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ASSESSING THE DYNAMICS OF INDOOR NATURAL ILLUMINANCE IN ADVANCED PACKAGES FOR BUILDING ENERGY ANALYSIS

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ABSTRACT

Advanced packages for building energy analysis require simplified methods to reduce the computational time in assessing the indoor visual environment. The paper develops and compares some simplified calculation procedures for a quick assessment of the minimum indoor natural illuminance on the working plane in office spaces when external shadings and light control systems are used. Simplified procedures are based on the split of the internal illuminance into two components due to direct and diffuse sun radiations, expressed by the Solar System Luminous Efficacies, calculated by the package Superlite. Comparisons are carried out on energetic basis by the hourly simulation program IENUS.

INTRODUCTION

Advanced and simplified energy analysis programs are widely used at different stages of the building design process to reach a good optimization, coordination and choice among available and possible thermal and light control systems.

Complex simulations are often not appropriate to outline basic daylighting strategies in a first approach and to solve simple, frequently occurring problems. At the same time, it can be useful to simplify lighting evaluations at maximum to reduce on one hand the running time of the more complex advanced programs, and on the other to have simple tools to use in the first phases of design.

Lumen methods and daylight factor methods are used in different ways into hourly building energy analysis programs. Routines evaluating daylight illuminance can be integrated in the main body of the program or pre-processed; besides, they can be based on geometric calculations or may be evaluated from empirically determined factors correlating daylight illuminance with the transmitted solar irradiance flowing through the windows.

In advanced packages, the major difficulty is to re-calculate internal illuminance at every time-step due to weather change, as the "standard" methods cannot be used in a dynamic mode. Although different approaches are used, most advanced packages pre-process indoor natural lighting calculations before entering in the thermal simulation. For example in DOE 2.1 (Winkelmann and Selkowitz, 1988) daylight factors (*DF*) are pre-calculated over a range of solar, while the TSBI3 approach (Grau and Johnsen, 1994) is based on Solar Light factors (*SF*).

The aim of this paper is to develop and compare simple calculation procedures to be used in building energy analysis for a quick assessment of the minimum illuminance on the working plane, in office spaces equipped with natural and artificial light control systems and external shading devices.

Also if many tools to optimize external shading devices have been developed, (IES Handbook 1984, ASHRAE Handbook 1997, Yener 2001, de Almeida 2001, Carbonari et al. 2001), none of them is susceptible to be easily implementable in dynamic simulations of the natural indoor illuminance.

The presented approach is based on the split of the internal illuminance into two components, due to the direct and the diffuse sun radiations, that are expressed by Solar System Luminous Efficacies, *SSLEs* introduced by Place et al., (1984), and calculated with the simulation package Superlite (1994). *SSLEs* are the ratio of the illuminance on a prefixed point to the external horizontal radiation per m^2. This approach was chosen depending on the fact that meteorological inputs for simulation packages are based on sun horizontal irradiations taken from typical years (TMY, DMY, etc.), while outside statistically significant illuminance data are generally not available, as generally not supplied over long periods.

Comparisons are carried out on energetic basis by the hourly simulation program IENUS (Gugliermetti et al., 1988, 2000a, 2000b, 2001, 2002, 2003) developed to assess building energy demand taking into account the integration between visual and thermal aspects also in complex cases in which light control systems and innovative transparent materials are present. The introduced improvement concerns so far the possibility to evaluate the contribution of fixed external shading devices.

CALCULATION HYPOTHESIS

Simulations for the evaluation of building energy demand are referred to a typical office room with three working places located in Rome (RM, 42° N). Room dimensions are 5m x 7m x 3m, with only one 5m x 3m external wall, that presents a central 3m x 2m window opening with its centre at 1.8 m from the floor. Working period for occupants (50 W/p of sensible heat, 50% convective and 50% radiative), equipment (800 W), HVAC and artificial light system is from 8.00 A.M. to 20.00 P.M., everyday. Latent loads, ventilation and infiltration rates are not considered. Room furnishing is ordinary without carpet. External wall thermal transmittance is U=0.80 W/(m^{2}K), while the envelope construction weight is about 200 Kg/m^2 of floor. A double window with clear glazings has been considered, whose characteristics have been evaluated by WINDOW 4.1 (Arasteh, 1994) on the base of the single angular glazing material properties.

Integration of natural and artificial light management is obtained with a photosensor connected to a controller: it detects the illuminance and dims lamps light output (0-600 W) to guarantee a minimum illuminance on the working plane at about 500 lux. A 3 equal zones dimming strategy for artificial light is considered to operate. Two kinds of daylight management have been considered to test the efficacy of the different SSLEs: a) an internal shading device, with an on/off strategy that closes the curtain when the direct solar radiation impinging on it after flowing through the glazing system is greater than the set point of the controller, here fixed at 30 W/m^2, code FET; the internal curtain present a shading coefficient SC=0.4 and T_{vnn}=50%, while the direct light transmitted diffusely is T_{vndiff}=10%. The angular dependence of curtain light transmission is not taken into account during illuminance and thermal calculations; b) only fixed external shading devices with previously defined depths, code FNT.

