Each one has its own properties, features and limitations, so the researcher must chose it depending on the case studied.

The method for calculating shadows on a point of a building façade using solar charts, consist of drawing the trajectory that the sun keeps along the day, for a specific Julian day and latitude. It can be made using solar charts software. In addition, the neighborhood buildings must also be represented in the solar chart. In Fig.2-3, two examples of analysis of shadows using stereographic and cylindrical solar charts are shown. The easiest way for drawing the projections of the obstacles is by an heliospheric picture, done over the studying point. These projections can be made with several softwares.

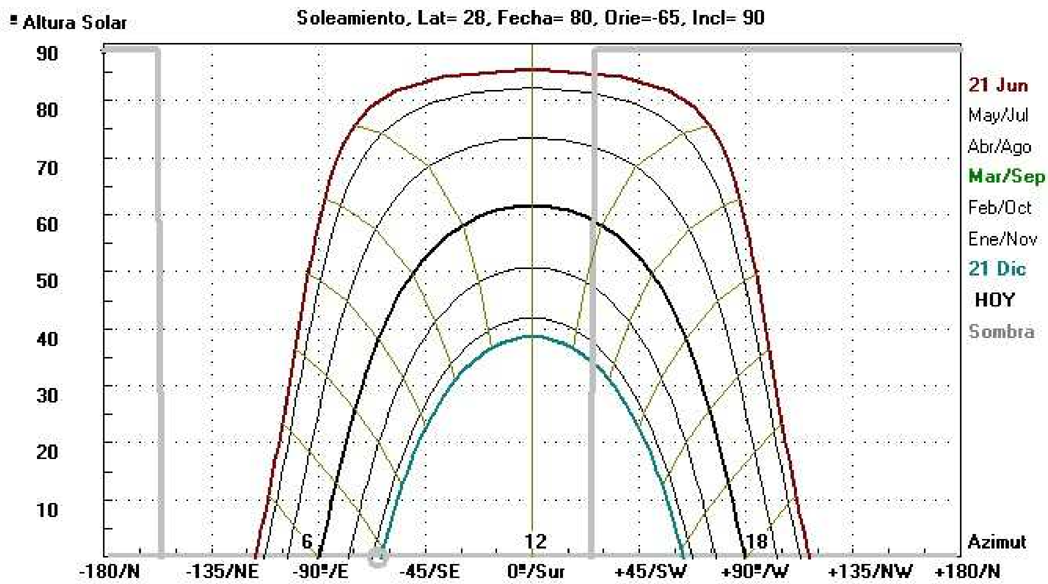

Figure 2: Representation of the obstacles on a cylindrical solar chart

The utilization of solar charts for studying obstacles and shadows presents some problems and limitations. The solar chart is made for a specific point, so if many points must be studied, it is necessary to design a chart for each one. Cylindrical projection cannot represent points with latitude of 90°, because a cylinder with an infinite length axis would be needed. That is why cylindrical solar chart is only used for points with latitude lower than 70°.

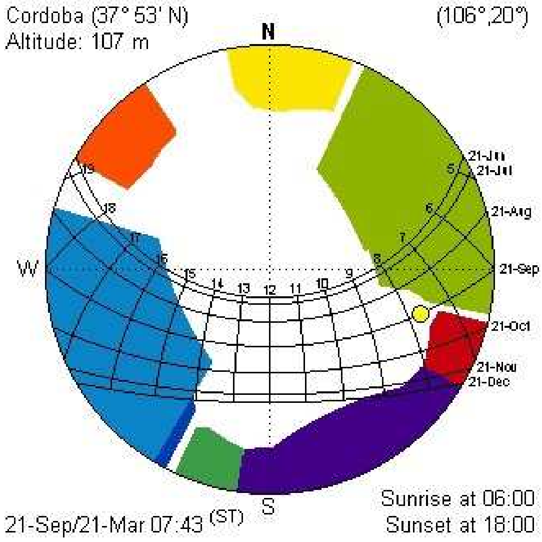

Figure 3: Representation of the obstacles on a stereographic solar chart

3.2 Solar and shadows control in urban environments

Solar radiation on buildings in urban environments has an important influence on the temperature inside them. Its comprehension is very interesting for the temperature regulation it along the year. Controlling this temperature, the energetic efficiency can be improved, reducing the housing loads in winter and summer, Salazar Trujillo et al. [2].

In neighborhoods where the houses do not have more than two or three floors, the shadows produced by the nearest buildings are not significant, Gómez-Muñoz and Porta-Gándara [3]. In these cases the most important elements for solar control are the trees which were studied by Gómez-Muñoz [4] et al. According to the authors, the trees can be modelled using cubes and a specific parametrization.

In Fig.4, the modeling of a tree by a rectangular parallelepiped is shown, where f_x, f_y and f_z represent the foliage density in each direction. The limitation of this method is that, for newly planted trees, a growth model for each kind of tree must be created. For that reason, the analysis of energy efficiency improvement in houses due to the trees cannot be easily made.

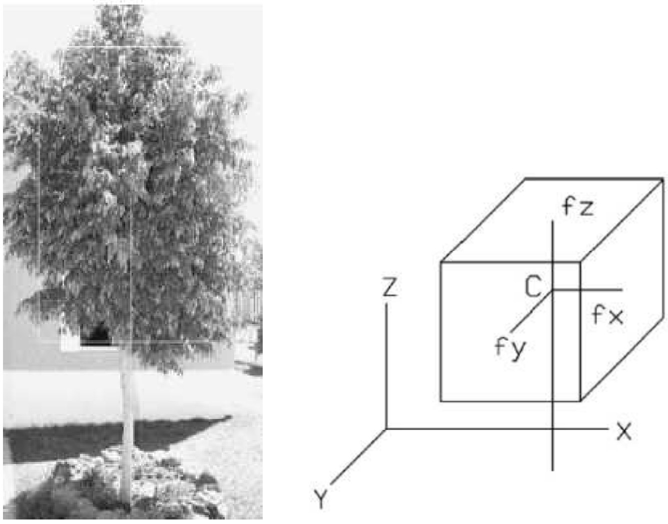

Figure 4: Modeling of a tree by a rectangular parallelepiped

In this kind of neighborhoods, which are formed by low height housings, it is very useful to design the building depending on the energetic efficiency. There are some researches as Tang Mingfang [5] whose objective is the reduction of the cold and heat loads at the conception stage of the house. These methods depend on the azimuth angle of the different façades of the building. The first step is that for a specific latitude, it is necessary to know the months of the year with the lowest and the highest temperatures. In the first case, the orientation of the main façades must get the maximum solar radiation along the day to reduce the heating inside the rooms. In the hottest months, the same orientation must be shaded as much as possible for reducing the cold loads. These two objectives are incompatible simultaneously in the majority of the cases, so the designer must choose one of them, attending to if the area is typically hot or cold.

Shadow control in urban environments has been studied continuously by many researchers along the last decades. In cities where the building heights are high, shadows on façades have an important influence on the lighting, temperature and quality of life, Kwang-Wook Park et al. [6]. In Fig.5 the geometric problem studied by Elasfouri et al. is shown [7]. For a specific time and latitude the position of the sun can be determined by the solar azimuth “ϕ”, and solar height “β”. Knowing the difference of the building heights “y”, and the distance between them “x”, the estimation of the shadows produced by each other can be easily calculated.

The shadow conditions for the scheme of Fig.5 are:

a) The vertical plane that crosses both buildings must form an angle with the south direction identical to the solar azimuth, for the considered moment.
b) The relation between the buildings distance “x” and the difference of buildings heights “y” must be lower than the cotangent of the solar height.

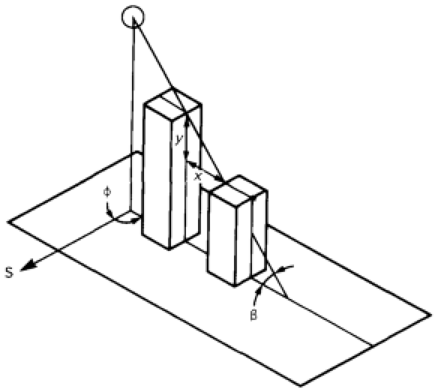

Figure 5: Shadow conditions for two neighbor buildings

If both shadow conditions are fulfilled simultaneously, the higher building will produce shadow on the lower one. Knowing the buildings heights and representing the cotangent of the solar height in a polar coordinates system, the distance between them can be estimated for getting shading or daylighting. It is demonstrated that it is not possible to achieve shadows in the heatest months and lighting in the coldest months.

3.3 Solar rights in urban environments

Many techniques and methods have been developed for establishing the construction limitations which guarantee solar rights in cities since the second half of the 20th century. During the history the daylighting has represented an important factor of quality of life, H. Alzoubi [8]. It affects to the health and human behaviors. With the construction of skyscrapers, it was necessary to fix some urban planning conditions to guarantee a minimum amount of daily solar radiation on buildings.

The researches in this field have detailed the definition of solar rights surfaces as the tridimensional geometric enveloping which describe the maximum height for buildable volumes for preserving a given amount of irradiance in adjacent places.

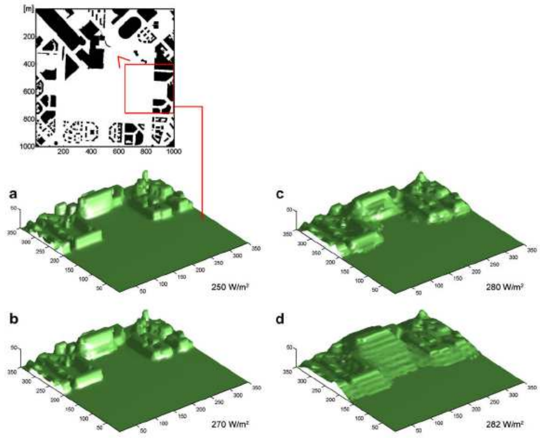

Figure 6: Solar rights surfaces

To obtain these surfaces E.Morello and C. Ratti [9] used a terrestrial digital model and a celestial model of the studied area, as it is shown in Fig.6. After calculating the average radiation values in a given region of the sky, applying algorithms that can be programmed in some software like Matlab, the previously mentioned solar surfaces are obtained, providing accurate information about the construction limitations in order to ensure certain values of solar radiation.

3.4 Software applications for the analysis of daylighting

The complexity for the calculation of shadows and radiation in urban environments is extremely high due to the large amount of factors and interactions that must be studied, Jianmin Shao [10]. For the analysis of large neighborhoods, it is necessary to use computer programs for the calculation of radiation, which reduces significantly the resolution time of the problem, Chitrarekha Kabre [11].

The Solene software, designed by CERMA, studies the distribution of daylighting in complex urban environments, F. Minguet [12]. Using this application it is possible to estimate the shadows produced by the adjacent buildings and the sunlighting on the façades and inside buildings. In Fig.7 an example of the study of the daylighting factor inside a room by two transparent windows is shown.

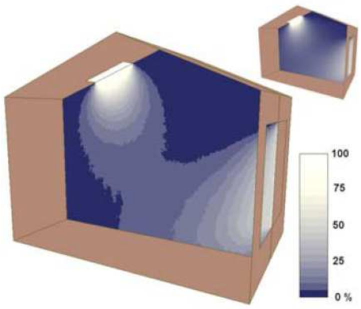

Figure 7: Daylighting factor inside a room using Solene software

This is quite useful for architects since it represents an easy tool for making simulations to decide the distribution of the windows in façades and roofs. This software also shows the losses of daylight due to passive elements such as meshes (Fig.8).

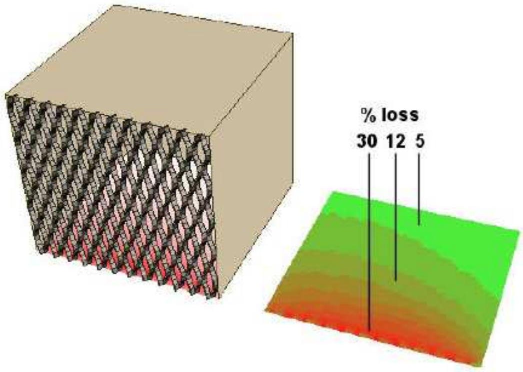

Figure 8: Estimation of the losses due to a mesh using Solene software

However, this application does not estimate values of irradiance and solar radiation on the different elements of the urban environment. Basically it is only a tool for the analysis of the distribution of the daylight.

For the study of the irradiance and solar radiation in urban environments, there are multiple applications, being Heliodon, created by Benoit Beckers and Luc Masset, one of the most important.

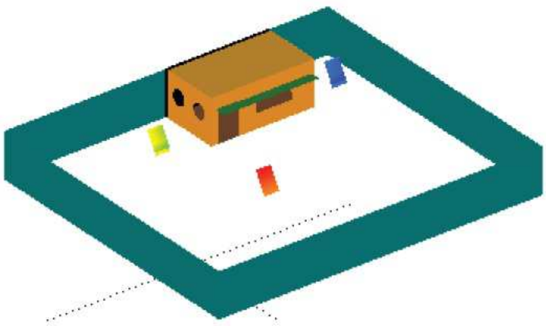

Figure 9: Three-dimensional model using Heliodon software

Heliodon provides graphics of irradiance and solar energy on building facades for different time intervals (Fig.9). This program is based on a very easy physical model, in order to reduce the execution and computation time, in which only the direct component of the solar radiation is considered, E. Antaluca et al. [13]. The model is based on extraterrestrial solar radiation determined by the time and space position of the calculation point on earth. The solar flux in KWh/m^2 arriving at a point on the earth's surface is calculated using the expression (Eq.1):

$$Hc = H_0.\tau^m \qquad (1)$$

Where H_0 is the extraterrestrial solar flux, τ is the atmospheric transmittance and m is the fraction between the real distance and the zenithal one. Heliodon uses H_0= 1380 W/m^2 and τ = 0.7 by default. The value of m is given by the equation (Eq.2):

$$m = \frac{pa}{101.3\ cos\psi} \quad (2)$$

Where pa is the atmospheric pressure and ψ the zenithal angle. The atmospheric pressure depends on the altitude in Km and it is given by the expression (Eq.3):

$$pa = 102.3.e^{\frac{-altitude}{8.2}} \quad (3)$$

This physical model is quite simple, since it only calculates the direct component of the irradiance, ignoring the diffuse and reflected ones. The albedo, whose importance in urban environments has been studied by A. Tsangrassoulis [14] is either considered. Furthermore, the model only considers clear skies and leaves to the user the decision of modifying the results for the case of the influence of the clouds.. The main inconvenient is that this program only offers global results for the specific element of the urban model so the user could not know the distribution of the values on the element (Fig.10).

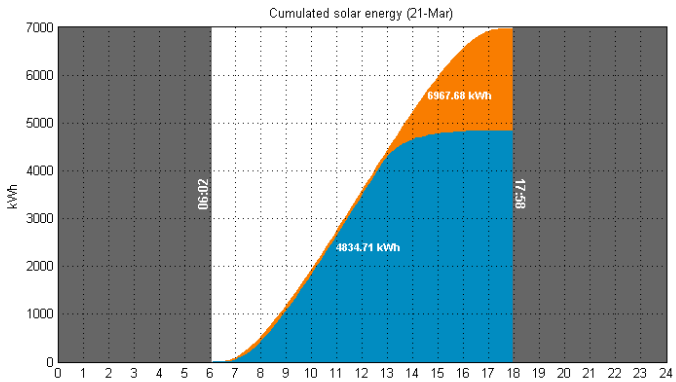

Figure 10: Daily solar radiation distribution using Heliodon software

To maximize the use of available solar energy in the cities, it is necessary to know the distribution of the irradiance in a very precise way. Due to the limited available space in the urban environments, the solar energy catchment systems should occupy a little surface and to ensure the electricity production, the design of the installation must be done using very accurate data. As a consequence, the aim of this project is the creation of an application software to study the irradiance and the radiation in every point of the different elements of the buildings and using a more precise physical model, the Collares-Pereira model [15], able to show more accurate results.

