ANALYSIS OF SOLAR RADIATION AND IMPLEMENTATION OF A CALCULATION MODEL FOR ENERGY CHARACTERIZATION OF FENESTRATION SYSTEMS.

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0. ABSTRACT

In the last years, as fenestration and shading systems have become more complex and sophisticated, a great improvement of thermal and solar-optical performance has been required and as a consequence old methods of characterization have become inadequate.

This evolution has yielded the introduction of new lumped parameters and the implementation of more sophisticated calculation models, which allow to evaluate the performance of fenestration and shading systems taking into account a large number of factors, such as the angular dependence of solar heat gain.

The suitability and usefulness of new parameters and models for a wide use depend on the level of knowledge of the interaction between fenestration systems and the external environment.

In the first part of this work an analysis of incident solar radiation on fenestration has been performed, by using the climatic data contained in the *average monthly days* of some sites representative of the main Italian climatic zones.

The ratio of direct solar radiation to diffuse solar radiation has been analyzed for different orientations of glazed surfaces and for different periods in the year. Moreover, the relation between direct radiation and its incident angle has been analyzed.

In the second part of this work a calculation model for the determination of the solar energy transmittance (TSET) of fenestration and shading systems has been developed.

The model is based on a reference tool developed by CSTB, which has been modified by the authors in order to increase its flexibility, to adequate it to the existent national and international standard and recommendation, to take into account the angular dependence of solar heat gain through complex fenestration and shading systems.

The combined application of the calculation model to some fenestration systems using the results of the external environment analysis has allowed to identify a wide range of cases and to obtain general rules about the applicability and usefulness of different calculation models depending on geometric and exposure features of glazed surfaces and on the period of the year.

1. INTRODUCTION

Transparent components and shading devices composing a fenestration system are characterized, from a solar-optical point of view, by incident angle-dependent transmission and reflection coefficients.

For conventional glazings the solar transmittance curve is constant over a great range of angle of incidence, whilst for innovative glazings it can change in a relevant way. Besides that, the presence of a shade can complicate the energy performance assessment of a fenestration system.

For energy analysis including hourly building performance simulation calculation, the use of a single-number indicator of normal-incidence solar heat gain is becoming inadequate. As a consequence it seems to be necessary to provide new methods in order to evaluate the energy behaviour of complex fenestration systems.

The most correct indicator of the solar heat gain through a fenestration system is the average total solar energy transmittance ($TSET_m$), which is defined as the ratio of the energy globally transmitted through the fenestration system to the incident solar radiation over the considered period.

In order to calculate the total solar energy transmittance of a fenestration system it is necessary to perform a detailed analysis of incident solar radiation versus location, considered period, orientation and climatic conditions.

The analysis of solar heat gain can be lead in different ways, with decreasing accuracy:

a) through the hour by hour detailed calculation of the incident angle of direct solar radiation, of the direct, diffuse and reflected solar irradiance impinging the examined component, of the total solar energy transmittance;
b) performing a hour by hour detailed computation of solar radiation passing through a reference glass and multiplying this value by the shading coefficient (SC) of the considered glass, obtained for normally incident radiation (ASHRAE method);
c) by the computation of the average total solar energy transmittance as the product of the total solar energy transmittance at normal radiation incidence by an exposition factor (or incidence factor), which takes into account the influence of the incident angle on the solar optical properties of the components;
d) using the total solar energy transmittance for normal radiation incidence.

In order to assess the suitability and the usefulness of different methods it is necessary to compare their results with those springing out from a detailed modelization of optical-solar and thermal behaviour of fenestration systems and from a complete analysis of the external environment over a defined period.

2. ANALYSIS OF SOLAR RADIATION

Solar radiation has been analyzed for two Italian locations (Turin, L=45°11’N and Naples L=40°53’N) with reference to three different periods: the whole year, the heating season, the summer design day.

The heating period of the two examined locations is different: it lasts from 15 October to 15 April for Turin and from 15 November to 31 March for Naples.

As far as the determination of the sun position in the sky is concerned, the summer design day is conventionally assumed as 21 July.

Two different conditions of external irradiation have been considered: mean conditions (average monthly day) and clear sky conditions. The first conditions have been used for the yearly period and for the winter period, the other ones for the summer design day.

2.1 Calculation of incident solar radiation

Solar irradiance on a tilted surface is obtained as the sum of direct, diffuse and reflected (albedo) contributions:

$$I = I_b + I_d + I_a \tag{1}$$

The sun position above the horizontal plane, described by the angular coordinates β_S and φ_S , is calculated for each locations and for each considered period.

For each surface, defined by its azimuth (φ) and slope (Σ), the incidence angle (θ) of direct solar radiation can be determined.

For calculating solar radiation in an average monthly day we applied the method suggested by Kusuda and Ishiti [2] which allows to obtain the daily diffuse solar irradiation on a horizontal plane by the following relation:

$$\frac{D_o}{H_{eo}} = k_0 + k_1 \cdot \frac{H_o}{H_{eo}} + k_2 \cdot \left(\frac{H_o}{H_{eo}}\right)^2 + k_3 \cdot \left(\frac{H_o}{H_{eo}}\right)^3 + k_4 \cdot \left(\frac{H_o}{H_{eo}}\right)^4 + k_5 \cdot \left(\frac{H_o}{H_{eo}}\right)^5 \tag{2}$$

where k_0, k_1, k_2, k_3, k_4, k_5 are experimental coefficients.

For every day of each month the daily global solar irradiation incident on a horizontal surface was assumed equal to the monthly mean value.

Data used for Turin and Naples are described in table 1.

Table 1: Average monthly values of daily irradiation on a horizontal plane.

Month	**H_o [Wh/m²d]**		**Month**	**H_o [Wh/m²d]**	
	Turin	**Naples**		**Turin**	**Naples**
January	1511	1844	July	6434	7429
February	2249	2631	August	5474	6452
March	3460	3848	September	4079	4957
April	4749	5192	October	2566	3505
May	5580	6596	November	1505	2076
June	6179	7224	December	1236	1523

H_{eo} value is obtainable as a function of the latitude and of the day of the year.

Hourly values of normally direct solar irradiance and diffuse solar irradiance are expressed as:

$$I_{bn} = \left(\frac{H_o}{H_{eo}} - \frac{D_o}{H_{eo}}\right) \cdot f \cdot e^{-B/\sin\beta_S} \tag{3}$$

$$I_{do} = \frac{\pi}{24} \cdot \frac{\cos(t) - \cos(t_s)}{\sin(t_s) - \frac{\pi}{180} \cdot t_s \cdot \cos(t_s)} \cdot D_o \tag{4}$$

where t is the hour angle of the sun at the considered time, t_s is the sunrise hour angle, B and f are parameters depending on the year’s period and location latitude.

In order to calculate the amount of solar radiation in conditions of clear sky, the ASHRAE model was used, which allows to determine the hourly values of direct normal irradiance and diffuse irradiance on horizontal plane, defined as:

$$I_{bn} = A \cdot e^{-B/\sin(\beta_S)} \tag{5}$$

$$I_{do} = C \cdot I_{bn} \tag{6}$$

where A, B, C are coefficients depending on the period of the year.

The calculation of solar irradiance was performed, hour by hour, for vertical surfaces with different orientations: S, SE/SW, E/W, NE/NW, N. The surfaces were considered with no external obstructions and the mean value of the ground reflectance was assumed equal to 0.2.
A good indicator of the relevance of analyzing the influence of the incident angle of solar radiation is the ratio of direct irradiation to global irradiation (table 2): greater is the value of this ratio, greater is the influence of the incident angle on the mean solar transmittance of the component.

Table 2: Ratio of direct irradiation to global irradiation.