4 METHODOLOGY

This general aim of this project is the creation of a software tool using Visual Basic language for analyzing in a deep way how the buildings of a neighborhood affect to the available solar energy on the façades of another one. For this reason, a study of the existing solar softwares is needed, to check how they work, their interfaces and the results obtained. That is very important due to the fact that one required goal is that the developed application must have an easy working during its data input stage and must have an useful data output management. As a consequence, the first step is the election of a neighborhood and the creation of its urban model, which will be used to obtain the results, using the existing solar radiation softwares and the developed solar maps software tool. In the following chapters each one of these steps are explained.

4.1 Creation of the urban model

In order to study solar radiation on buildings façades, it is necessary to start from an exact geometric definition of all elements of the urban environment. The case studied is a 3 dimensional problem, in which the buildings are fixed in relation to a global reference system and the sun has a motion that depends on the latitude and longitude of the emplacement and the particular time of the year. For that reason the first step is the creation of the urban model.

The place selected is located in the city of Córdoba. The name of this neighboring is Vista Alegre Square and its geographic coordinates are latitude 37.85°N and longitude 4.85°W. The aspect of this urban environment is shown in Fig.11.

Figure 11: Situation of Vista Alegre neighborhood in Cordoba

This place (Fig.11) has been selected because there are several representative urban elements. The neighboring is a consolidate zone in which there are both wide and narrow streets, a square, buildings with different kind of façades and a public sport center. That is very important to study the influence of the interactions between the façades in the shadows, irradiance and solar radiation. In the following chapters, the steps for the creation of the urban model are presented.

4.1.1 Cartography of the studied area

To establish the geometric definition of the place selected, a cartographic map is required. Using a file .dwg provided by Gerencia de Urbanismo de Córdoba, the neighborhood in 2-dimensions is determined.

The cartography belongs to the photogrammetric flight 1996 sheet 4.15. However, building heights data are not available in the city of Córdoba, so it is necessary to make measurements for its determination.

4.1.2 Determination of building heights

To make accurate measurements of the building heights, a theodolite is used. Due to the fact that the author of the project has no help for this measurement, a method based on the use of the available cartography is applied.

This method consists on setting the theodolite at any point situated in the square. From this point, the two horizontal angles formed by three consecutive edges, are measured. In the cartography these two angles are represented by their major arches. With this technique the point where the theodolite is situated is determined, so using the cartography, the distance between the theodolite and the edges of the buildings are known. After that, the vertical angle that an edge of a building forms is measured. By simple trigonometry the building height is calculated. The same process is done for the rest of the buildings. The steps are detailed in the following paragraphs.

At any place of the Vista Alegre square, the theodolite is set, keeping the condition that from this point at least one edge of each building must be visible. Once the point is chosen and the theodolite is placed, it is necessary to level it out.

a) First Step. Determination of the theodolite localization point

The 2 horizontal angles formed by the edges 1, 2 and 3 are measured (Fig.12). For that, the 3 horizontal angles of these edges are read with the theodolite. Table.1 shows the results.

Table 1: Horizontal angles for the selected edges

Horizontal Angles for each edge	Measurement (centesimal degrees °)
Lh1	40,5
Lh2	134,9
Lh3	228,7

With the results obtained, the 2 horizontal angles (Fig.12) are calculated (Table.2).

Table 2: Determination of the two horizontal angles

Horizontal angles	Centesimal Degrees	Sexagesimal degrees
Lh12	94,4	84,9
Lh23	93,8	84,4

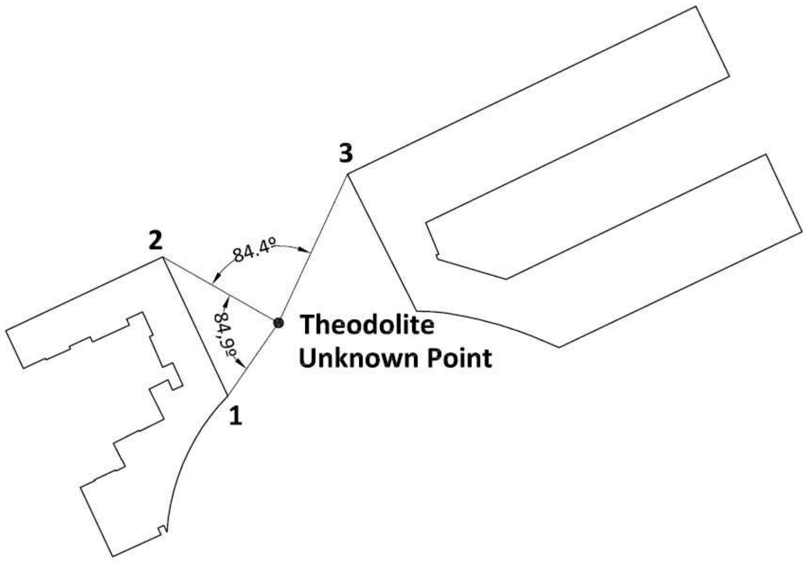

Figure 12: Horizontal angles measured for determining the theodolite location

With these two angles, over the cartography of the neighboring, the major arches for Lh12 and Lh23 are drawn. The intersection point will be the place where the theodolite is located (Fig.13).

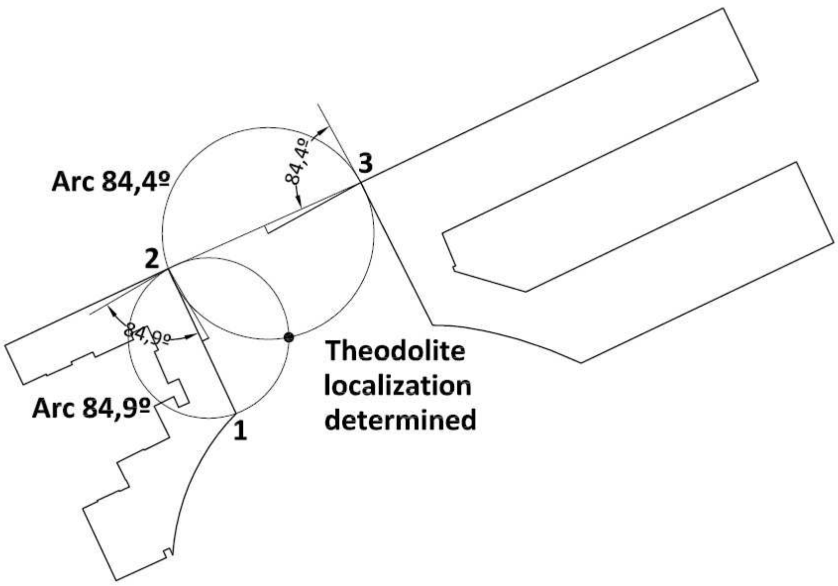

Figure 13: Determination of the theodolite localization point

Once the accurate point is known, the distances between the theodolite and the building edges can be measured directly using the cartography file dwg.

b) Second Step. Determination of buildings' heights

Using the theodolite and from the same point, the vertical angles that each building edge forms with the ground, are measured. Knowing these angles and the distance between the theodolite and each edge, the heights are estimated by trigonometry. In Fig.14 the edge chosen for each building is shown.

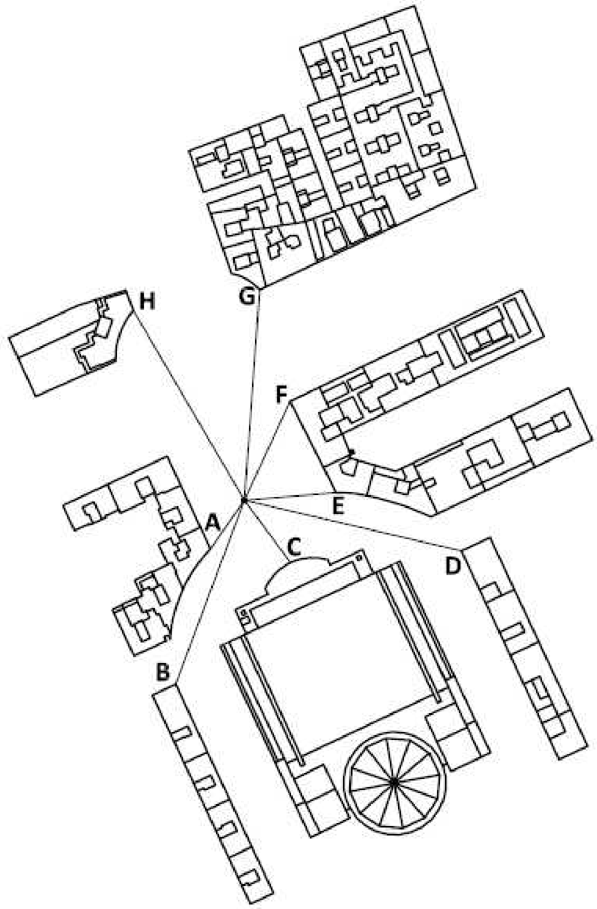

Figure 14: Chosen Edges of each building

With the information collected and using the expression (4) the heights are easily estimated.

$$Hi = Li * tag\ (Lvi) \quad (4)$$

Where:

Hi represents the height of the building i
Li represents the distance between the theodolite and the edge of the building i
Lvi represents the vertical angle that the edge of the building i forms

In Table.3, the building heights are shown.

Table 3: Determination of the building heights

Building	Distance (m)	Vertical Angle(°)	Height (m)
A	23,17	47,2	25,02
B	76,51	17,5	24,12
C	30,41	33,6	20,20
D	87,30	15,6	24,37
E	36,08	34,6	24,89
F	42,66	31,8	26,45
G	82,59	18,1	26,99
H	86,1	16,9	26,16

4.1.3 Three-dimensional urban model

Knowing the buildings heights and with the support of the cartography, the 3D urban model is created. SketchUp software has been used to develop the model because it represents an easy and intuitive tool for that purpose. Finally, the urban model for Vista Alegre neighborhood is created and shown in Fig.15.

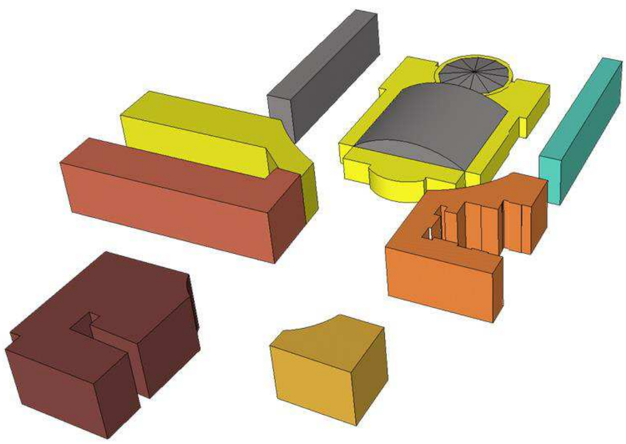

Figure 15: Three-dimensional urban model of Vista Alegre neighborhood

4.2 Solar Position and solar radiation software

Once, that the three-dimensional model of the neighborhood is created, it can be imported to some solar position and solar radiation softwares. In this project a review of SunPath software and Heliodon software has been done. Their interfaces, data input and data output are shown in the following epigraphs.

4.2.1 SunPath Software

SunPath application is a software developed by the Florida Solar Energy Center whose main objective is, to locate the position of the sun for a specific place and time. It has a library with some localizations and allows the creation of new ones, by its latitude, longitude and horary zone. For a chosen place, some tools are available for locating the sun under different conditions.

In this epigraph the most important applications for the urban environment which has been represented in the three-dimensional model, Vista Alegre neighborhood, are shown.

The first step involves introducing the localization of Vista Alegre Square using its data:

Table 4: Configuration of the studied area in SunPath software

Localization	Cordoba
Latitude	037:53:05
West Long	004:46:44
Time Zone	23 (GMT+01:00)

Once the localization is created, SunPath shows the main menu, with seven tools, which are explained below for Vista Alegre square.

a) Sun Position for a single selected date and time

Introducing a date time and a specific hour, SunPath calculates and shows solar azimuth and solar altitude. For example, for the civil time 19:15:02 and date 23/03/2013 the results are:

- Solar altitude: 003°17'28''
- Solar azimuth: 269°46'07''

b) SunPath for a sequence of times and dates

Beginning and final dates of the studied interval are introduced, with the step in days. After that, the process is repeated with the beginning and final hour and the step in hours, minutes and seconds. SunPath shows an .ascii file with the civil time, solar time and solar azimuth and altitude for the selected interval.

In Fig.16 the results for an interval between 1st and 2nd July 2013, with a step of two hours, are shown.

```
TIME INTERVAL IN MINUTES =  120 NO. POINTS= 5
TIME INTERVAL IN SECONDS =  7200
COVERING TIMES:  08:00:00 TO 17:00:00
ON JULIAN DAYS  182 TO  183

             SUNPATH THROUGH THE SKY

RUN DATE:  03-23-2013  19:08:54   SUNPATH CALCULATIONS USING PROGRAM SUNPATH
SOLAR POSITIONS FOR: Cordoba, España   YEAR:  2013
LATITUDE = 037°53'05"  LONGITUDE = 004°46'44"
TIME ZONE =  23 OR GMT+01:00
TIME INTERVALS ARE EQUAL INTERVALS IN CIVIL TIME
       |CIVIL  CIVIL  |SOLAR  SOLAR  |SOLAR   ALTITUDE |SOLAR    AZIMUTH
MO DA JUL|HOUR  HR:MI:SE|HOUR  HR:MI:SE|DEGREE  DEG:MI:SE|DEGREE    DEG:MI:SE
 7  1 182|    8  8:00:00|6.613  6:36:49| 20.917  20:55:02| 76.4981   76:29:53
 7  1 182|   10 10:00:00|8.613  8:36:48| 44.383  44:23:01| 93.9102   93:54:36
 7  1 182|   12 12:00:00|10.61 10:36:47| 66.809  66:48:35| 123.939  123:56:21
 7  1 182|   14 14:00:00|12.61 12:36:47| 73.167  73:10:03| 210.508  210:30:30
 7  1 182|   16 16:00:00|14.61 14:36:46| 53.429  53:25:45| 257.416  257:24:58

             SUNPATH THROUGH THE SKY

RUN DATE:  03-23-2013  19:08:54   SUNPATH CALCULATIONS USING PROGRAM SUNPATH
SOLAR POSITIONS FOR: Cordoba, España   YEAR:  2013
LATITUDE = 037°53'05"  LONGITUDE = 004°46'44"
TIME ZONE =  23 OR GMT+01:00
TIME INTERVALS ARE EQUAL INTERVALS IN CIVIL TIME
       |CIVIL  CIVIL  |SOLAR  SOLAR  |SOLAR   ALTITUDE |SOLAR    AZIMUTH
MO DA JUL|HOUR  HR:MI:SE|HOUR  HR:MI:SE|DEGREE  DEG:MI:SE|DEGREE    DEG:MI:SE
 7  2 183|    8  8:00:00|6.610  6:36:38| 20.838  20:50:17| 76.5432   76:32:35
 7  2 183|   10 10:00:00|8.610  8:36:37| 44.306  44:18:21| 93.9744   93:58:27
 7  2 183|   12 12:00:00|10.61 10:36:36| 66.723  66:43:24| 124.007  124:00:28
 7  2 183|   14 14:00:00|12.60 12:36:35| 73.113  73:06:48| 210.256  210:15:23
 7  2 183|   16 16:00:00|14.60 14:36:35| 53.420  53:25:12| 257.263  257:15:48

♀
```

Figure 16: Sequence of times and dates using SunPath software

c) Cylindrical solar chart

This interesting tool shows the cylindrical solar chart for a specific place and time. Superposing an heliospheric picture of the studied point on the cylindrical solar chart, an useful tool for the analysis of obstacles is obtained. In Fig.17 the solar chart generated by the software for Vista Alegre square for 2013 is shown.