	TURIN					**NAPLES**				
	S	**SE/SW**	**E/W**	**NE/NW**	**N**	**S**	**SE/SW**	**E/W**	**NE/NW**	**N**
Yearly period	0.661	0.639	0.537	0.304	0.066	0.669	0.657	0.577	0.355	0.081
Heating period	0.783	0.732	0.546	0.149	0.001	0.776	0.721	0.535	0.129	0.000
Summer design day	0.589	0.661	0.662	0.527	0.199	0.532	0.639	0.657	0.534	0.203

2.2 Angular distribution of direct solar radiation

The angular distribution of direct solar radiation was performed dividing the incident angles range into a series of intervals having a width of 2 degrees.
In fig. 1 it is presented the procedure used for obtaining the angular distribution curve of direct solar radiation on a South oriented vertical surface, with reference to an interval of time lasting from 8 a.m. to 12 a.m. of a generic day (17 January) in Turin on mean conditions.
The profiles of direct solar irradiance and of incident angle are obtained by linear interpolation from hourly values. For the first hour after sunrise the interpolation is carried out between E_b and θ values at the considered time and the values assumed for the sunrise time for which it E_b is supposed to be equal to 0. A similar procedure is adopted for the last hour before sunset.
For every incident angle band having a width of 2 degrees, identified on the ordinates, it is possible to determine on the abscissas the correspondent temporal range for which direct solar radiation presents incident angles falling into the considered band. The corresponding direct irradiation is obtained by integrating the direct solar irradiance curve over the assumed temporal range.
With reference to figure 1, as an example, the direct solar irradiation for incident angle varying from 50 to 52 degrees is represented by the shadowed area.

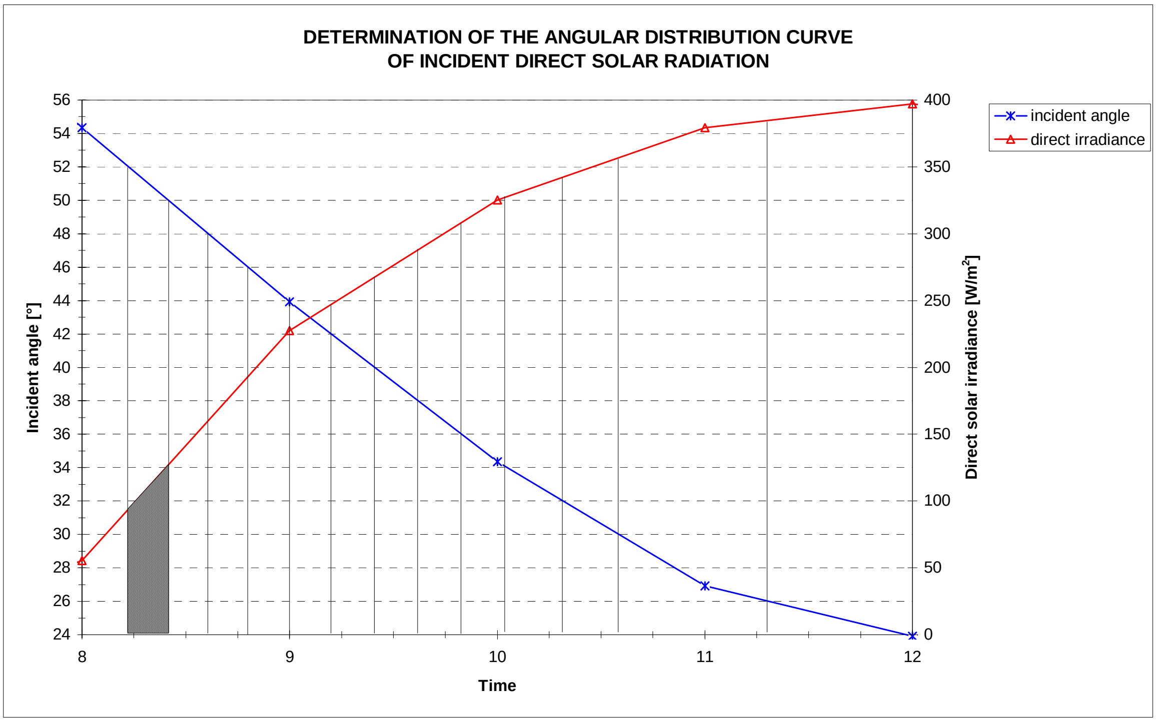


Figure 1

The angular distribution curve of incident direct solar radiation was obtained calculating the summation, over every day of the considered period, of contributions of direct solar irradiation referred to each band of incident angle:

$$\frac{dE_b(\theta_i)}{d\theta} = \frac{\sum_{j=1}^{N_{days}} E_{b,daily,j}\left(\theta \in [\theta_i - 1, \theta_i + 1]\right)}{2} \tag{7}$$

where θ_1=1°, θ_2=2°, θ_3= 3°,...., θ_{45}=89°.

Figures 2-7 show the angular distribution of incident direct solar radiation for different orientations, for the examined locations (Turin and Naples) and for the considered environmental conditions (yearly period, heating period, summer design day).

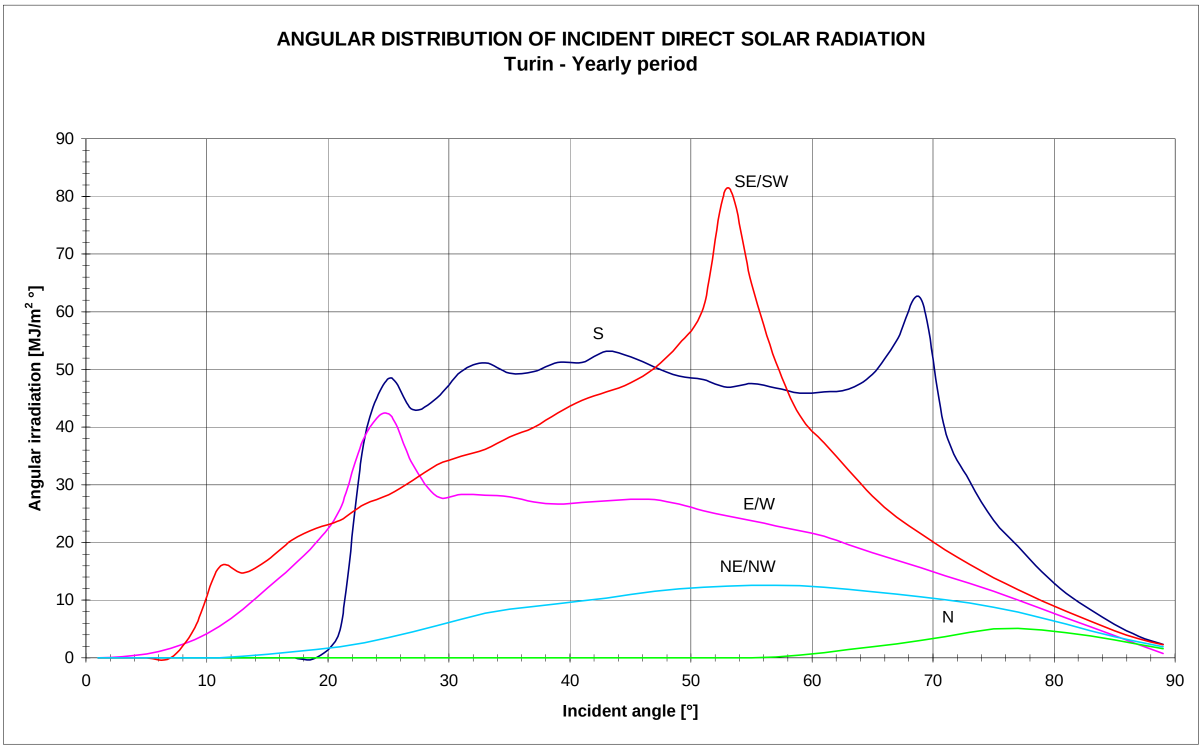


Figure 2

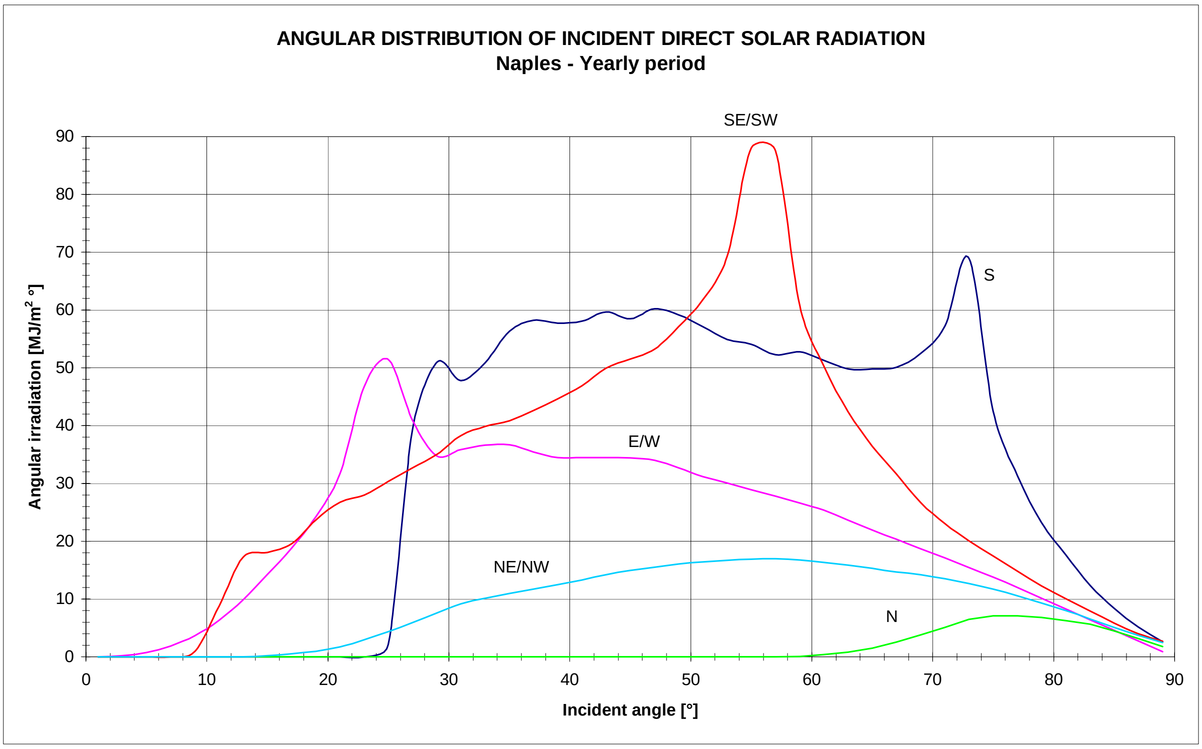


Figure 3

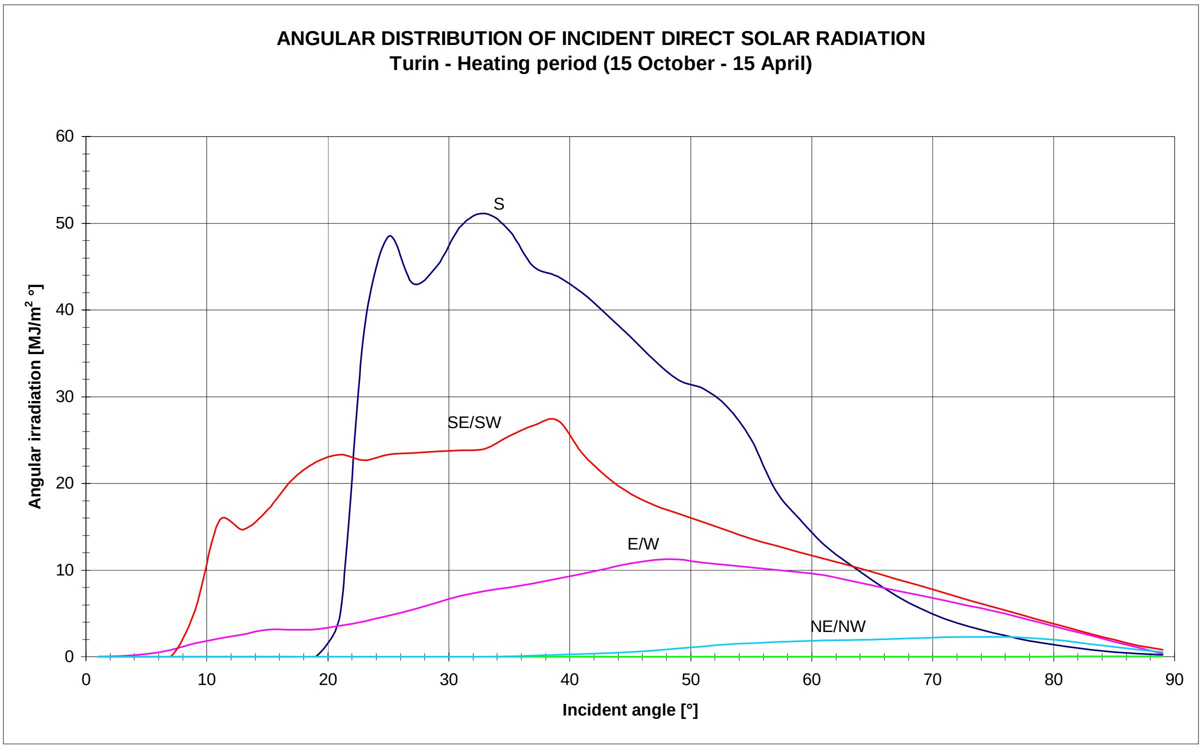


Figure 4

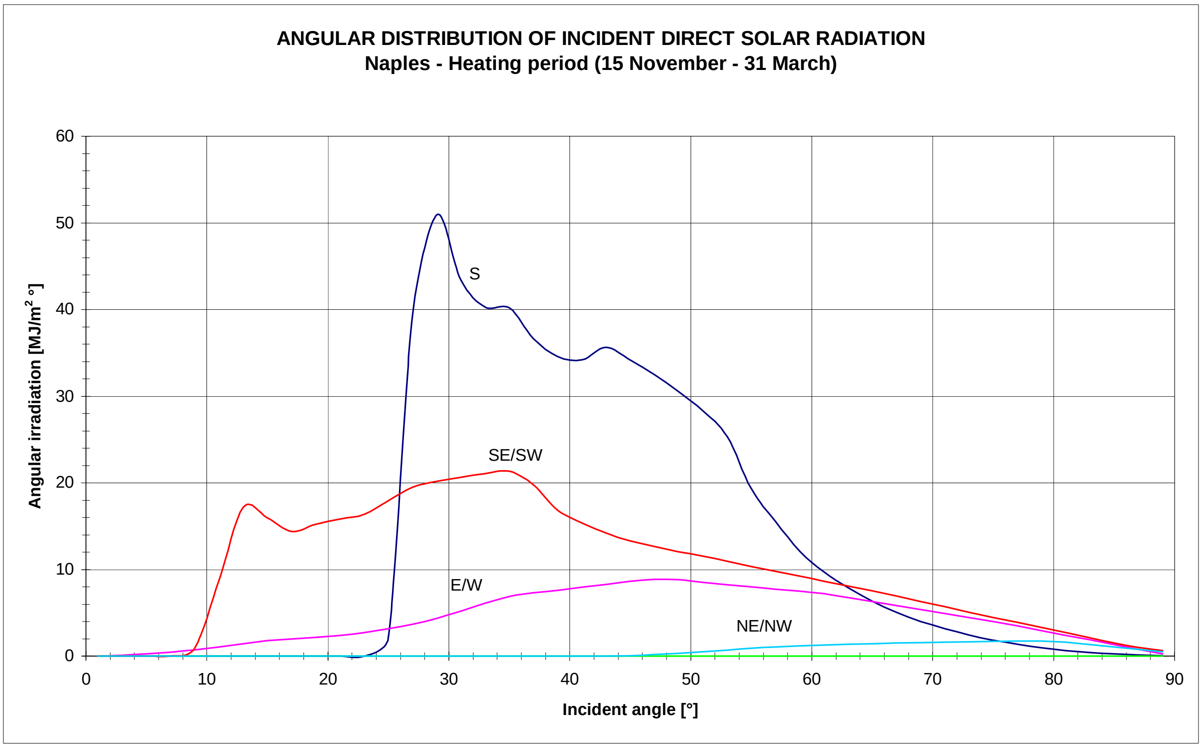
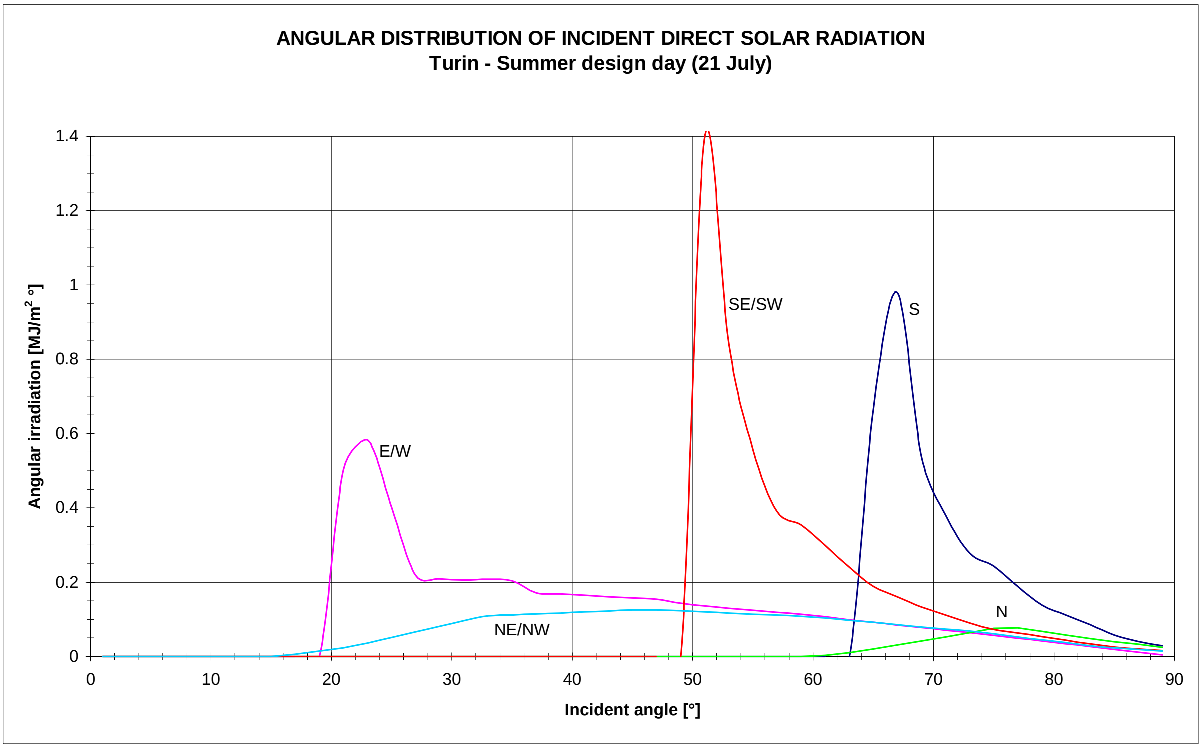


Figure 5



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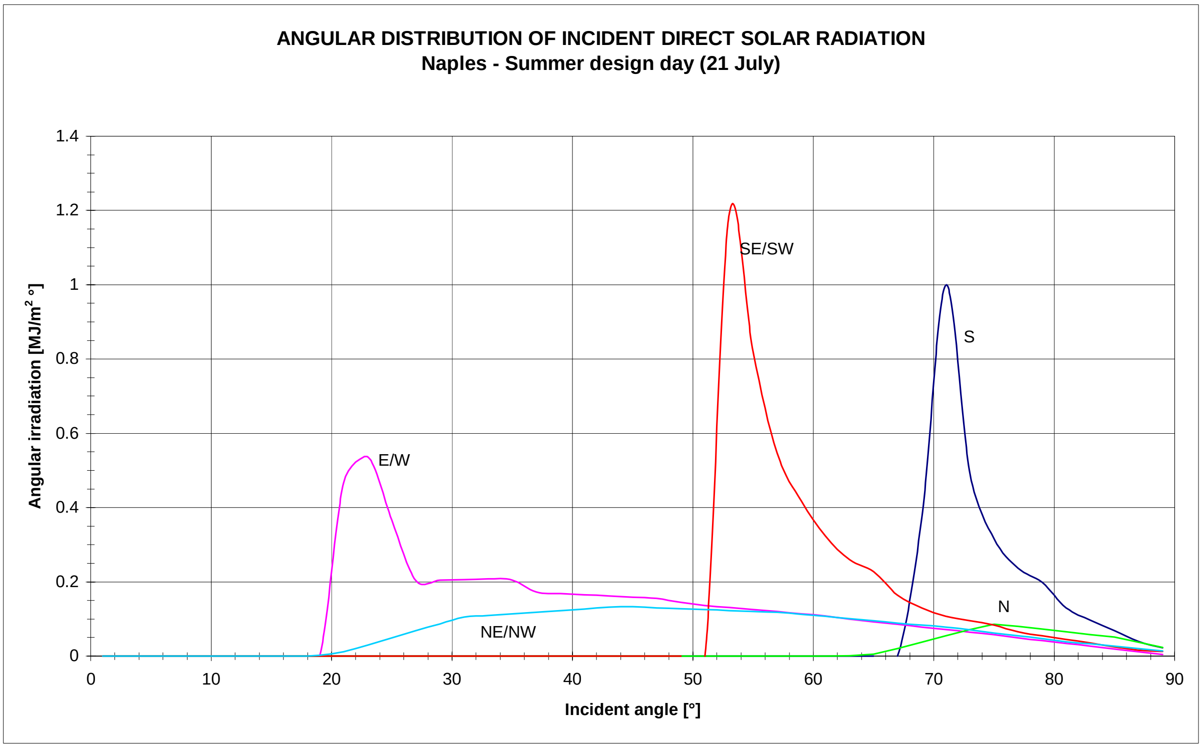

Figure 7

3. DESCRIPTION OF THE CALCULATION MODEL

3.1 General features

The calculation model developed by the authors, is based on the model WINSOL of CSTB [8], which allows to analyze the energy behaviour of a fenestration system by means of an equivalent electrical network consisting of 10 nodes and 14 resistances, as shown in fig. 8.