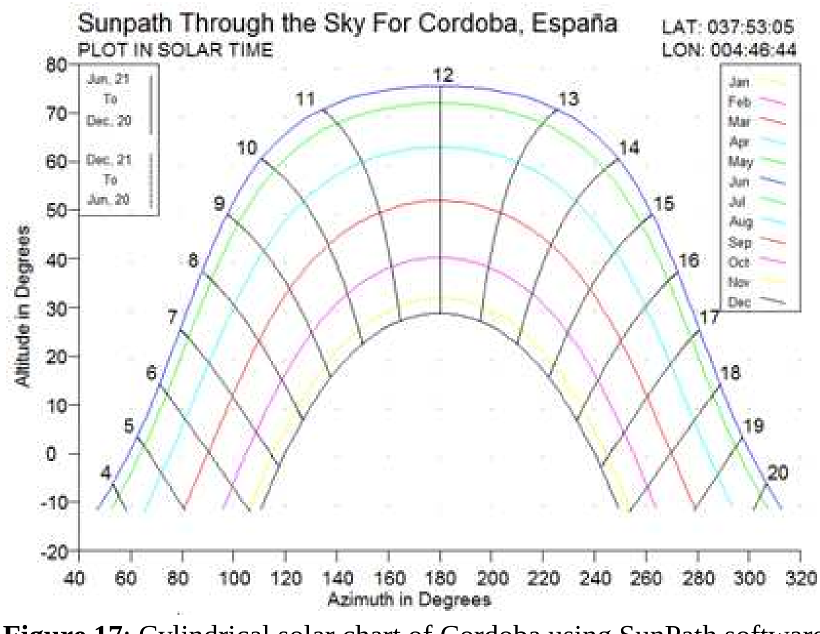

Figure 17: Cylindrical solar chart of Cordoba using SunPath software

d) Solstices and equinoxes determination

Choosing the year and the localization, SunPath creates an .ascii file with the dates of the solstices and equinoxes in Local and GMT times. For Vista Alegre square, in Cordoba, and for the year 2013, the results are shown in Fig.18.

```
FOR: Cordoba, España
LATITUDE = 037°53'05"LONGITUDE = 004°46'44"
TIME ZONE = 23 OR GMT+01:00

FOR YEAR  2013 THE EQUINOXES AND SOLSTICES OCCUR AS FOLLOWS:

MAR EQUINOX     JUN SOLSTICE    SEP EQUINOX     DEC SOLSTICE
DAY HR MN SEC   DAY HR MN SEC   DAY HR MN SEC   DAY HR MN SEC
 20 11:03:18     21 05:05:12     22 20:45:38     21 17:12:40 UT or GMT &
 19 12:03:18     20 06:05:12     21 21:45:38     20 18:12:40 LOCAL TIME

LOCAL TIME IS LOCAL STANDARD TIME IN THIS TIME ZONE

TO DO SUNPATH CALCULATIONS FOR ONE OR MORE OF THESE DATES,
WRITE DOWN THE DATES AND TIMES OF INTEREST AND THEN RUN
OPTION 2 FROM THE MAIN MENU.
♀
```

Figure 18: Determination of the solstices and equinoxes in Cordoba using SunPath software

e) Sunrise and sunset times and day length

Selecting a specific day of the year or an interval of time, the program shows the Civil and Solar times of the sunrise and sunset in an .ascii file, and calculates the day length. In Fig.19 this information is shown for Vista Alegre square, in Cordoba, for the 6th of July 2013.

```
    SUNRISE AND SUNSET TIMES USING PROGRAM SUNPATH

FOR: Cordoba, España   RUN DATE:  03-23-2013  19:33:55
LATITUDE = 037°53'05"LONGITUDE = 004°46'44"
TIME ZONE = GMT+01:00*
DATE SELECTED FOR THIS CALCULATION: MONTH: 3 DAY: 21 JUL DAY= 80 YEAR 2013
*NOTE: FOR THIS DATA
TIMES GIVEN ARE IN DECIMAL HOURS PAST MIDNIGHT


*****  SUN RISE TIME IS AT 8:19:36 DAYLIGHT SAVING TIME *****
      |CIVIL  CIVIL  |SOLAR  SOLAR  |SOLAR  ALTITUDE |SOLAR    AZIMUTH
MO DA JUL|HOUR  HR:MI:SE|HOUR  HR:MI:SE|DEGREE  DEG:MI:SE|DEGREE    DEG:MI:SE
 3 21  80| 8.32  8:19:36|5.893  5:53:35| -.2675  -0:16:03| 88.4532   88:27:11


*****  SUN SET TIME IS AT 20:32:54 DAYLIGHT SAVING TIME *****
      |CIVIL  CIVIL  |SOLAR  SOLAR  |SOLAR  ALTITUDE |SOLAR    AZIMUTH
MO DA JUL|HOUR  HR:MI:SE|HOUR  HR:MI:SE|DEGREE  DEG:MI:SE|DEGREE    DEG:MI:SE
 3 21  80| 20.5 20:32:54|18.11 18:07:02|-.26750  -0:16:03| 271.801  271:48:05

********* DAY LENGTH IS  12.2216237543019 HOURS OR  12:13:17 **********
```

Figure 19: Sunrise and sunset in Cordoba on 6th of July 2013 using SunPath software

f) Date and time for a selected solar position

With this tool, dates and times along the year in which the sun presents a selected position are calculated. It is important to remark that SunPath offers the possibility for choosing the number of iterations and the maximum allowed error. In Fig.20 this information is shown for Vista Alegre square in Cordoba, for the year 2013, a solar altitude of 45° and a solar azimuth of 130°.

```
SUNPATH TIMEFIND RESULTS FOR
LATITUDE: 037°53'05"  LONGITUDE: 004°46'44"
SELECTED SOLAR ALTITUDE ANGLE:  45 DEGREES
SELECTED SOLAR AZIMUTH  ANGLE:  130 DEGREES
MAXIMUM ALLOWED ANGULAR ERROR =  .1 DEG
SEARCHING EACH DAY OF THE YEAR FOR COINCIDENCES
JULIAN       LOCAL  SOLAR     D E G R E E S
DATE  MO  DAY  TIME   TIME   ALTITUDE  AZIMUTH  N
092  04  02-  13:11  09:49   45,07    130,01  07
254  09  11-  13:05  09:49   45,07    130,01  07

FOUND AT LEAST ONE TIME MATCHING THE CONDITIONS
N ABOVE IS THE NUMBER OF ITERATIONS TO FIND RESULT
```

Figure 20: Date and time for a solar altitude of 45º and solar azimuth of 130º in Cordoba

g) Continuous readout of solar position

SunPath synchronises itself with the computer clock and shows in a dynamic way, in real time, the sun position by its solar altitude and azimuth.

4.2.2 Heliodon Software

There are several softwares for daylighting and shadows analysis in urban environments. One of them is Heliodon software, developed by Benoit Beckers and Luc Masset. The simple interface and representation of its results, provides a very useful application for calculating solar radiation on buildings. Exporting the three-dimensional model created in SketchUp to a .stl file, the urban model can be imported directly to Heliodon.

The workspace is divided in three windows, which shows the floor of the studied area, its perspective and the projection of the urban model from a particular selected point. This program allows choosing between three different projections: stereographic, equivalent and orthographic. The most useful one is the stereographic projection because it shows the obstacles viewed from the studied point and the sun trajectories for a single day.

Introducing the data for Vista Alegre square in Cordoba, shown in Table.5, and importing the urban model created in SketchUp, the workspace presents the aspect of Fig.21.

Table 5: Configuration of the studied area in Heliodon software

Options for Cordoba	Data input
Latitude	37° 53’ N
Longitude	4° 46’ W
Altitude of Vista Alegre square	107 meters
Horary zone	GMT + 1:00
DST offset	+1:00 h
DST start	Last Sunday of March
DST stop	Last Sunday of October

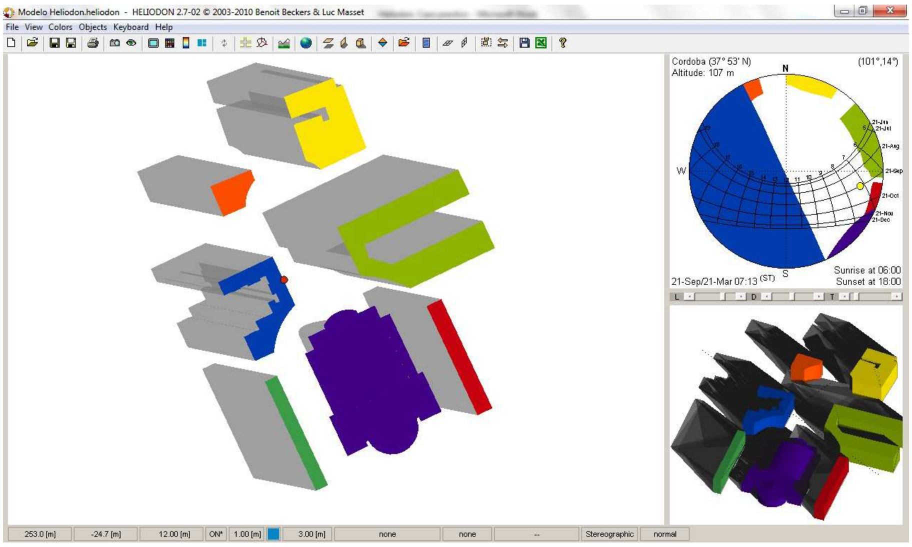

Figure 21: Urban model in Heliodon software. View of the workspace

In Fig.21 a point situated in the axis of the façade 1 in with a height over the ground of 12 meters for the spring equinox and solar time 07:13 is represented. As it can be seen in Fig.21 shadows are represented in floor and in perspective. Using the stereographic solar chart, an obstacle study can be easily made for the selected point, in Fig.21 in red color, as follows.

a) Obstacles study for the selected point

For the data input of the selected point (Table.5) and for the spring equinox, the results shown in Fig.22 are:

- Direct irradiance starts at 6:28 solar time
- Direct irradiance finishes at 10:58 solar time
- The temporary interval with direct irradiance is 4 hours and 30 minutes

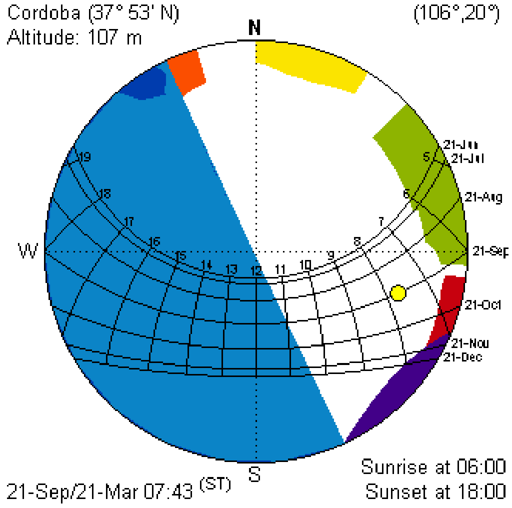

Figure 22: Stereographic solar chart for the selected point on 21st of March

In addition, stereographic solar chart shows that the neighborhood building which shades the selected point is the pale green one in Fig.22.

However, the most important application of Heliodon consists on the analysis of the solar radiation exploitation on a plane element. For doing it, the program has two tools.

b) Vertical and Horizontal Mesh

Using this tool a vertical or horizontal mesh can be introduced in the urban model. The mesh can be configured changing its dimensions and its height over the ground. The mesh is formed by triangles and its amount represents the resolution of the mesh. Increasing the amount of triangles in the mesh, the results obtained will be more accurate. Heliodon shows estimations for the solar irradiance available without obstacles, solar irradiance received, solar energy available without obstacles, solar energy received, percentage of lighted surface and solar irradiance losses. It is important to remark than using this tool the results are referred to the two faces of the mesh.

c) Solar Panel

This tool is similar to the mesh but with two differences. In this case, besides choosing the dimensions, it is possible to change the azimuth angle of the panel and its slope. The magnitudes obtained are the same as using the mesh, but with the solar panel, they are referred to only one of its faces.

d) Case studied. Solar panel on a façade of the urban model

For the study of this case, a solar panel is introduced on the façade 1 in Fig.23 of the urban environment of Vista Alegre square. Its data input belongs to the city of Cordoba, shown in Table.5. The slope of the panel is 90° and the azimuth angle is 65°, the same as the façade. The façade selected is shown in Fig.23 having a surface of 1000.29 m^2.

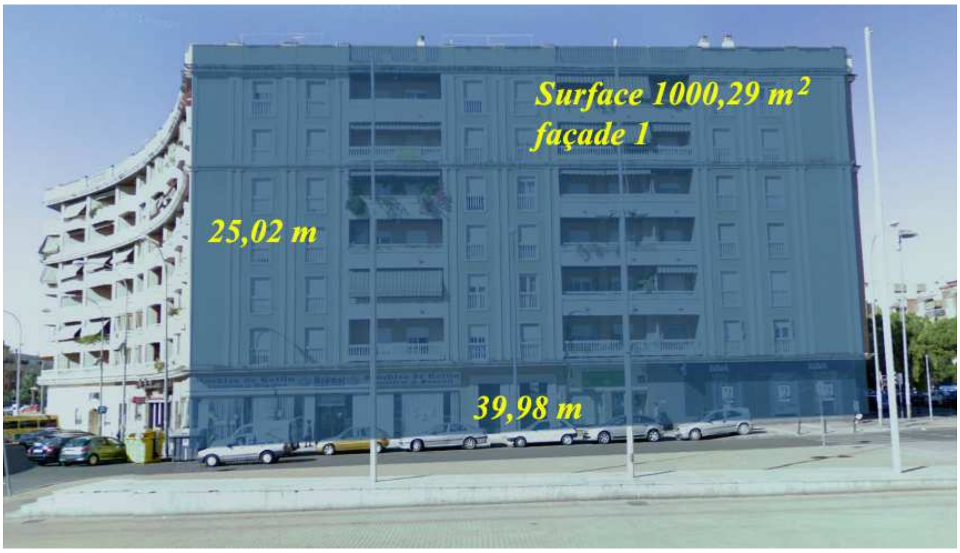

Figure 23: Dimensions of the façade 1

In order to get accurate estimations, the resolution of the solar panel is 90384 triangles, having each one an edge length of 0.16 m. For the spring equinox the results are shown in the following epigraphs.

Solar irradiance

For the façade 1, in Fig.24, the solar irradiance received is shown in blue. The irradiance starts at 6:00 solar time and finishes at 11:12 solar time. In Fig.24 the orange area represents the part of irradiance not received due to the shadows produced by the neighboring buildings. The maximum value for irradiance is reached at 8:23 solar time, being 372.10 KW.