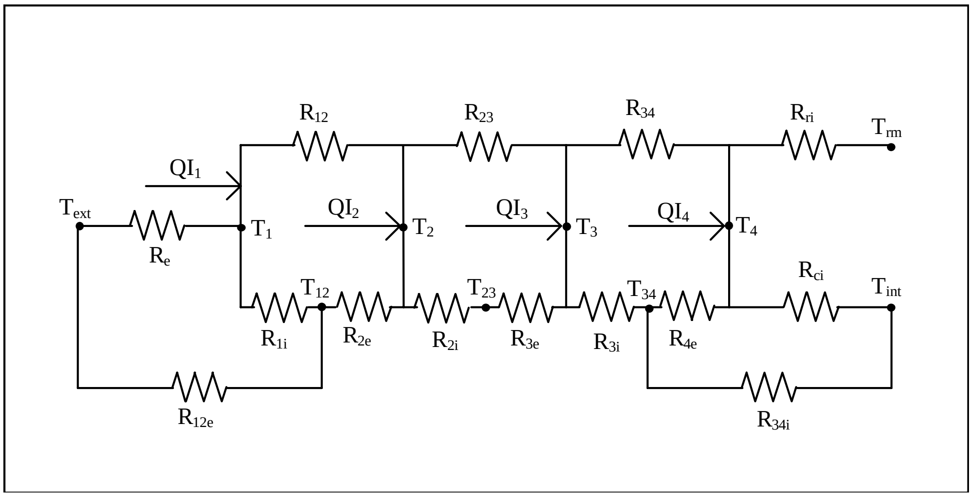

Figure 8: System equivalent electrical network.

The system can be composed of a number of components varying from a minimum of one (single glass) to a maximum of four (outer shade, double glass, inner shade).

The thermal resistances of single components are neglected. The air layer between a glass and a shade can be sealed or ventilated, with variable air entrance and exit sections.

The components (outer shade, glazing and inner shade) are represented by nodes 1, 2, 3, 4. Nodes 12, 23, 34 represent the air layers between the components.

The external environment is represented by a single node (ext) while the internal environment is represented by two nodes (int, rm), the former one representing the indoor air, the second one representing the radiant surfaces.

Air layers 12 and 34 can be ventilated. In this case, resistances R_{12e} and R_{34i} represent respectively the heat transfer resistances related to ventilation for stack effect between the outer shade and the glass and between the inner shade and the glass.

Heat flows QI_1, QI_2, QI_3, QI_4 represent solar radiation absorbed by the different components.

The mathematical algorithm used to compute the total solar energy transmission coefficient (TSET) consists of the following calculation steps:

- resolution of the short-wave radiation balance (calculation of the absorbed flows);
- iterative procedure consisting of:
  - calculation of heat transfer coefficients: external surface heat transfer coefficient, internal surface convective and radiative heat transfer coefficients, radiative heat transfer coefficients between panes, convective heat transfer coefficients between panes and sealed air layers, convective heat transfer coefficients between panes and ventilated air layers, convective heat transfer coefficients between ventilated air layers and environment for stack effect);
  - resolution of the overall thermal balance in order to calculate the temperatures of the nodes.

3.2 Improvements of the model

The improvements of the model concerned the short-wave energy balance resolution (solar radiation).

In particular, the solar radiation incident on the fenestration system has been differentiated into its direct and diffuse components.

The solar-optical properties of components for directly incident radiation ($\tau_{S,\theta}$, $\rho_{S,\theta}$) are angle-dependent. From experimental data it is possible to define functions $\tau_{S,\theta}(\theta)$ and $\rho_{S,\theta}(\theta)$.

For diffuse radiation a uniform radiance sky model has been assumed. Consequently, solar-optical properties of components for a diffuse incident radiation can be determined as:

$$\tau_{S,d} = \int_0^{90} \tau_{S,\theta} \cdot 2 \cdot \sin(\theta) \cdot \cos(\theta) \cdot d\theta \qquad (8)$$

$$\rho_{S,d} = \int_0^{90} \rho_{S,\theta} \cdot 2 \cdot \sin(\theta) \cdot \cos(\theta) \cdot d\theta \qquad (9)$$

Direct radiation incident on each component is transmitted and reflected, as short-wave radiation, partly in a direct way and partly in a diffuse way (as shown in fig. 9a).

The diffuse radiation incident on each component is transmitted and reflected in a totally diffuse way (as shown in fig. 9b).

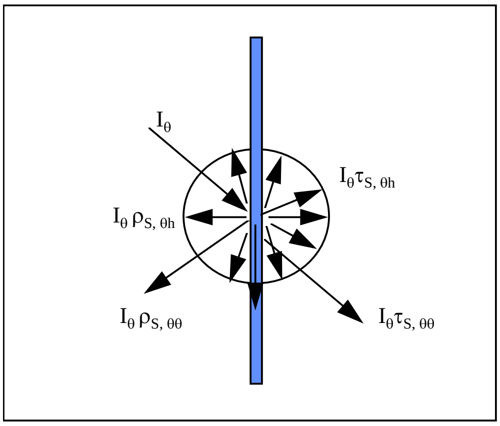

Figure 9a

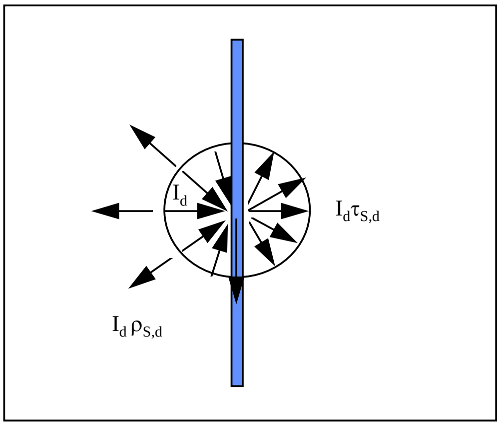

Figure 9b

All the solar-optical properties of the components can be differentiated versus the direction of radiation, from outside to inside or viceversa.

The developed model solves the system short-wave energy balance taking into account all the infinite reflections and transmissions of each component and allows to compute the absorbed solar radiation flows per unit area (QI_1, QI_2,..., QI_5).

With reference to the solar-optical properties of glazings, the transmission and reflection coefficients versus the incident angle can be described by means of a fifth order polynomial expression as [10]:

$$\tau_{S,\theta} = \sum_{i=0}^{5} t_i \cos^i\theta \qquad (10)$$

$$\rho_{S,\theta} = \sum_{i=0}^{5} r_i \cos^i\theta \qquad (11)$$

where coefficients t_i and r_i have different values according to the kind of glass (e.g. coated, uncoated).
The diffuse transmission and reflection coefficients, in conformity with the assumption of a uniform radiance sky model, are:

$$\tau_{S,d} = 2 \cdot \left(\frac{t_0}{2} + \frac{t_1}{3} + \frac{t_2}{4} + \frac{t_3}{5} + \frac{t_4}{6} + \frac{t_5}{7} \right) \tag{12}$$

$$\rho_{S,d} = 2 \cdot \left(\frac{r_0}{2} + \frac{r_1}{3} + \frac{r_2}{4} + \frac{r_3}{5} + \frac{r_4}{6} + \frac{r_5}{7} \right) \tag{13}$$

As far as shades are concerned, angle-dependent transmission and reflection coefficients can be obtained from normal incidence values through the following functions [9]:

$$\tau_{S,\theta} = \tau_{S,\theta}(0) \cdot \sqrt{1 - \left(\frac{\theta}{90} \right)^2} \tag{14}$$

$$\rho_{S,\theta} = 1 - \left[1 - \rho_{S,\theta}(0) \right] \cdot \sqrt{1 - \left(\frac{\theta}{90} \right)^2} \tag{15}$$

According to the hypothesis of a uniform radiance sky model, the diffuse transmission and reflection coefficients for a shade are:

$$\tau_{S,d} = 0.82445 \cdot \tau_{S,\theta}(0) \tag{16}$$

$$\rho_{S,d} = 1 - 0.82445 \cdot \left[1 - \rho_{S,\theta}(0) \right] \tag{17}$$

3.3 Input/Output of the calculation model

The inputs of the model are differentiated into two groups: parameters for the system characterization and variables for the characterization of environmental conditions.
As far as system characterization is concerned, the following variables are required:

- coefficients necessary to calculate the angle-dependent values of internal/external directional, hemispherical and diffuse transmission and reflection coefficients of glazings and shades, according to eq. (10-17);
- external/internal emissivity of components;
- width of air layers (between glasses and between inner or outer shade and glass);
- width of air entrance and exit sections in ventilated air layers.

As far as environmental conditions are concerned, the following variables are required:

- directional, hemispherical, diffuse reflection coefficients of the room surfaces facing the window;
- height of the window;
- incident angle of solar radiation, direct and diffuse solar irradiance;
- external temperature, internal air temperature, internal mean radiant temperature;
- external surface heat transfer coefficient, internal convective heat transfer coefficient, internal radiative heat transfer coefficient for a component with an ordinary emissivity.

The output of the model includes heat transfer coefficients, node temperatures, heat transfer flows (short-wave radiation, infra-red radiation, convection), system solar parameters (τ_S, TSET).

4. APPLICATION OF THE CALCULATION MODEL

The model has been applied to three fenestration systems: a double-glazed window consisting of two 6-mm clear glasses, separated by a 12-mm air layer (system 1); an identical double-glazed window with a 200-mm distant inner shade (system 2); a double-glazed window composed of a 6-mm reflective glass and a 6-mm clear glass with a 12-mm air layer (system 3).

In the application of the calculation model the following assumptions have been adopted:

- all the direct radiation incident on a glazing is transmitted and reflected in a direct way ($\tau_{Se,\theta h} = \tau_{Si,\theta h} = \rho_{Se,\theta h} = \rho_{Si,\theta h} = 0$);
- all the direct radiation incident on a shading device is transmitted and reflected in a diffuse way ($\tau_{Se,\theta\theta} = \tau_{Si,\theta\theta} = \rho_{Se,\theta\theta} = \rho_{Si,\theta\theta} = 0$);
- the directional, hemispherical, diffuse reflection coefficients of the room have been set to zero.

The coefficients used to calculate the solar-optical properties of glazings according to eq. (10) and (11) are summarized in table 3.

Table 3: Coefficients used to determine solar-optical properties of glazings.

	t_0	t_1	t_2	t_3	t_4	t_5
clear glass	0.00000	2.17304	-0.33208	-5.39562	6.98396	-2.66045
reflective glass	0.00000	0.60127	- 0.39883	-0.37357	0.58827	-0.19844
	r_0	r_1	r_2	r_3	r_4	r_5
clear glass	1.00000	-4.07717	7.58221	-7.45426	3.84784	-0.82265
reflective glass	0.99896	-3.16711	5.83160	-4.69159	1.00309	0.34219

All the glazings are supposed to have an emissivity equal to 0.837 both on external and on internal faces.

As far as shading devices are concerned, a light coloured roller shade was chosen with normal transmittance equal to 0.40, normal reflectance equal to 0.50, both internal and external emissivity equal to 0.90.

It was supposed that the air layer between glass and shade was ventilated with air entrance and exit sections of 50 mm.

In table 4 are presented the standard environmental conditions used to calculate the solar parameters of fenestration systems.

Table 4: Standard environmental conditions.

H [m]	I_b [W/m^2]	I_d [W/m^2]	T_{ext} [°C]	T_{int} [°C]	T_{rm} [°C]	h_e [W/m^{2}K]	h_{ci} [W/m^{2}K]	h_{ri0} [W/m^{2}K]
1.50	750	0.00	20	20	20	23	3.6	4.4

The developed calculation model has allowed to calculate the angle-dependent values of solar transmittance (τ_S) and total solar energy transmittance (TSET) for the analyzed fenestration systems. The results are shown in figures 10 and 11 compared with those of the ASHRAE reference glass.