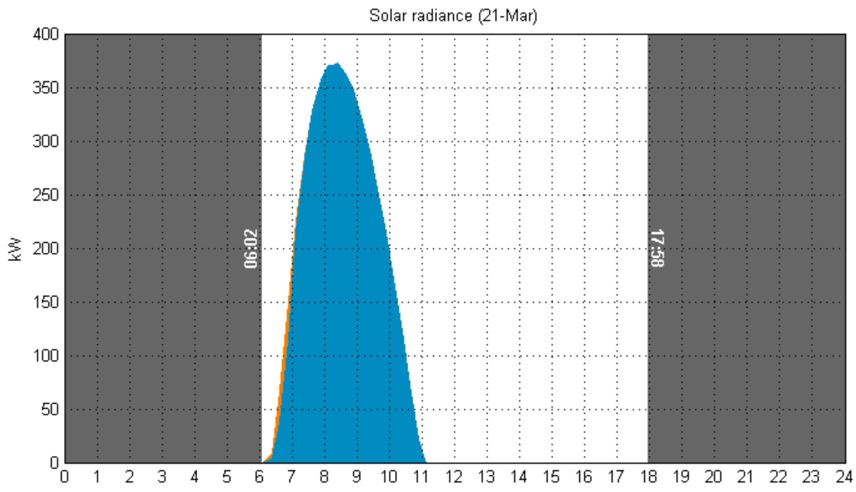

Figure 24: Solar irradiance on 21st of March on the façade 1

Solar radiation

The accumulated energy during the whole day is 1065.35 Kwh, having the losses by the shadows produced by the obstacles a value of 21.02 Kwh. It can be observed in Fig.25.

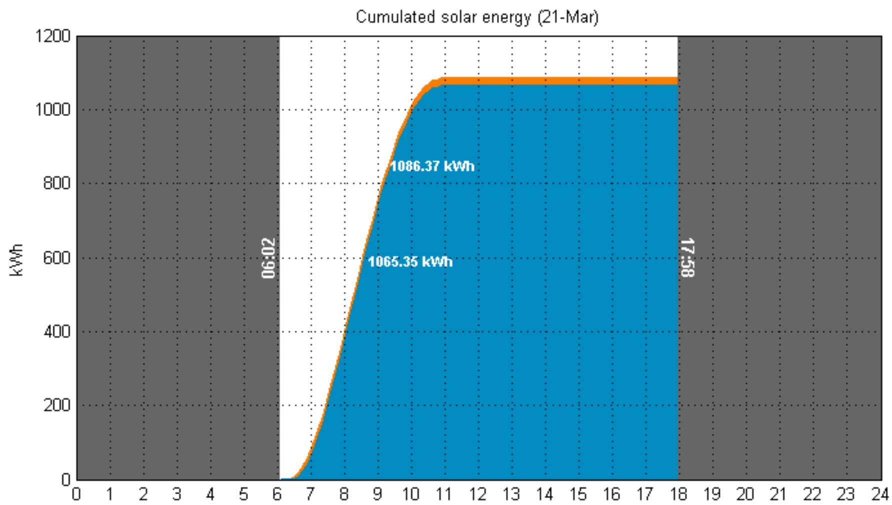

Figure 25: Daily solar radiation on 21st of March on the façade 1

Percentage of lighted surface

After the sunrise, the façade starts to be lighted, rising the 100% of the surface at 8:00 solar time. After 11:00 the façade is completely shaded as it can be seen in Fig.26.

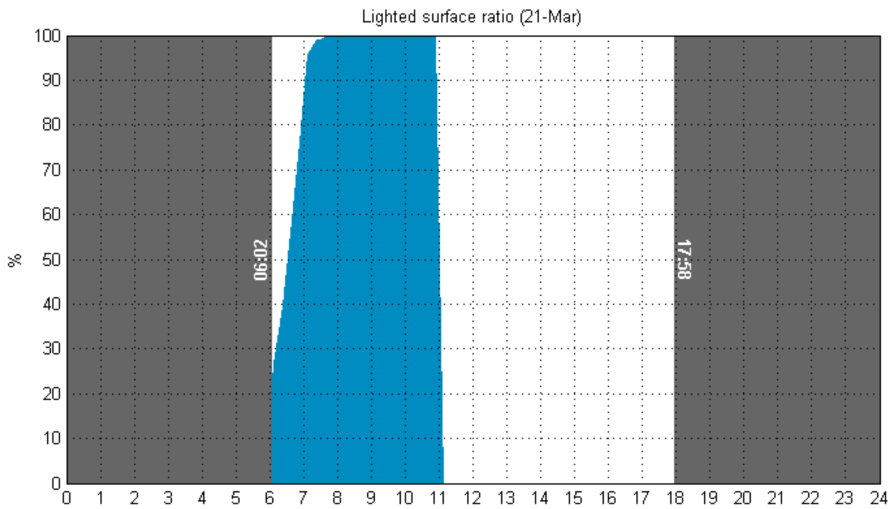

Figure 26: Percentage of lighted surface on 21st of March on the façade 1

Solar irradiance losses

In Fig.27, the moment in which the losses occur due to the shadows produced by the neighbor buildings is shown. This information is complementary to the results obtained in Fig.24 where it can be observed that the losses of irradiance happen between 6:00 and 7:00 solar time. It maximum value is 35.79 kW and it is reached at 6:53 solar time.

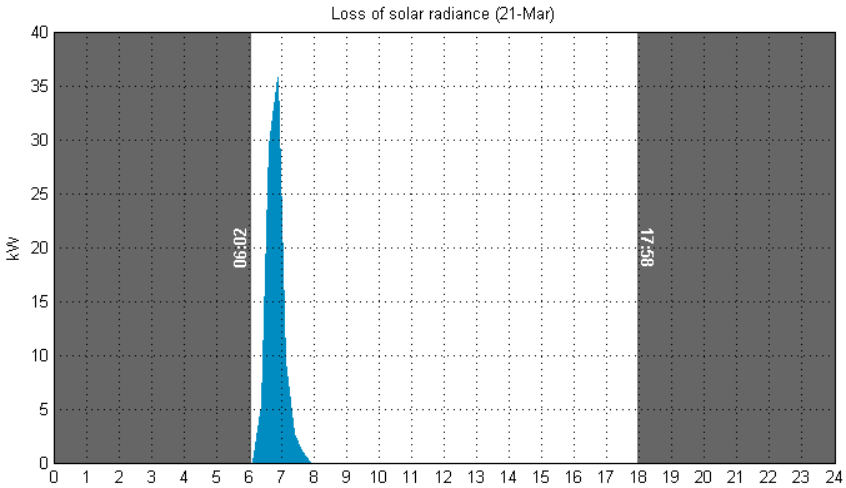

Figure 27: Losses of irradiance on 21st of March on the façade 1

4.3 Creation of a toolbox engineering software for the analysis of shadows, irradiance and solar radiation on buildings

In this project a collection of functions has been developed for calculating instantaneous shadows and irradiance, and daily radiant exposure, for every point of a façade in urban environments. With this information, for a representative period of time, flat owners could estimate by their own, the best localization for the panels and the expected electricity production. Microsoft Excel is an easy software tool, utilized by many people, so it represents a good alternative for commercial software. For this reason, the functions have been created using Visual Basic language in an Excel environment. This collection of functions represents an open toolbox, so any interested user can check the code and could create new functions to complete and increase the model.

4.3.1 Collection of Functions

In this epigraph, the functions created for the analysis the shadows, irradiance and daily solar radiation on façades in urban environments are introduced. Other simpler functions have been used and they belong to the SolarNet Collection. All of them are explained in the following sections and their computing code is collected in the Appendix A.

a) Shadow Function

This function uses Julian day, latitude, selected façade, solar time and two parameters, which indicate a point on the chosen façade. Each façade is represented by a local reference system with axis ρ and µ. Their values belong to the interval (0-1), with a step of 0.1, as it is shown in Fig.28. It means that there are 121 studied points in each façade.

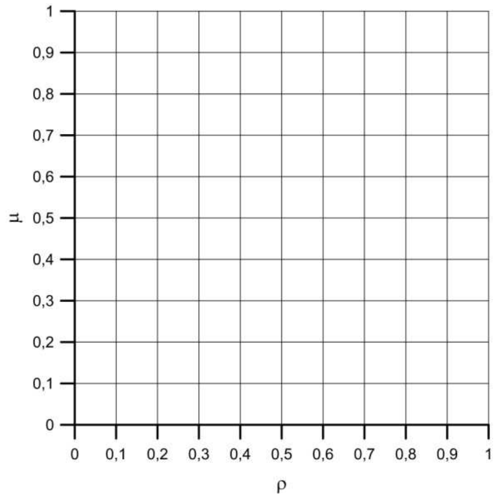

Figure 28: Representation of the façade by a grid

The value obtained with the Shadow Function will be 0 if the point is shaded and 1 if not. For calculating the state of the point, first of all, it is necessary to establish its Cartesian coordinates inside the global reference system of the urban environment. After that, the sun position will be determined for the Julian day, latitude and solar time selected.

At this point, the function will calculate the intersections between the straight line going form the sun to the point of study (sun-façade point) and the planes that contain the neighbor façades (Fig.29). To calculate the intersection point, a three equations system must be solved, Fig.30, and the values for a, b and c, Fig.30 will be determined. The studied point will be shaded if “a” is greater than cero and “b” and “c” belong to the interval (0-1).

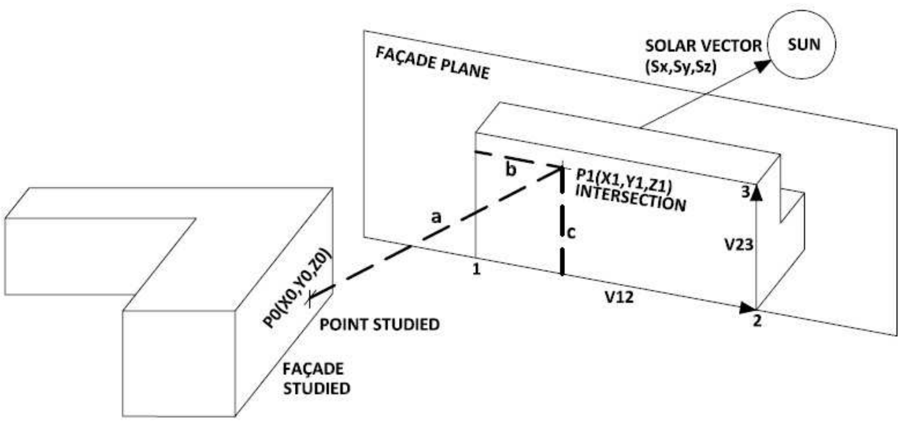

Figure 29: Representation of the geometric problem

$$\begin{pmatrix} X0 \\ Y0 \\ Z0 \end{pmatrix} + a\begin{pmatrix} Sx \\ Sy \\ Sz \end{pmatrix} = \begin{pmatrix} X1 \\ Y1 \\ Z1 \end{pmatrix} + b\begin{pmatrix} V12x \\ V12y \\ V12z \end{pmatrix} + c\begin{pmatrix} V23x \\ V23y \\ V23z \end{pmatrix}$$

Figure 30: Equations system

If the function checks that one intersection point is inside a façade of an adjacent building, it will stop and its value will be 0, condition 1 in Fig.31. This response will be also 0, if the selected solar time is before sunrise or after sunset, condition 2 in Fig.31. The last condition for shading is that the normal vector of the external face of the façade cannot form an obtuse angle with the solar vector, condition 3 in Fig.31.

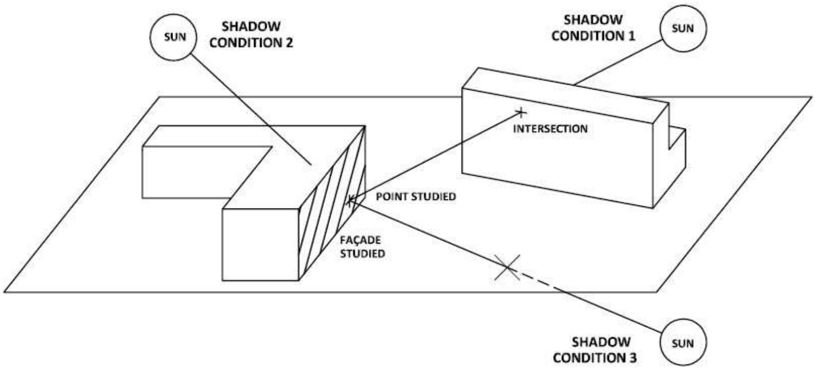

Figure 31: Representation of the shading conditions

If none of these conditions happens, the output value for the Shadow Function will be 1 and the studied point will be lighted.

b) Instantaneous Irradiance Function

The Instantaneous irradiance function is a routine created with the aim of estimating the irradiance (W/ m^2) in a particular point of the chosen façade and for a specific solar time. The data input of this function is the latitude, the Julian day, the solar time, the parameters ρ and μ of the local reference system of the façade, the selected façade, the global radiation on an horizontal surface for the specific month and the albedo. This function uses the expression (5) according to the model developed by Collares-Pereira [15].

$$I = \frac{\vec{n}.\vec{s}}{\vec{k}.\vec{s}} Ib + \frac{1+\vec{n}.\vec{k}}{2} Id + \frac{1-\vec{n}.\vec{k}}{2} \rho(Ib + Id) \qquad (5)$$

Where

$\vec{n}$: Normal vector of the external face of the façade

$\vec{s}$: Solar vector

$\vec{k}$: Normal vector of the tangent plane of the studied place

ρ : Albedo

Ib : Instantaneous direct irradiance on horizontal surface

Id : Instantaneous diffuse irradiance on horizontal surface

The first term of the expression (Eq.5) represents the direct irradiance due to the sun on the particular point. The second term corresponds to the diffuse component and the third one to the reflected irradiance. Thus, as the direct component is zero only in the case in which the particular point of the façade is shaded, for the programming of the expression, the result of the shadow function is used, being 0 if the point is shaded and 1 if it is lighted.

The expression (5) presents the problem that for the estimation of the diffuse and the reflected component, only the vectors $\vec{n}$ and $\vec{k}$ are used. As a consequence, this expression ignores the influence on the irradiance that the height of the point over the ground has. The experience shows that a point situated on the highest part of a façade has much more irradiance that another located on a lower place, because the first one sees a bigger celestial surface portion. To simulate this effect, a routine called Sky View Factor Function has been created and the values of the diffuse and reflected component will depend on it (Eq.5).

c) Sky View Factor Function

In a completely shaded façade, the different points do not have the same level of irradiance. This happens because the points with a greater elevation over the ground see a bigger part of the surface celestial than the points with a lower elevation, which see more obstacles. As a consequence, the higher points have a greater component of diffuse irradiance than the other ones. The points situated in a lower height have a greater reflected component due to the neighbor façades. As the importance of the diffuse component is bigger than the reflected one, the result is that the points with greater elevation have higher values of irradiance. To simulate this phenomenon, the Sky View Factor (SVF) Function is created.

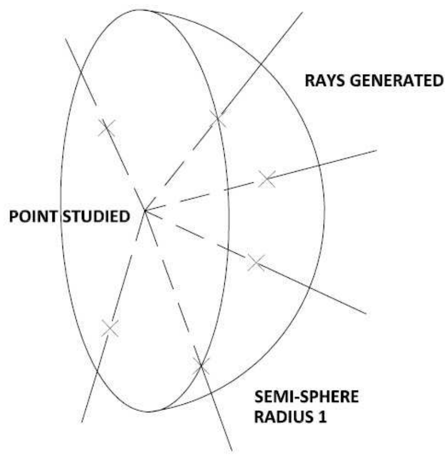

Figure 32: Generation of the rays on the selected point

This function generates 1012 rays in different directions (Fig.32), for each one of the 121 points of the selected façade. Afterwards, it studies for each ray, if it intersects with the ground or with an adjacent building, or if it has a celestial surface direction. The function counts the amount of rays with sky direction and calculates the Sky View Factor as the proportion of that amount and the total of rays generated. This value and its complementary are used for estimating in a more real way, the diffuse and reflected component. Consequently, the expression for the Instantaneous Irradiance changes (Eq.6), using the sky View Factor.

$$I = \frac{\vec{n}.\vec{s}}{\vec{k}.\vec{s}}.Ib + SVF.Id + (1 - SVF).\rho.(Ib + Id) \qquad (6)$$

Where SVF is the Sky View Factor.

This factor depends exclusively on the geometry of the urban environment introduced and on the studied point, so it is constant along the time

d) Daily Solar Radiation Function

The daily solar radiation function estimates, for each particular point of the selected façade, the accumulated energy (kWh/m^2) for a particular day of the year. This function shows the most important value, that a house owner must know to study the viability invest of a photovoltaic or solar thermal installation, set on a piece of his façade. This routine uses the instantaneous irradiance function, calculating its value each 6 minutes along the 24 hours of a day and multiplying the value obtained for 0.1 hour, getting the energy for that interval. Afterwards, this function adds the values of all intervals, in order to obtain the energy for a whole day.

e) Other simpler functions

During the programming of the four functions introduced, others simpler routines have been used with the objective of reducing the execution time of Excel. These simpler functions are available in the SolarNet Collection for the interested users. All of them are cited below.

Normal Function

This Function estimates the normal vector to the external face of the selected façade since the global coordinates of three of its corners, introduced necessarily with a counterclockwise direction. This routine has been created specifically for this software application for decreasing the execution time.

Solar Vector Function

This function belongs to the SolarNet Collection. For a Julian day, solar time and latitude, this function calculates the three components of the solar position vector. It has been used for the analysis of shadows and instantaneous irradiance.

Instantaneous direct radiation function

Its data input is Julian day, solar time, latitude and global radiation on horizontal surface. With this information, this routine calculates the instantaneous direct radiation on horizontal surface. This function belongs to the SolarNet Collection and has been utilized for the estimation of the Instantaneous Irradiance.

Instantaneous diffuse radiation function

This routine estimates the value of the instantaneous diffuse radiation on horizontal surface for a particular Julian day, solar time, latitude and global radiation on horizontal surface. This function has been used for programming the instantaneous irradiance function and belongs to the SolarNet Collection.

Inverse matrix function

For a specific matrix, this routine calculates its inverse matrix by the Gauss method. This function has been utilized for solving the three equations system of the ray and façade intersection problem that is needed to determinate in the Shadow Function and Sky View Factor Function.

4.3.2 Data Input

For the introduction of the urban environment studied, the façades which form the different buildings must be introduced. As a consequence, the cartography of the studied area and the height of the buildings must be known. Each one of the façades must be introduced using the global coordinates of three corners in counterclockwise direction. That is quite important because the normal vector of the façade must be positive in the direction of its external face. The introduction of the global coordinates is made using the available space of the worksheet of Excel, having established a maximum of 100 façades in the programming. This limit can be easily changed for the introduction of larger urban environments.

Any plane with any surface can be introduced in this application. That is very useful in the case in which the user wants to calculate the solar radiation on curve planes such as vaults or curve façades. They can be approximated with several tangent planes.

Each one of the introduced façades is identified with a number from 1 to 100. With its number, the user could select the façade for its studying in a fast and easy way. The functions created, will read the coordinates of the façades for obtaining the results.

Once the urban model is introduced, the rest of the data input is written using the corresponding cells. The data input required is:

- Julian day
- Latitude
- Solar time
- Façade selected
- Global radiation on horizontal surface
- Albedo

4.3.3 Data Output

The programmed functions, Shadow function, Sky View Factor function, Instantaneous Irradiance function and Daily Solar Radiation function give the results for a specific point of the selected façade. To improve the data output, each façade is shown as a two-dimension reference system. Its axes are divided in ten parts, from 0 to 1 and with a step of 0.1. As a consequence, the selected table is represented in Excel by a two-dimension table with 121 points. For more detailed results, the step can be easily changed in the programming. For example, using a step of 0.05, the façade would be represented by 441 points.

In the worksheet in Excel, four control buttons manage the creation of the tables. Pushing the respective button, the shadow table, sky view factor table, instantaneous irradiance table and daily solar radiation table are generated.

4.3.4 Management of the results

Once the four tables are generated and with the aim of improving the comprehension of the results, a contour map software is used. In this case the software chosen is Surfer Software. Its management is quite easy and fast for the creation of this kind of maps. In addition, using a picture of the selected façade, for example extracted from Google StreetView, both, the contour map and the picture can be superposed, showing in a very clear way the results obtained.

4.3.5 Practical Case. Solar radiation contour map

In this epigraph, a practical case using the software application which has been developed in Visual Basic of Excel is introduced. In order to compare the results obtained with the functions created, with the results of SunPath software and Heliodon software, the urban model will be the same one, Vista Alegre neighborhood. The different buildings are introduced in Excel by the plane that each façade forms. Using the cartography of Vista Alegre neighborhood in AutoCad, a specific number is assigned to every façade. In this way, the identification of each one is simple and fast. Façades (3-6) and (12-14) in Fig.33 are used for representing two curved planes by an approximation.

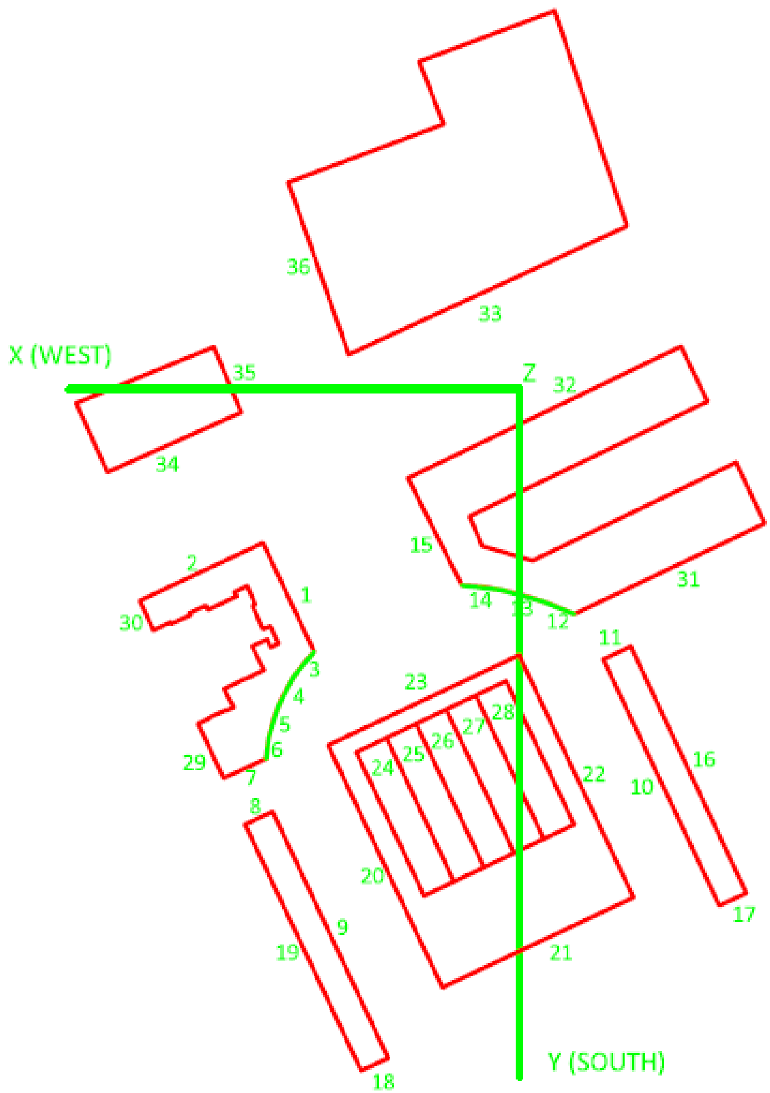

Figure 33: Cartography of the façades which form the urban model

The thirty-six façades compounding the neighborhood are introduced in Excel using the reserved cells and by their respective numbers. XYZ (Fig.34) are the coordinates of the three corners of each façade, introduced in counter clockwise direction. The urban model data input is shown in Fig.34.

FAÇADES	X1	Y1	Z1	X2	Y2	Z2	X3	Y3	Z3
1	68,2	87,19	0	85,15	50,98	0	85,15	50,98	25,02
2	85,15	50,98	0	126,01	70,2	0	126,01	70,2	25,02
3	74,87	95,44	0	68,2	87,19	0	68,2	87,19	25,02
4	79,94	105,02	0	74,87	95,44	0	74,87	95,44	25,02
5	83,09	115,39	0	79,94	105,02	0	79,94	105,02	25,02
6	84,05	122,55	0	83,09	115,39	0	83,09	115,39	25,02
7	98,2	128,99	0	84,05	122,55	0	84,05	122,55	25,02
8	81,84	140,15	0	90,98	144,45	0	90,98	144,45	24,12
9	43,58	221,91	0	81,84	140,15	0	81,84	140,15	24,12
10	-27,81	89,72	0	-66,24	171,38	0	-66,24	171,38	24,37
11	-36,95	85,42	0	-27,81	89,72	0	-27,81	89,72	24,37
12	-7,5	70,3	0	-18,11	74,59	0	-18,11	74,59	24,89
13	6,35	66,49	0	-7,5	70,3	0	-7,5	70,3	24,89
14	19,03	65,14	0	6,35	66,49	0	6,35	66,49	24,89
15	37,04	29,45	0	19,03	65,14	0	19,03	65,14	26,45
16	-75,21	167,18	0	-36,95	85,42	0	-36,95	85,42	24,37
17	-66,24	171,38	0	-75,21	167,18	0	-75,21	167,18	24,37
18	52,55	226,11	0	43,58	221,91	0	43,58	221,91	25,02
19	90,98	144,45	0	52,55	226,11	0	52,55	226,11	24,12
20	63,46	118,16	0	25,6	198,53	0	25,6	198,53	10,57
21	25,6	198,53	0	-37,86	168,55	0	-37,86	168,55	10,57
22	-37,86	168,55	0	0,17	88,17	0	0,17	88,17	10,57
23	0,17	88,17	0	63,46	118,16	0	63,46	118,16	10,57
24	54,16	120,4	10,57	31,63	168,03	10,57	21,68	163,32	17,25
25	44,22	115,69	17,25	21,68	163,32	17,25	11,74	158,62	20,2
26	34,28	110,98	20,2	11,74	158,62	20,2	1,8	153,92	20,2
27	-8,15	149,21	17,25	14,4	101,55	17,25	24,34	106,27	20,2
28	-18,17	144,47	10,57	4,38	96,81	10,57	14,4	101,55	17,25
29	106,61	110,98	0	98,2	128,99	0	98,2	128,99	25,02
30	126,01	70,2	0	121,44	80,03	0	121,44	80,03	25,02
31	-18,11	74,59	0	-81,32	44,46	0	-81,32	44,46	24,89
32	-53,66	-14,18	0	37,04	29,45	0	37,04	29,45	26,45
33	56,74	-11,51	0	-35,79	-54,05	0	-35,79	-54,05	26,99
34	136,69	27,45	0	92,26	7,67	0	92,26	7,67	26,16
35	92,26	7,67	0	101,43	-14,07	0	101,43	-14,07	26,16
36	76,65	-68,54	0	56,74	-11,51	0	56,74	-11,51	26,99

Figure 34: Introduction of the façades in Excel

In Fig.35 the cells for the data input are shown. The selected façade is the number one in Fig.33. The study is made for March 21st and for the latitude of Cordoba. The shadows and the instantaneous irradiance are studied at 6:24 solar time of that day. The value of the albedo is 0.2 by default.

Julian Day	Latitude	Solar Time	Façade	GRHS	Albedo
80	37,88	-5,6	1	14158000	0,2

Figure 35: Introduction of the data in Excel

Once the data input is selected, using the control buttons, the tables associated to the results of each function are generated. Every table represents the study façade by 121 points in its local reference system. In Fig.36 the local reference system for the façade 1 is shown.

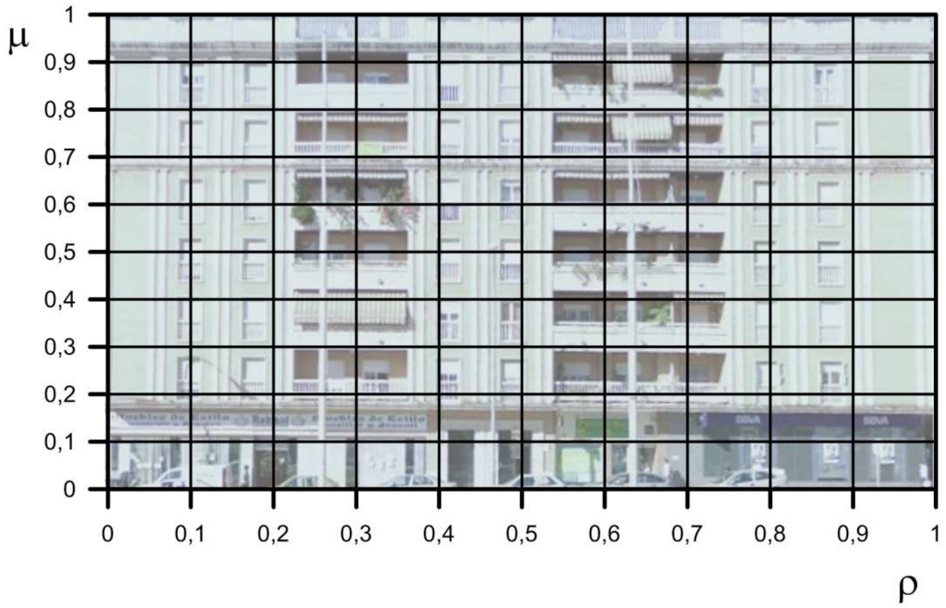

Figure 36: Local reference system and grid for the façade 1

Pushing the Sky View Factor Function button, the results of this function for the 121 points of the façade is generated in Excel (Fig.37). The points situated in the higher parts of the façade have a greater sky view factor. It means that the diffuse component of the solar irradiance is bigger for these points because they see a larger portion of sky than the rest. The values in this table are constant along the year, since the SVF is a geometric parameter that does not depend on the time.