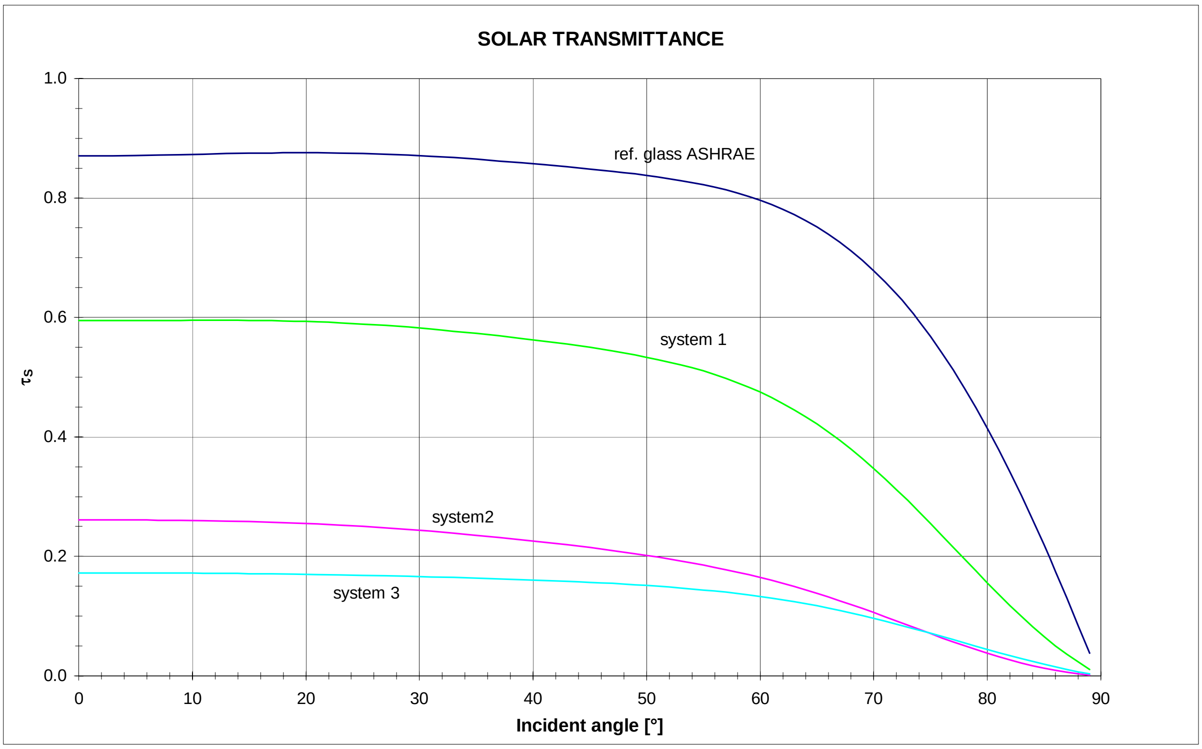

Figure 10

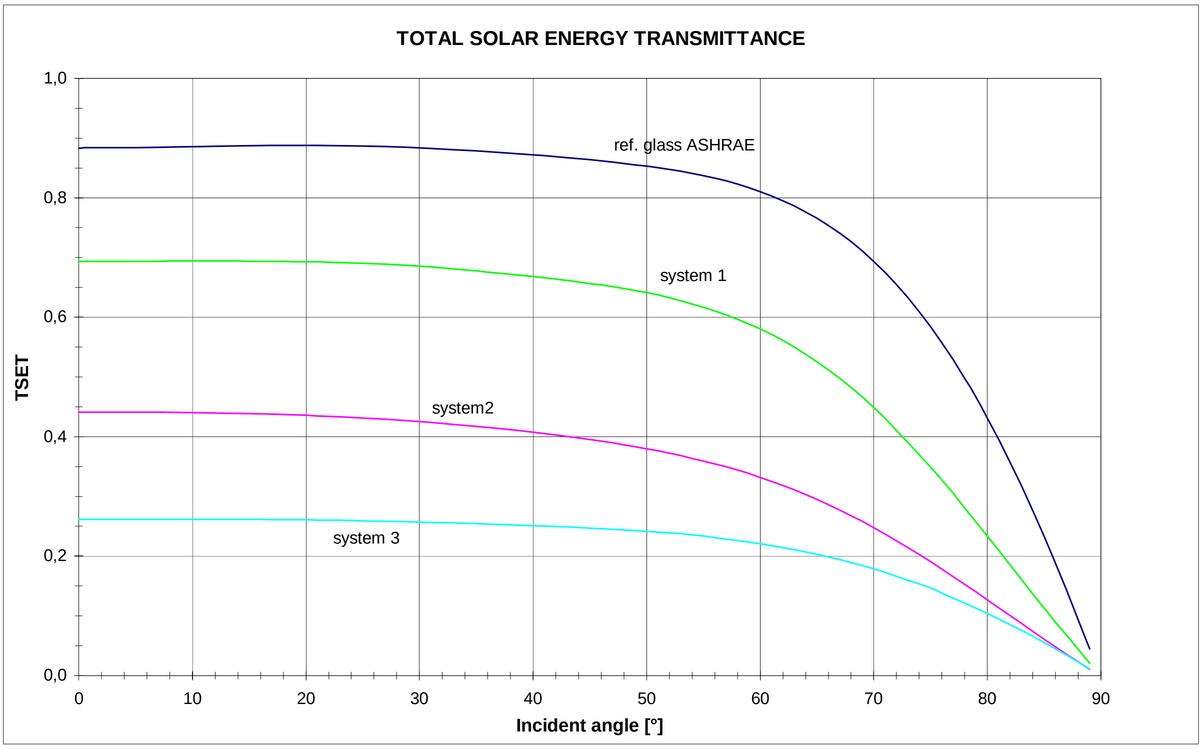

Figure 11

5. CALCULATION OF AVERAGE TOTAL SOLAR ENERGY TRANSMITTANCE

Combining the analysis of the solar radiation and the results of the developed simulation model, it has been possible to calculate the average system solar parameters for the considered case studies.
This analysis is based on the following main assumptions:

- heat gain through a fenestration system can be determined considering separately the effect of solar radiation and the effect of temperature difference;
- solar heat gain through a fenestration system can be determined considering separately the effect of direct solar radiation and the effect of diffuse solar radiation.

The average value of solar transmission coefficient can be obtained as the ratio of the transmitted solar energy to the solar radiation incident on the system over the considered period:

$$\tau_{S,m} = \frac{\sum_{i=1}^{45} E_b(\theta_i) \cdot \tau_{S,\theta}(\theta_i) + (E_d + E_a) \cdot \tau_{S,d}}{E_b + E_d + E_a} \qquad (18)$$

where $\theta_1=1°$, $\theta_2=3°$, ..., $\theta_{45}=89°$.

An analogous expression can be used to calculate the average solar reflection coefficient:

$$\rho_{S,m} = \frac{\sum_{i=1}^{45} E_b(\theta_i) \cdot \rho_{S,\theta}(\theta_i) + (E_d + E_a) \cdot \rho_{S,d}}{E_b + E_d + E_a} \qquad (19)$$

where $\theta_1=1°$, $\theta_2=3°$, ..., $\theta_{45}=89°$.

In tables 3, 4, 5 are presented the average values of solar energy transmittance for the analyzed systems referred to the considered conditions.

Table 5: Average solar energy transmittance ($\tau_{S,m}$) of system 1.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.595	0.488	0.503	0.502	0.477	0.472	0.475	0.499	0.504	0.475	0.467
Heating period		0.534	0.521	0.488	0.468	0.488	0.532	0.520	0.488	0.466	0.489
Summer design day		0.394	0.475	0.515	0.484	0.435	0.374	0.468	0.514	0.483	0.431

Table 6: Average solar energy transmittance ($\tau_{S,m}$) of system 2.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.261	0.184	0.192	0.193	0.178	0.176	0.177	0.190	0.194	0.177	0.173
Heating period		0.210	0.205	0.184	0.173	0.183	0.208	0.205	0.184	0.173	0.183
Summer design day		0.135	0.172	0.201	0.182	0.159	0.128	0.169	0.200	0.181	0.158

Table 7: Average solar energy transmittance ($\tau_{S,m}$) of system 3.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.172	0.139	0.143	0.143	0.136	0.134	0.135	0.142	0.143	0.135	0.133
Heating period		0.152	0.148	0.139	0.133	0.139	0.151	0.148	0.139	0.133	0.139
Summer design day		0.111	0.134	0.147	0.138	0.124	0.106	0.132	0.146	0.137	0.123

The average value of total solar energy transmittance can be obtained as the ratio of the globally transmitted energy to the solar radiation incident on the fenestration system over the considered period:

$$\mathrm{TSET_m} = \frac{\sum_{i=1}^{45} E_b(\theta_i) \cdot \mathrm{TSET}_\theta(\theta_i) + (E_d + E_a) \cdot \mathrm{TSET_d}}{E_b + E_d + E_a} \qquad (20)$$

where $\theta_1=1°$, $\theta_2=3°$, ..., $\theta_{45}=89°$.

In the application of the developed model for the calculation of TSET, different values have been assumed for environmental temperatures and surface heat transfer coefficients depending on the considered periods (see table 8).

Table 8: Environmental temperatures and surface heat transfer coefficients.

	T_{ext} [°C]	**T_{int} [°C]**	**T_{rm} [°C]**	**h_e [W/m^{2}K]**	**h_{ci} [W/m^{2}K]**	**h_{ri0} [W/m^{2}K]**
Yearly period	20	20	20	23	3.6	4.4
Heating period	15	15	15	23	3.6	4.4
Summer design day	25	25	25	14.5	2.7	5.5

In tables 9, 10, 11 the average values of total solar energy transmission coefficient (TSET) of the three systems are presented for different locations, orientations and environmental conditions.

Table 9: Average total solar energy transmittance ($\mathrm{TSET_m}$) of system 1.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.694	0.591	0.605	0.604	0.578	0.572	0.577	0.601	0.606	0.576	0.567
Heating period	0.694	0.637	0.623	0.590	0.569	0.590	0.636	0.622	0.590	0.566	0.591
Summer design day	0.709	0.510	0.596	0.634	0.603	0.549	0.488	0.589	0.633	0.602	0.544

Table 10: Average total solar energy transmittance ($TSET_m$) of system 2.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.442	0.350	0.361	0.361	0.341	0.337	0.341	0.358	0.363	0.340	0.334
Heating period	0.442	0.385	0.377	0.351	0.335	0.349	0.383	0.376	0.350	0.333	0.349
Summer design day	0.462	0.303	0.359	0.393	0.368	0.333	0.291	0.354	0.392	0.368	0.330

Table 11: Average total solar energy transmittance ($TSET_m$) of system 3.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.262	0.226	0.231	0.231	0.222	0.221	0.221	0.229	0.231	0.221	0.219
Heating period	0.261	0.241	0.236	0.225	0.218	0.226	0.240	0.236	0.225	0.217	0.226
Summer design day	0.298	0.226	0.256	0.271	0.259	0.240	0.218	0.254	0.270	0.259	0.238

Tables 12, 13, 14 report the average values of incidence factors of the three systems referred to the total solar energy transmittance ($TSET_m/TSET_n$) for different locations, orientations and environmental conditions.

Table 12: Average incidence factor ($TSET_m/TSET_n$) for the yearly period.