SKY VIEW FACTOR FUNCTION

1	0,497	0,500	0,500	0,500	0,500	0,500	0,500	0,500	0,500	0,500	0,499
0,9	0,455	0,479	0,478	0,477	0,478	0,477	0,477	0,476	0,477	0,477	0,476
0,8	0,437	0,459	0,458	0,459	0,458	0,459	0,457	0,457	0,458	0,457	0,458
0,7	0,418	0,439	0,438	0,438	0,439	0,439	0,436	0,437	0,440	0,441	0,442
0,6	0,399	0,419	0,417	0,419	0,417	0,419	0,420	0,420	0,426	0,424	0,427
0,5	0,384	0,405	0,403	0,406	0,402	0,405	0,401	0,403	0,410	0,409	0,412
0,4	0,366	0,385	0,384	0,389	0,387	0,390	0,386	0,390	0,395	0,393	0,398
0,3	0,341	0,360	0,361	0,364	0,363	0,366	0,367	0,371	0,379	0,378	0,383
0,2	0,324	0,345	0,343	0,346	0,347	0,349	0,347	0,353	0,361	0,361	0,368
0,1	0,304	0,327	0,326	0,331	0,331	0,338	0,336	0,342	0,352	0,350	0,355
0	0,295	0,308	0,307	0,311	0,308	0,318	0,316	0,324	0,334	0,333	0,343
	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

Figure 37: Sky View Factor for the façade 1

In Fig.38 the results for the Shadow function are shown. For the solar time selected, this table shows the points that are shaded (0) or lighted (1). At 6:24 solar time, there are two shaded regions and one lighted. The neighbor buildings produce shadows in the lateral parts of the selected façade and only the central portion and the points with a greater height are lighted.

SHADOW FUNCTION

1	1	1	1	1	1	1	1	1	1	1	1
0,9	1	1	1	1	1	1	1	1	1	1	1
0,8	1	1	1	1	1	1	1	1	0	0	0
0,7	1	1	1	1	1	1	1	0	0	0	0
0,6	0	0	0	1	1	1	0	0	0	0	0
0,5	0	0	0	1	1	1	0	0	0	0	0
0,4	0	0	0	1	1	1	0	0	0	0	0
0,3	0	0	0	1	1	1	0	0	0	0	0
0,2	0	0	0	1	1	1	0	0	0	0	0
0,1	0	0	0	1	1	1	0	0	0	0	0
0	0	0	0	1	1	1	0	0	0	0	0
	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

Figure 38: Shadows for the façade 1

The result of the Instantaneous Irradiance function at 6:24 solar time for the façade 1 is shown in Fig.39. The results obtained for every point are expressed in W/m^2 and they depend on the Sky View Factor Function values (Fig.37). It is important to mention that the points situated in the lighted region (Fig.38) do not have a constant value of irradiance. This also happens for the two shaded regions and it is due to the Sky View Factor, which provides different values for the diffuse and reflected component of the irradiance.

INSTANTANEOUS IRRADIANCE FUNCTION (W/m2)

1	54,86	54,94	54,94	54,94	54,94	54,94	54,94	54,94	54,94	54,94	54,92
0,9	53,67	54,36	54,34	54,31	54,34	54,31	54,31	54,28	54,31	54,31	54,28
0,8	53,17	53,81	53,78	53,81	53,78	53,81	53,73	53,73	20,63	20,58	20,63
0,7	52,65	53,23	53,20	53,20	53,23	53,23	53,15	20,03	20,11	20,14	20,16
0,6	18,98	19,53	19,47	52,68	52,62	52,68	19,56	19,56	19,72	19,67	19,75
0,5	18,56	19,14	19,09	52,32	52,21	52,29	19,03	19,09	19,28	19,25	19,34
0,4	18,04	18,59	18,56	51,85	51,79	51,87	18,62	18,73	18,87	18,81	18,95
0,3	17,34	17,87	17,90	51,13	51,10	51,18	18,06	18,17	18,42	18,40	18,53
0,2	16,87	17,45	17,40	50,63	50,66	50,71	17,51	17,68	17,90	17,90	18,09
0,1	16,32	16,96	16,93	50,22	50,22	50,41	17,21	17,37	17,65	17,59	17,73
0	16,07	16,43	16,40	49,66	49,58	49,86	16,65	16,87	17,15	17,12	17,40
	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

Figure 39: Instantaneous irradiance for the façade 1

The last table is the Daily Radiation Function table (Fig.40). For every point of the façade 1, the solar radiation along the day 21st of March is calculated. The results are shown in KWh/m^2 and they are estimated with a precision of 6 minutes. The influence of the sky view factor is also important on the solar radiation since it directly depends on the irradiance.

DAILY RADIATION FUNCTION (KWh/m2)

1	1,59	1,60	1,60	1,60	1,60	1,60	1,60	1,59	1,59	1,59	1,59
0,9	1,48	1,54	1,54	1,54	1,54	1,54	1,54	1,53	1,53	1,53	1,53
0,8	1,43	1,49	1,49	1,49	1,49	1,49	1,48	1,48	1,48	1,47	1,48
0,7	1,38	1,43	1,44	1,44	1,44	1,43	1,42	1,42	1,42	1,43	1,43
0,6	1,33	1,38	1,38	1,39	1,38	1,38	1,38	1,38	1,38	1,37	1,38
0,5	1,29	1,34	1,34	1,36	1,34	1,35	1,33	1,33	1,34	1,32	1,33
0,4	1,23	1,29	1,29	1,31	1,31	1,31	1,29	1,29	1,30	1,28	1,29
0,3	1,17	1,22	1,22	1,24	1,24	1,25	1,24	1,24	1,26	1,24	1,23
0,2	1,12	1,17	1,17	1,19	1,20	1,20	1,19	1,19	1,21	1,20	1,19
0,1	1,06	1,12	1,12	1,14	1,15	1,18	1,16	1,16	1,18	1,16	1,16
0	1,03	1,07	1,07	1,09	1,09	1,12	1,11	1,12	1,13	1,12	1,13
	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1

Figure 40: Daily solar radiation for the façade 1

The results of the Daily Radiation Function Table can be set in columns and exported to Surfer software. Using this program, the daily solar radiation contour map for the façade 1 and for the day 21st of March is created and shown in Fig.41. In this map, the mayor and minor contour lines show the points of the façade with equal solar radiation. The blue-red color scale displays the value of the solar radiation on every region of the façade 1.

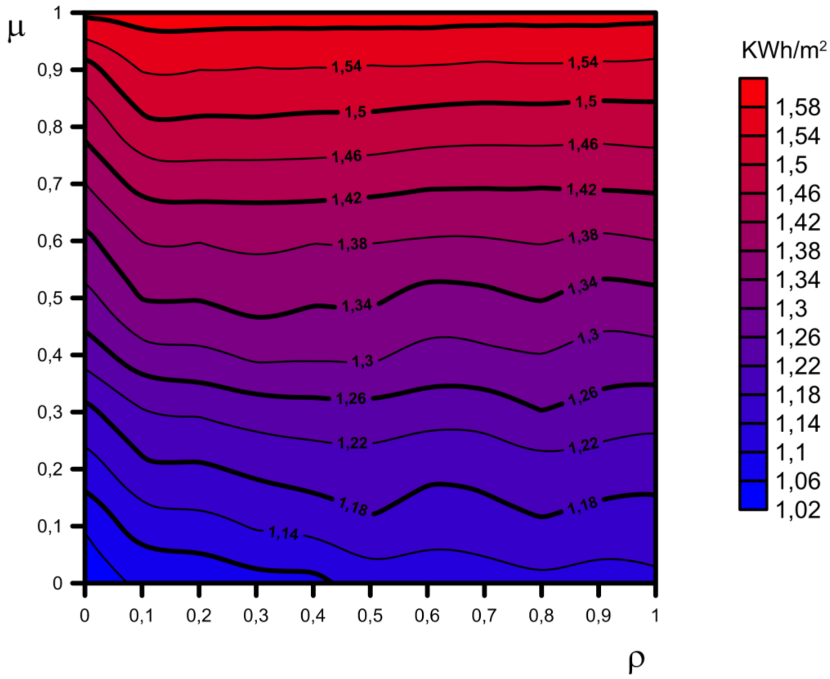

Figure 41: Daily solar radiation contour map for the façade 1

However, the axes of the contour map do not have the same proportion than the façade 1, so it does not represent an intuitive tool. In order to improve the visualization of the outcome, the contour map is adapted to a picture of the façade 1, obtained from Google StreetView (Fig.42). This solar radiation contour map is also interesting for the study of shadows. Horizontal lines represent homogenous shadows caused by an unique neighbor building. When the contour lines ascend, the time that this part of the façade has been shaded is greater than when the contour lines descend.

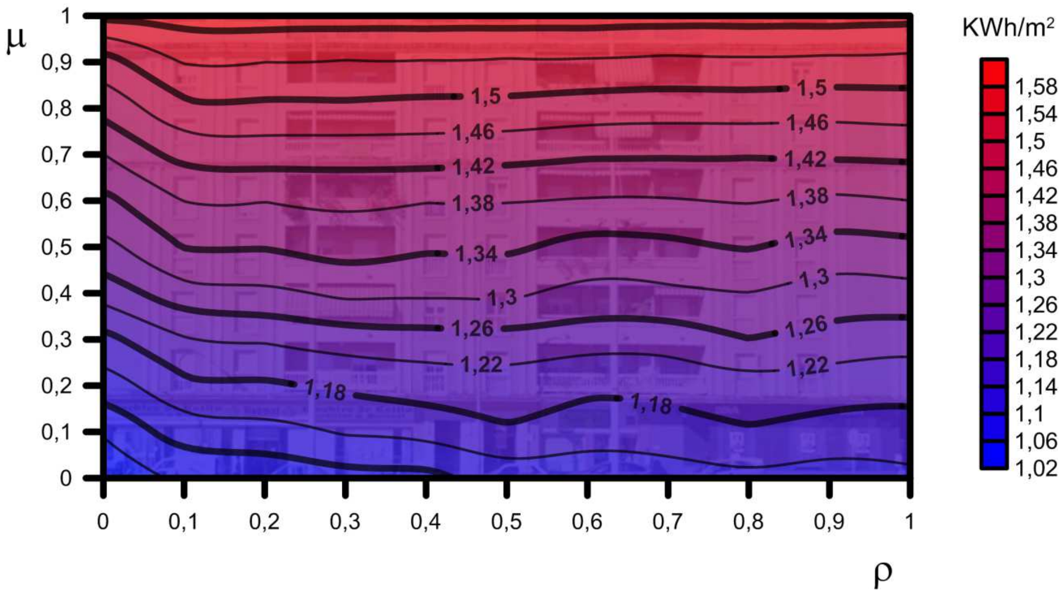

Figure 42: Superposition of the contour map and the picture of the façade 1

For the studied case, the analysis of the vertical and horizontal gradient of the solar radiation is possible by the study of two profiles (Fig.43). For a vertical profile ρ=0.6, the result shows that the daily radiation keeps a lineal variation, so its gradient is constant (Fig.44). For a horizontal profile μ=0.5, the graphic generated (Fig.45) shows that its gradient is quite variable. This phenomenon is due to the fact that the shadows on the façade 1 are produced by different buildings.

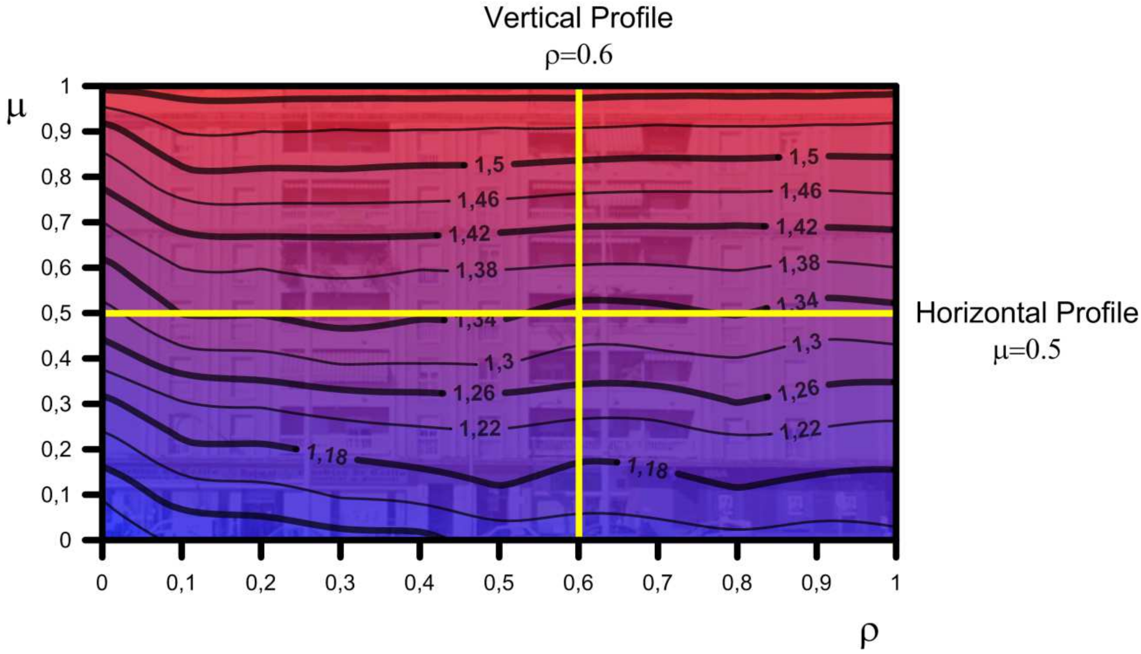

Figure 43: Tracing of the vertical and horizontal profiles on the contour map of the façade 1

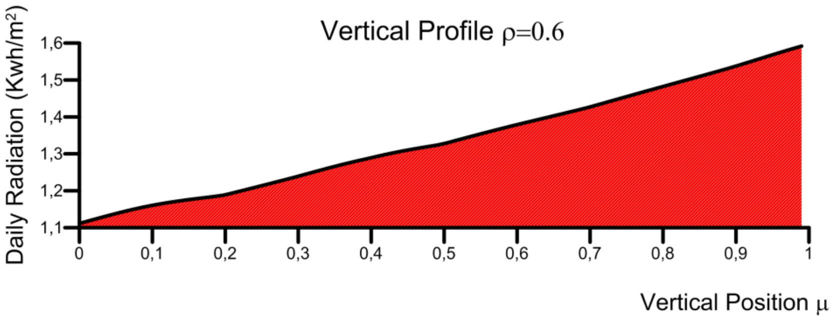

Figure 44: Representation of the vertical profile ρ = 0.6

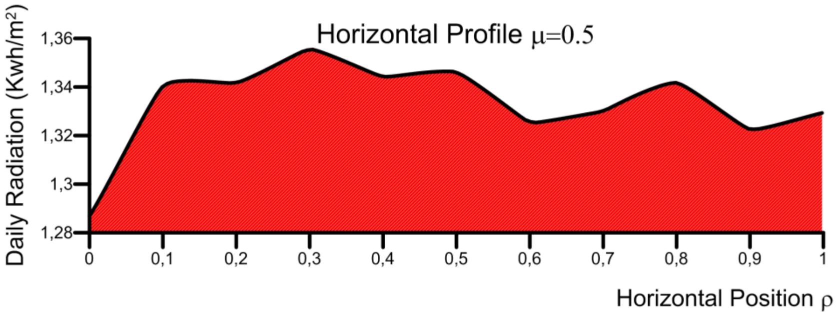

Figure 45: Representation of the horizontal profile μ = 0.5

5 COMPARISON OF RESULTS AND DISCUSSION

After having shown the results of the shadows, irradiance and radiation, which have been estimated by the functions developed in Visual Basic language, the aim of this epigraph is to know the differences between them and the results obtained with the Heliodon software.

For this reason, the irradiance on the façade 1 (Fig.33) of the urban model on 21st of March, is estimated using the Heliodon software and the Irradiance Function developed in Visual Basic language. The values of the Irradiance Function have been calculated by the arithmetic mean of the 121 points of the façade. In order to obtain accurate curves, the irradiance has been estimated every 15 minutes for both, Heliodon software and Irradiance Function. The curves generated are shown in Fig.46.