Orientation	System 1		System 2		System 3	
	Turin	Naples	Turin	Naples	Turin	Naples
S	0.852	0.832	0.794	0.772	0.862	0.844
SE/SW	0.873	0.867	0.818	0.810	0.881	0.875
E/W	0.871	0.873	0.818	0.821	0.880	0.882
NE/NW	0.834	0.830	0.773	0.769	0.849	0.845
N	0.825	0.817	0.764	0.756	0.842	0.835

Table 13: Average incidence factor ($TSET_m/TSET_n$) for the heating period.

Orientation	System 1		System 2		System 3	
	Turin	Naples	Turin	Naples	Turin	Naples
S	0.919	0.917	0.871	0.867	0.923	0.921
SE/SW	0.898	0.897	0.852	0.851	0.905	0.904
E/W	0.850	0.850	0.793	0.792	0.862	0.862
NE/NW	0.819	0.816	0.757	0.754	0.837	0.834
N	0.850	0.851	0.789	0.790	0.866	0.867

Table 14: Average incidence factor ($TSET_m/TSET_n$) for the summer design day.

Orientation	System 1		System 2		System 3	
	Turin	Naples	Turin	Naples	Turin	Naples
S	0.719	0.687	0.657	0.630	0.760	0.733
SE/SW	0.841	0.830	0.777	0.766	0.861	0.852
E/W	0.894	0.892	0.851	0.848	0.908	0.907
NE/NW	0.850	0.848	0.798	0.796	0.871	0.869
N	0.775	0.767	0.722	0.715	0.807	0.800

Tables 15, 16, 17 report the average values of shading coefficient (SC_m) of the three systems for different locations, orientations and environmental conditions. SC_m is calculated as:

$$SC_m = TSET_m / TSET_m^{(ASHRAE)} \tag{21}$$

The average value of total solar energy transmittance for the ASHRAE reference glass ($TSET_m^{(ASHRAE)}$) is calculated following the procedure described in eq. (20).
For normal incidence the value of $TSET^{(ASHRAE)}$ is equal to 0.883 both for the yearly period and for the heating period, it is equal to 0.889 for the summer design day.

Table 15: Average shading coefficient (SC_m) of system 1.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.785	0.731	0.738	0.737	0.725	0.721	0.726	0.736	0.739	0.724	0.720
Heating period	0.785	0.752	0.748	0.731	0.720	0.726	0.751	0.748	0.731	0.719	0.726
Summer design day	0.798	0.703	0.741	0.760	0.746	0.726	0.696	0.737	0.759	0.745	0.725

Table 16: Average shading coefficient (SC_m) of system 2.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.500	0.434	0.440	0.441	0.428	0.425	0.429	0.438	0.442	0.427	0.424
Heating period	0.501	0.455	0.452	0.434	0.424	0.430	0.453	0.452	0.434	0.424	0.430
Summer design day	0.520	0.418	0.446	0.471	0.456	0.441	0.415	0.442	0.470	0.445	0.440

Table 17: Average shading coefficient (SC_m) of system 3.

	Normal	TURIN					NAPLES				
		S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Yearly period	0.297	0.279	0.281	0.282	0.279	0.278	0.278	0.281	0.282	0.278	0.278
Heating period	0.295	0.284	0.283	0.279	0.276	0.278	0.283	0.283	0.279	0.276	0.278
Summer design day	0.335	0.312	0.318	0.324	0.321	0.318	0.311	0.318	0.324	0.321	0.318

6. CONCLUSIONS

This study has pointed out the importance of a correct characterization of fenestration systems and has allowed to draw some conclusions about the applicability of the most common methods for the calculation of solar heat gain.

The use of total solar energy transmittance for normal incidence ($TSET_n$) should be preferably avoided: errors in the determination of solar heat gains can exceed 50 %.

A better accuracy in the characterization of fenestration and shading systems can be obtained by correcting the total solar energy transmittance for normal radiation ($TSET_n$) by an incidence factor.

This factor, used in some Italian Standards, is also called “exposition factor”: it is expressed as a function of fenestration orientation and of the considered period, but it should be independent of the locality and of the kind of system.

Actually, the incidence factor shows to be quite independent of the locality (differences less than 1% moving from Turin to Naples), except for the South exposition during the yearly period (differences exceed 2%) and during the summer design day (differences of about 4%).

More evident is the dependence on the kind of system: with regard to the ASHRAE reference glass, it shows negative deviations varying from 4% to 12% for the clear doubled-glazed window, from 9 to 20% for the clear doubled-glazed window with an inner shade, from 3% to 7% for the reflective doubled-glazed window.

These results point out that even the use of exposition factors do not always allow to obtain an acceptable accuracy.

The use of a shading coefficient calculated for normal incidence (SC_n) combined with a detailed analysis of an ASHRAE reference glass under the same environmental conditions does not give better results. The error range is from 5% to 15% for the clear doubled-glazed window (system 1), from 10% to 24% for the clear doubled-glazed window with an inner shade (system 2), from 3% to 8% for the reflective doubled-glazed window (system 3).

The approach followed in this work, consisting of a detailed modelization of fenestration and shading systems coupled with a statistical analysis of solar radiation, represents an effective way towards the overcoming of old characterization methods.

In order to extend the applicability of the model to complex fenestration systems, in the next future the spectral dependence of solar-optical properties will be taken into account.

The final aim is to analyze a great number of systems and environmental conditions in order to get simple correlations appliable in most design cases.

7. NOMENCLATURE

L	location latitude	[°]
H_{eo}	daily extraterrestrial solar irradiation on horizontal plane	[Wh/m^{2}d]
H_o	daily global solar irradiation on horizontal plane	[Wh/m^{2}d]
D_o	daily diffuse solar irradiation on horizontal plane	[Wh/m^{2}d]
I_{bn}	normal direct solar irradiance	[W/ m^2]
I_{bo}	direct solar irradiance on horizontal plane	[W/ m^2]
I_{do}	diffuse solar irradiance on horizontal plane	[W/ m^2]
I_b	direct solar irradiance on the component	[W/ m^2]
I_d	diffuse solar irradiance on the component	[W/ m^2]
I_a	reflected solar irradiance on the component	[W/ m^2]
E_b	direct solar irradiation on the component over the considered period	[MJ/ m^2]
E_d	diffuse solar irradiation on the component over the considered period	[MJ/ m^2]
E_a	reflected solar irradiation on the component over the considered period	[MJ/ m^2]
θ	incident angle of direct solar radiation	[°]

δ	solar declination	[°]
φ_S	solar azimuth	[°]
β_S	solar altitude	[°]
φ	azimuth of the component	[°]
Σ	slope angle of the component relative to the horizontal	[°]
TSET	total solar energy transmission coefficient	[-]
τ_S	solar transmission coefficient	[-]
ρ_S	solar reflection coefficient	[-]
α_S	solar absorption coefficient	[-]
$\tau_{S,d}$	solar transmission coefficient for diffuse radiation	[-]
$\tau_{S,\theta}$	solar transmission coefficient for direct radiation	[-]
$\tau_{S,\theta\theta}$	directional solar transmission coefficient for direct radiation	[-]
$\tau_{S,\theta h}$	hemispherical solar transmission coefficient for direct radiation	[-]
ε	emissivity	[-]
H	height of the window	[m]
T_{ext}	external temperature	[°C]
T_{int}	internal temperature	[°C]
T_{rm}	mean radiant temperature	[°C]
h_{ci}	internal convective heat transfer coefficient	[W/ m^{2}K]
h_{ri}	internal radiative heat transfer coefficient	[W/ m^{2}K]
h_{ri0}	internal radiative heat transfer coefficient for a std emissivity component	[W/ m^{2}K]
h_e	external surface heat transfer coefficient	[W/ m^{2}K]
SC	shading coefficient	[-]

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