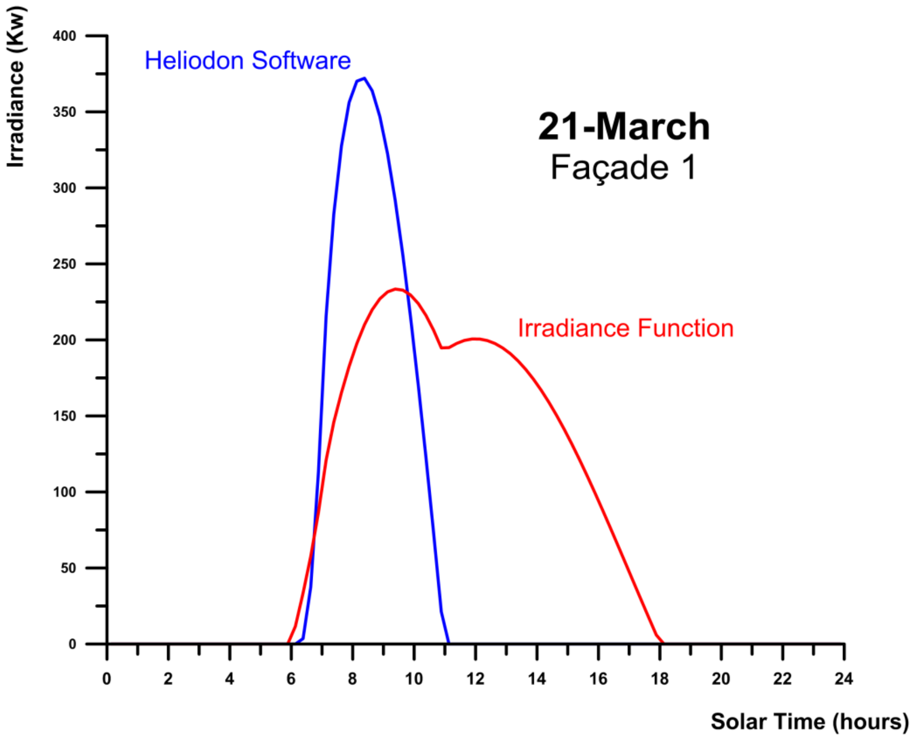

Figure 46: Comparison of the irradiance obtained with Heliodon and the Irradiance Function

There are two main differences between the curves corresponding to the Heliodon software and the Irradiance function:

- For the façade 1, Heliodon estimates that the irradiance is different to zero only between 6:00 and 11:00 and that means that the façade is completely shaded the rest of the time. However, the Irradiance Function shows that there is irradiance between 6:00 and 18:00. This difference is due to the fact that the physical model of Heliodon only considers the direct component of the irradiance, while the Irradiance Function also considers the values of the diffuse and reflected components. The physical model used by the Irradiance Function is the Collares-Pereira model which offers results that are closer to the reality.

- For the façade 1, Heliodon obtains the maximum value of the irradiance at 8:00. Its value is 375 kW while for the Irradiance Function this maximum is 230 kW. This difference is due to the fact that Heliodon uses a simple physical model only based on the estimation of the direct irradiance, the zenithal angle, the atmospheric pressure and the altitude of the selected point. This model does not use the global radiation on horizontal surface in the studied area and neither the effect of the clouds. The Irradiance Function, based on the Collares-Pereira model, offers more realistic results.

```
SUNRISE AND SUNSET TIMES USING PROGRAM SUNPATH

FOR: Cordoba, España   RUN DATE:  06-21-2013  10:49:27
LATITUDE = 037°53'05"LONGITUDE = 004°46'44"
TIME ZONE = GMT+01:00*
DATE SELECTED FOR THIS CALCULATION: MONTH: 3 DAY: 21 JUL DAY= 80 YEAR 2013
*NOTE: FOR THIS DATA
TIMES GIVEN ARE IN DECIMAL HOURS PAST MIDNIGHT

*****  SUN RISE TIME IS AT 8:19:36 DAYLIGHT SAVING TIME *****
       |CIVIL  CIVIL  |SOLAR  SOLAR  |SOLAR  ALTITUDE |SOLAR    AZIMUTH
MO DA JUL|HOUR  HR:MI:SE|HOUR  HR:MI:SE|DEGREE  DEG:MI:SE|DEGREE    DEG:MI:SE
 3 21  80| 8.32  8:19:36|5.893  5:53:35| -.2675  -0:16:03| 88.4532  88:27:11
```

Figure 47: Sunrise on 21st of March in Cordoba

Using the SunPath software, the sunrise on 21st of March for the studied urban model can be estimated in a very precise way. The sunrise happens at 5:53:35 solar time (Fig.47). This also represents another difference in the quality of the results obtained by Heliodon and the Irradiance Function, since as it can be seen in Fig.46, the Irradiance Function shows a sunrise more accurate than Heliodon.

In Fig.48 the daily solar radiation on the façade 1, on 21st of every month of the year estimated by Heliodon and the Daily Radiation Function is shown. As it can be seen, only in May the value of the radiation is greater using Heliodon. In the rest of the months, the Daily Radiation Function offers greater values. This fact happens because during the spring, the amount of hours in a day with sun increases. As the maximum value of irradiance obtained with Heliodon is much greater than the Irradiance Function one, the accumulated energy on 21st of May is bigger with Heliodon. This influence of the maximum irradiance and the amount of hours of sun can be easily appreciated in Fig.48 where the results using both physical models are similar during the spring. The contrary effect occurs during the summer and autumn when the amount of hours of sun is decreasing.

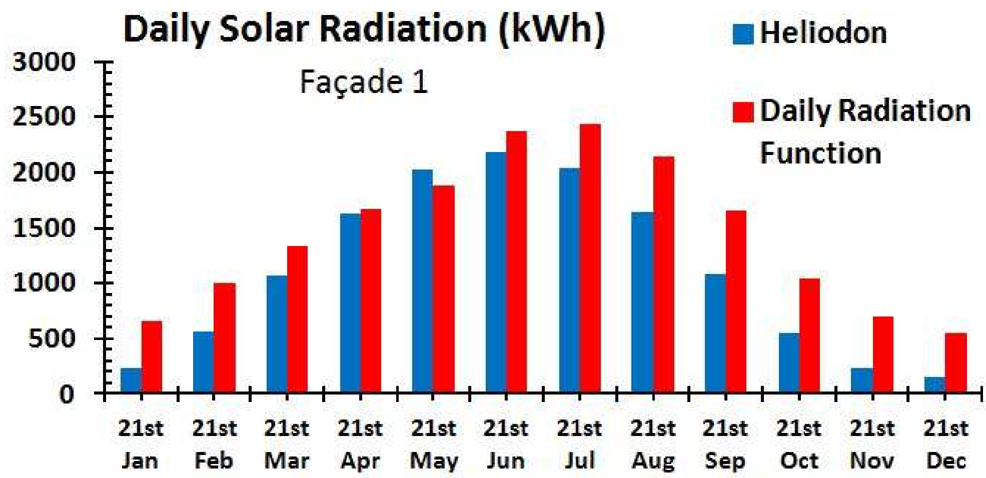

Figure 48: Comparison of the daily solar radiation obtained with Heliodon and with the Daily Radiation Function

Although using the Heliodon software, the maximum value of irradiance is greater than using the Irradiance Function, the accumulated energy is in general bigger for the Daily Radiation Function. This fact is due to the consideration of the diffuse and reflected irradiance in the software application developed in Visual Basic language based on the Collares-Pereira model.

6 CONCLUSIONS

In this project an open software for the analysis of instantaneous shadows, irradiance and daily solar radiation in urban environments has been developed. Using this application, it is possible to study the best places of the urban elements, such as façades or roofs, to set a photovoltaic or a solar thermal installation. This software represents an useful tool to implant electricity generation systems in the context of the distributed renewable energies. The most relevant conclusions can be summarized as follows:

- The functions created using Visual Basic language, provide an easy way of studying the solar radiation in urban environments.
- The introduction of the urban model is fast, using only 3 corners of each façade, and the output data management allows the creation of solar radiation contour maps on facades in a very fast way.
- The results obtained using the functions created show very accurate data since they are based on the physical model of Collares-Pereira [15], which uses the global radiation on horizontal surface and takes into account the direct, diffuse and reflected irradiance.
- The effect of the obstacles in the reflected and diffuse irradiance by the Sky View Factor allows obtaining values of irradiance and solar radiation more accuracy.
- The daily solar radiation contour maps on facades allow knowing in a very accurate way, the most appropriate points to set photovoltaic or solar thermal systems. Furthermore others applications such as the study of daylighting inside rooms or the effect of the neighbor buildings in the solar rights are possible.
- The functions created, represent an open toolbox software. Interested users could modify the computing code to adapt and use the subroutines for the resolution of others problems of solar radiation and daylighting.

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APPENDIXES

APPENDIX A. Computing code of the functions and the subroutines

SHADOW FUNCTION

The data input of this function is:

- Latitude, in sexagesimal degrees
- Julian day
- Solar time in hours, from -12 to 12, being 0 at noon.
- Coordinates ρ and µ of the local reference system of the selected façade
- Selected façade, by its associate number
- Number of façades compounding the urban model

Its data output is "0" if the point of the façade is shaded and "1" if it is lighted. The computing code is shown below:

```
Function sombra(latitud, dia_juliano, hsolar, ro, mu, fachadaestudio, nparamentos, x1(), y1(), z1(), x2(),
y2(), z2(), x3(), y3(), z3())


Dim matriz_coeficientes(3, 3), terminos_independientes(3), matriz_inversa(3, 3), vector_sombreado(100)

Xest = x1(fachadaestudio) + ro * (x2(fachadaestudio) - x1(fachadaestudio)) + mu * (x3(fachadaestudio) -
x2(fachadaestudio))
Yest = y1(fachadaestudio) + ro * (y2(fachadaestudio) - y1(fachadaestudio)) + mu * (y3(fachadaestudio) -
y2(fachadaestudio))
Zest = z1(fachadaestudio) + ro * (z2(fachadaestudio) - z1(fachadaestudio)) + mu * (z3(fachadaestudio) -
z2(fachadaestudio))

producto = 1
Z = 0
fin = 0
Call normal(fachadaestudio, nx, ny, nz)
sx = vsolarx(dia_juliano, hsolar, latitud)
sy = vsolary(dia_juliano, hsolar, latitud)
sz = vsolarz(dia_juliano, hsolar, latitud)
escalar_ns = nx * sx + ny * sy + nz * sz

  If (escalar_ns < 0) Or (sz < 0) Then
      fin = 1
      producto = 0
End If
```

```
While ((Z < nparamentos) And (fin = 0))
      Z = Z + 1
      If (Z <> fachadaestudio) Then
         matriz_coeficientes(1, 1) = sx
         matriz_coeficientes(2, 1) = sy
         matriz_coeficientes(3, 1) = sz
         matriz_coeficientes(1, 2) = -(x2(Z) - x1(Z))
         matriz_coeficientes(2, 2) = -(y2(Z) - y1(Z))
         matriz_coeficientes(3, 2) = -(z2(Z) - z1(Z))
         matriz_coeficientes(1, 3) = -(x3(Z) - x2(Z))
         matriz_coeficientes(2, 3) = -(y3(Z) - y2(Z))
         matriz_coeficientes(3, 3) = -(z3(Z) - z2(Z))

         terminos_independientes(1) = x1(Z) - Xest
         terminos_independientes(2) = y1(Z) - Yest
         terminos_independientes(3) = z1(Z) - Zest

         Call INVMATRIZ(3, matriz_coeficientes, matriz_inversa, DET, NOINVERTIBLE)
         If NOINVERTIBLE = 0 Then
              parametro_a = matriz_inversa(1, 1) * terminos_independientes(1) + matriz_inversa(1, 2) *
              terminos_independientes(2) + matriz_inversa(1, 3) * terminos_independientes(3)
              parametro_b = matriz_inversa(2, 1) * terminos_independientes(1) + matriz_inversa(2, 2) *
              terminos_independientes(2) + matriz_inversa(2, 3) * terminos_independientes(3)
              parametro_c = matriz_inversa(3, 1) * terminos_independientes(1) + matriz_inversa(3, 2) *
              terminos_independientes(2) + matriz_inversa(3, 3) * terminos_independientes(3)

              If ((parametro_a > 0) And ((parametro_b > 0) And (parametro_b < 1)) And   ((parametro_c > 0)
                        And (parametro_c < 1))) Then
                        vector_sombreado(Z) = 0
                        fin = 1
              Else
                        vector_sombreado(Z) = 1
              End If
          Else
              vector_sombreado(Z) = 1
          End If
      End If
Wend

For i = 1 To nparamentos
       If i <> fachadaestudio Then
            producto = producto * vector_sombreado(i)
       End If
Next i

sombra = producto

End Function
```

SHADOW TABLE SUBROUTINE

This subroutine is associated to the control button which generates the Shadow Table and makes use of the Shadow Function. The computing code is shown below.

```
Sub tablaSombras()

dia__juliano = Cells(11, 40).Value
latitud__ = Cells(11, 41).Value
hor_sol = Cells(11, 42).Value
param_ = Cells(11, 43).Value
radiacion_ = Cells(11, 44).Value
albedo_ = Cells(11, 45).Value

Dim x1(100), y1(100), z1(100), x2(100), y2(100), z2(100), x3(100), y3(100), z3(100)
nparamentos = 0

For i = 1 To 100

    x1(i) = Cells(18 + i, 5).Value
    y1(i) = Cells(18 + i, 6).Value
    z1(i) = Cells(18 + i, 7).Value
    x2(i) = Cells(18 + i, 8).Value
    y2(i) = Cells(18 + i, 9).Value
    z2(i) = Cells(18 + i, 10).Value
    x3(i) = Cells(18 + i, 11).Value
    y3(i) = Cells(18 + i, 12).Value
    z3(i) = Cells(18 + i, 13).Value

    If (x1(i) <> 0 Or y1(i) <> 0 Or z1(i) <> 0 Or x2(i) <> 0 Or y2(i) <> 0 Or z2(i) <> 0 Or x3(i) <> 0 Or  y3(i)
    <> 0 Or z3(i) <> 0) Then
        nparamentos = nparamentos + 1
    End If
Next i

For k = 0 To 10 Step 1
    For p = 0 To 10 Step 1
        Cells(22 - p, 25).Value = p / 10
        Cells(23, 26 + k).Value = k / 10
        Cells(22 - p, 26 + k).Value = sombra(latitud__, dia__juliano, hor_sol, k / 10, p / 10, param_,
        nparamentos, x1(), y1(), z1(), x2(), y2(), z2(), x3(), y3(), z3())
    Next p
Next k

End Sub
```

SKY VIEW FACTOR TABLE SUBROUTINE

This subroutine is associated to the control button which generates the Sky View Factor Table. Its data input is:

- Latitude in sexagesimal degrees
- Selected façade, by its associated number

Its data output is the value of the Sky View Factor for every point of the façade selected. This factor does not have units and its value belongs to the interval (0-0.5). The computing code is shown below:

```
Sub tablafactorvisiondecielo()

latitud__ = Cells(11, 41).Value
fachadaestudio = Cells(11, 43).Value


Dim x1(100), y1(100), z1(100), x2(100), y2(100), z2(100), x3(100), y3(100), z3(100)
Dim matriz_coeficientes(3, 3), terminos_independientes(3), matriz_inversa(3, 3)
nparamentos = 0

For i = 1 To 100

    x1(i) = Cells(18 + i, 5).Value
    y1(i) = Cells(18 + i, 6).Value
    z1(i) = Cells(18 + i, 7).Value
    x2(i) = Cells(18 + i, 8).Value
    y2(i) = Cells(18 + i, 9).Value
    z2(i) = Cells(18 + i, 10).Value
    x3(i) = Cells(18 + i, 11).Value
    y3(i) = Cells(18 + i, 12).Value
    z3(i) = Cells(18 + i, 13).Value

    If (x1(i) <> 0 Or y1(i) <> 0 Or z1(i) <> 0 Or x2(i) <> 0 Or y2(i) <> 0 Or z2(i) <> 0 Or x3(i) <> 0 Or y3(i)
        <> 0 Or z3(i) <> 0) Then
         nparamentos = nparamentos + 1
    End If
Next i

For k = 0 To 10 Step 1
    For p = 0 To 10 Step 1
       PASO = 0.056
       NPUNTOSX = Int(1 / PASO) + 1
       cuenta = 0
       mu = p / 10: ro = k / 10
       Xest = x1(fachadaestudio) + ro * (x2(fachadaestudio) - x1(fachadaestudio)) + mu *
      (x3(fachadaestudio) - x2(fachadaestudio))
```

```
Yest = y1(fachadaestudio) + ro * (y2(fachadaestudio) - y1(fachadaestudio)) + mu *
(y3(fachadaestudio) - y2(fachadaestudio))
Zest = z1(fachadaestudio) + ro * (z2(fachadaestudio) - z1(fachadaestudio)) + mu *
(z3(fachadaestudio) - z2(fachadaestudio))
Call normal(fachadaestudio, nx, ny, nz)
hx = -ny / (nx ^ 2 + ny ^ 2) ^ 0.5
hy = nx / (nx ^ 2 + ny ^ 2) ^ 0.5
hz = 0
VX = ny * hz - nz * hy
vy = nz * hx - nx * hz
vz = nx * hy - ny * hx
totalpuntos = 0

For i = -NPUNTOSX To NPUNTOSX
    For j = -NPUNTOSX To NPUNTOSX
        X = i * PASO + 0.5 * PASO
        Y = j * PASO + 0.5 * PASO
        If (X ^ 2 + Y ^ 2) < 1 Then
            Z = (1 - X ^ 2 - Y ^ 2) ^ 0.5
            dx = X * hx + Y * VX + Z * nx
            dy = X * hy + Y * vy + Z * ny
            dz = X * hz + Y * vz + Z * nz
            puntodedifusa = 1
            fin = 0
            If dz < 0 Then
                puntodedifusa = 0
                fin = 1
            End If
            PZ = 0
            While ((PZ < nparamentos) And (fin = 0))
                PZ = PZ + 1
                If (PZ <> fachadaestudio) Then
                    matriz_coeficientes(1, 1) = dx
                    matriz_coeficientes(2, 1) = dy
                    matriz_coeficientes(3, 1) = dz
                    matriz_coeficientes(1, 2) = -(x2(PZ) - x1(PZ))
                    matriz_coeficientes(2, 2) = -(y2(PZ) - y1(PZ))
                    matriz_coeficientes(3, 2) = -(z2(PZ) - z1(PZ))
                    matriz_coeficientes(1, 3) = -(x3(PZ) - x2(PZ))
                    matriz_coeficientes(2, 3) = -(y3(PZ) - y2(PZ))
                    matriz_coeficientes(3, 3) = -(z3(PZ) - z2(PZ))
                    terminos_independientes(1) = x1(PZ) - Xest
                    terminos_independientes(2) = y1(PZ) - Yest
                    terminos_independientes(3) = z1(PZ) - Zest

                    Call INVMATRIZ(3, matriz_coeficientes, matriz_inversa, DET,
                    NOINVERTIBLE)
                    If NOINVERTIBLE = 0 Then
                        parametro_a = matriz_inversa(1, 1) * terminos_independientes(1)
                        + matriz_inversa(1, 2) * terminos_independientes(2) +
                        matriz_inversa(1, 3) * terminos_independientes(3)
                        parametro_b = matriz_inversa(2, 1) * terminos_independientes(1)
                        + matriz_inversa(2, 2) * terminos_independientes(2) +
                        matriz_inversa(2, 3) * terminos_independientes(3)
```

```
                                        parametro_c = matriz_inversa(3, 1) * terminos_independientes(1)
                                        + matriz_inversa(3, 2) * terminos_independientes(2) +
                                        matriz_inversa(3, 3) * terminos_independientes(3)

                                        If ((parametro_a > 0) And ((parametro_b > 0) And (parametro_b
                                        < 1)) And ((parametro_c > 0) And (parametro_c < 1))) Then
                                                puntodedifusa = 0
                                                fin = 1
                                        End If

                                    End If
                                End If
                            Wend
                            totalpuntos = totalpuntos + puntodedifusa
                        End If
                    Next j
                Next i

            Cells(122 - p, 25).Value = p / 10
            Cells(123, 26 + k).Value = k / 10
            Cells(122 - p, 26 + k).Value = totalpuntos / 1012
    Next p
Next k

End Sub
```

INSTANTANEOUS IRRADIANCE FUNCTION

This function uses as data input:

- Latitude in sexagesimal degrees
- Julian day
- Solar time in hours, from -12 to 12, being 0 at noon.
- Coordinates ρ and μ of the local reference system of the selected façade
- Selected façade, by its associate number
- Global radiation on horizontal surface in Joules
- Number of façades compounding the urban model
- Sky View Factor
- Albedo, in so much per one

Its data output is the instantaneous irradiance in W/m^2 for every point of the selected façade. This function makes use of the Instantaneous Direct Irradiance on Horizontal Surface and the Instantaneous Diffuse Irradiance on Horizontal Surface, both belonging to the Collection SolarNet. The computing code is shown below:

```
Function irradiancia(latitud, dia_juliano, hsolar, ro, mu, fachadaestudio, radiacion_global, SVF, albedo,
nparamentos, x1(), y1(), z1(), x2(), y2(), z2(), x3(), y3(), z3())

factor = sombra(latitud, dia_juliano, hsolar, ro, mu, fachadaestudio, nparamentos, x1(), y1(), z1(), x2(),
y2(), z2(), x3(), y3(), z3())

irrad_B = directainstantanea(dia_juliano, hsolar, latitud, radiacion_global)
irrad_D = difusainstantanea(dia_juliano, hsolar, latitud, radiacion_global)

Call normal(fachadaestudio, nx, ny, nz)
sx = vsolarx(dia_juliano, hsolar, latitud)
sy = vsolary(dia_juliano, hsolar, latitud)
sz = vsolarz(dia_juliano, hsolar, latitud)

escalar_ns = nx * sx + ny * sy + nz * sz
escalar_ks = sz
escalar_nk = nz

irradiancia = factor * escalar_ns * irrad_B / escalar_ks + SVF * irrad_D + (1 - SVF) * albedo * (irrad_B +
irrad_D)

End Function
```

INSTANTANEOUS IRRADIANCE TABLE SUBROUTINE

This subroutine has the same data input that the Instantaneous Irradiance Function. It is associated to the control button which generates the Instantaneous Irradiance Table. The computing code is shown below:

```
Sub tablaIrradiacion()
dia__juliano = Cells(11, 40).Value
latitud__ = Cells(11, 41).Value
hor_sol = Cells(11, 42).Value
param_ = Cells(11, 43).Value
radiacion_ = Cells(11, 44).Value
albedo_ = Cells(11, 45).Value

Dim x1(100), y1(100), z1(100), x2(100), y2(100), z2(100), x3(100), y3(100), z3(100)
nparamentos = 0

For i = 1 To 100

    x1(i) = Cells(18 + i, 5).Value
    y1(i) = Cells(18 + i, 6).Value
    z1(i) = Cells(18 + i, 7).Value
    x2(i) = Cells(18 + i, 8).Value
    y2(i) = Cells(18 + i, 9).Value
    z2(i) = Cells(18 + i, 10).Value
    x3(i) = Cells(18 + i, 11).Value
    y3(i) = Cells(18 + i, 12).Value
    z3(i) = Cells(18 + i, 13).Value

    If (x1(i) <> 0 Or y1(i) <> 0 Or z1(i) <> 0 Or x2(i) <> 0 Or y2(i) <> 0 Or z2(i) <> 0 Or x3(i) <> 0 Or y3(i)
   <> 0 Or z3(i) <> 0) Then
        nparamentos = nparamentos + 1
    End If
Next i

For k = 0 To 10 Step 1
    For p = 0 To 10 Step 1
        SVF = Cells(122 - p, 26 + k).Value
        Cells(40 - p, 25).Value = p / 10
        Cells(41, 26 + k).Value = k / 10
        Cells(40 - p, 26 + k).Value = irradiancia(latitud__, dia__juliano, hor_sol, k / 10, p / 10, param_,
       radiacion_, SVF, albedo_, nparamentos, x1(), y1(), z1(), x2(), y2(), z2(), x3(), y3(), z3())
    Next p
Next k

End Sub
```

DAILY SOLAR RADIATION TABLE SUBROUTINE

This subroutine is associated to the control button which generates the Daily Solar Radiation Table. Its data input is:

- Latitude, in sexagesimal degrees
- Julian day
- Solar time in hours, from -12 to 12, being 0 at noon.
- Selected façade, by its associate number
- Global radiation on horizontal surface, in Joules
- Albedo, in so much per one

Its data output is the daily solar radiation in KWh/m^2 for every point of the selected façade. The computing code is shown below:

```
Sub tablaRadiacionDiaria()

dia__juliano = Cells(11, 40).Value
latitud__ = Cells(11, 41).Value
hor_sol = Cells(11, 42).Value
param_ = Cells(11, 43).Value
radiacion_ = Cells(11, 44).Value
albedo_ = Cells(11, 45).Value

Dim x1(100), y1(100), z1(100), x2(100), y2(100), z2(100), x3(100), y3(100), z3(100)
nparamentos = 0

For i = 1 To 100

    x1(i) = Cells(18 + i, 5).Value
    y1(i) = Cells(18 + i, 6).Value
    z1(i) = Cells(18 + i, 7).Value
    x2(i) = Cells(18 + i, 8).Value
    y2(i) = Cells(18 + i, 9).Value
    z2(i) = Cells(18 + i, 10).Value
    x3(i) = Cells(18 + i, 11).Value
    y3(i) = Cells(18 + i, 12).Value
    z3(i) = Cells(18 + i, 13).Value

    If (x1(i) <> 0 Or y1(i) <> 0 Or z1(i) <> 0 Or x2(i) <> 0 Or y2(i) <> 0 Or z2(i) <> 0 Or x3(i) <> 0 Or
    y3(i) <> 0 Or z3(i) <> 0) Then
        nparamentos = nparamentos + 1
    End If
Next i
```

```
Dim radiacion(100, 100)
PASO = 0.1

For k = 0 To 10 Step 1
    For p = 0 To 10 Step 1
        SVF= Cells(122 - p, 26 + k).Value
        Cells(60 - p, 25).Value = p / 10
        Cells(61, 26 + k).Value = k / 10
        radiacion(p, k) = 0
        For h_solar = -12 To 12 Step PASO
            radiacion(p, k) = radiacion(p, k) + 3600 * PASO * irradiancia(latitud__, dia__juliano,
            h_solar, k / 10, p / 10, param_, radiacion_, SVF, albedo, nparamentos, x1(), y1(), z1(),
            x2(), y2(), z2(), x3(), y3(), z3())
        Next h_solar
        Cells(60 - p, 26 + k).Value = radiacion(p, k) / 3600000
    Next p
Next k

End Sub
```

NORMAL SUBROUTINE

This subroutine is used for solving the geometric problem of the intersection of the straight sun-studied point with the neighbor buildings. Its data input is the selected façade. This subroutine provides the normal vector to the selected façade by its three components. The computing code is shown below:

```
Sub normal(fachadaestudio, nx, ny, nz)

Dim x1(100), y1(100), z1(100), x2(100), y2(100), z2(100), x3(100), y3(100), z3(100)

 i = fachadaestudio
 x1(i) = Cells(18 + i, 5).Value
 y1(i) = Cells(18 + i, 6).Value
 z1(i) = Cells(18 + i, 7).Value
 x2(i) = Cells(18 + i, 8).Value
 y2(i) = Cells(18 + i, 9).Value
 z2(i) = Cells(18 + i, 10).Value
 x3(i) = Cells(18 + i, 11).Value
 y3(i) = Cells(18 + i, 12).Value
 z3(i) = Cells(18 + i, 13).Value

vx12 = x2(fachadaestudio) - x1(fachadaestudio)
vy12 = y2(fachadaestudio) - y1(fachadaestudio)
vz12 = z2(fachadaestudio) - z1(fachadaestudio)
vx23 = x3(fachadaestudio) - x2(fachadaestudio)
vy23 = y3(fachadaestudio) - y2(fachadaestudio)
vz23 = z3(fachadaestudio) - z2(fachadaestudio)

vnx = vy12 * vz23 - vy23 * vz12
vny = -vx12 * vz23 + vx23 * vz12
vnz = vx12 * vy23 - vx23 * vy12

nx = vnx / (vnx ^ 2 + vny ^ 2 + vnz ^ 2) ^ 0.5
ny = vny / (vnx ^ 2 + vny ^ 2 + vnz ^ 2) ^ 0.5
nz = vnz / (vnx ^ 2 + vny ^ 2 + vnz ^ 2) ^ 0.5

End Sub
```

APPENDIX B. Publications

This project has been sent to the "12º Certamen Universitario Arquimedes 2013" participating in the category "2173#14-IEL: Ingeniería eléctrica, electrónica y automática" under the title "ANÁLISIS E IMPLEMENTACIÓN DE MAPAS DE RADIACIÓN SOLAR SOBRE FACHADAS EN ENTORNOS URBANOS MEDIANTE UNA APLICACIÓN INFORMÁTICA ABIERTA"

This project has been presented in the "6th International Conference on Solar Radiation and Daylighting, Granada 2013" by the article titled "TOOLBOX ENGINEERING SOFTWARE FOR THE ANALYSIS OF SUNLIGHT ON BUILDINGS" being selected for its publication in the "International Journal of Low-Carbon Technologies. Oxford Journals"


SOLARIS 2013

The 6th International Conference on Solar Radiation and Daylighting

The Organizing Committee of the 6th International Conference on Solar Radiation and Daylighting, SOLARIS 2013, held in Granada on May 16th and 17th

Certify that:

MARQUEZ GARCÍA, A

Appears as author of the paper:

TOOLBOX ENGINEERING SOFTWARE FOR THE ANALYSIS OF SUNLIGHT ON BUILDING

Dr. Javier Ordoñez Garcia

President of the Organizaing Committee

SOLARIS 2013

The 6th International Conference on Solar Radiation and Daylighting

ALVARO MARQUEZ GARCIA

has participated in The 6th International Conference on Solar Radiation and Daylighting.
SOLARIS 2013, held in Granada on May 16th and 17th.

Dr. Javier Ordoñez Garcia
President of the Organizaing Committee

Asunto	**Solaris 2013**
Remitente	Eulalia
Destinatario	z22magaa@uco.es
Fecha	2013-06-04 11:24

Dear Sir/Madam

Your comunication titled "Toolbox engineering software for the analysis of sunlight on buildings" has been selected for the Solaris Conference Proceedings Editors.

You can submit your comunication to the journal "International Journal of Low Carbon Technologies" using the online system www.ijlct.oxfordjournals.org.

Best Regards

Eulalia Jadraque Gago
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