Analyzed overhangs, for South window, and vertical fins, for East window, are supposed to be infinite respect to window dimensions, while their depth was determined by sun path chart and the protractor (Olgyay et al., 1957) to shade fully the window during the summer period. This "optimal" depth is 1.60m (*S1*) for the overhang and 2.40m (*E1*) for vertical fins. Besides other four depths for South orientation, and two for East, respectively 1.20m, 1.00m (*S2*), 0.80m and 0.40m (*S3*), and 1.50m (*E2*) and 0.60m (*E3*) are also explicitly analyzed to better evaluate the functionality and the accuracy of the proposed method.

SSLE CALCULATION PROCEDURE

In this paper, all the Solar System Luminous Efficacies are calculated by the package Superlite for each hour of a month central day for December and June; all the months of the year are then obtained by linear interpolation between December and June. Luminous efficacies of 115 lm/W for the direct component of the solar irradiation and 120 lm/W for the diffuse one have been used. Five inter-reflections are considered to calculate the reflected component with no ground reflectance. Visible reflectance for the walls is 50%, for the floor 20%, for the ceiling 80%, and 40% for the external shading devices. All surfaces are considered as lambertians.

The minimum indoor illuminance on the working plane is calculated in IENUS by splitting it into two different components, respectively produced by the horizontal direct (I_{dir}) and diffuse (I_{dif}) solar radiation and using *SSLEs*, obtained with no external shadings, in the following generalized equation:

$$E_{tot} = SSLE_{dif} I_{dif} + SSLE_{dir} I_{dir} \quad (1)$$

Equation (1) can be extended to the case with fixed external shading devices by developing new values of *SSLEs** explicitly referred to the considered case. This means to evaluate a specific couple of *SSLEs** for each specific case. Otherwise, in order to avoid the recalculation of the Solar System Luminous Efficacies in presence of external overhangs and fins, a simplified procedure expressed by the following equation can be used:

$$E_{tot} = SSLE_{dif} I_{dif} + \frac{A_D}{A_T} SSLE_{dir} I_{dir} \quad (2)$$

being A_D and A_T respectively the window sunlit area and the total window area, and *SSLE*s the same of Equation (1). From a lighting design viewpoint, Equation (2) introduces very large and instable approximations, and cannot be considered as a tool in illuminance calculations. Anyway, in energy analysis simulations, in which overall computations could admit also greater approximations, it introduces sensible simplifications that make it an interesting and useful tool.

Equation (2) with *SSLEs** shows a great reliability (Bisegna et al., 2002a), and it can be used with no significant approximations to assess minimum illuminance values (i.e. Table 1 and Table 2 referred to the considered room, external shading devices and no ground reflectance). A series of illuminance measurements on an appositely built up scale model have been developed to test and validate the efficacy of Equation (2) with *SSLEs**; Figure 1 shows the case of a South oriented room, with real values of radiation.

The reflected component of sun diffuse and direct radiation I_{rif} is not explicitly reported in equations (1) and (2), but its influence on the minimum indoor illuminance can be approximately calculated substituting I_{dif} with (I_{dif}+ I_{rif}). This last approximation increases with outdoor reflectance, but it results also acceptable for the indoor darkest point, being less then 5%.

The A_D/A_T ratio, when required, and the sun reflected component, are calculated by the formula reported in Ashrae 1976, 1993.

Figure 2 and Figure 3 report, as examples, some *SSLEs** and their interpolations for the case of a South oriented room with a 1.0m external overhang used then in the following simulations.

RESULTS

Analysis was developed with the aim to understand the approximations introduced by using equation (1), with *SSLE*,* and Equation (2) in the evaluation of an office space energy demand when using fixed external shading devices. The overall energy performance and the heating (H), cooling (C) and lighting (L) behaviors of the room have been compared, when only the external shading device is foreseen (FNT) or when the internal curtain works together with the external shading device (FET), as an integration to control daylighting.

Heating, cooling and artificial lighting are reported into petroleum equivalent tons (Tep) with the following conversion factors:

- cooling system: 2.17×10^{-2} tep/GJ (performance COP=3.2);
- heating system: 3.23 x 10-2 tep/GJ (efficiency η=0.8);
- artificial light system: 8.68 x 10-2 tep/GJ (ballast factor BF=0.8).

Figure 4 shows the approximations between Equation (2) and Equation (1) with *SSLEs** for several dimensions of the shading devices and for two main orientations (South and East) in terms of overall energy demand, tep. Following the same way, Figure 4 shows approximations in terms of partial results (H, C, L).

Figures show a good accordance between the two kinds of simulations: specifically, simulations carried out with Equation (2) present always smaller energy consumption values with the exception of the two cases of South with overhang 0.4m and 0.8m, both FNT and FET, in respect to Equation (1). This is because Equation (2) tends to alter the effect of the diffuse radiation only for a little quantity due to the difference between $SSLE_{dif}$ (Equation 2) and $SSLE_{dif}$* (Equation 1), while the effect of the direct one is greatly influenced by the ratio $A_D/A_T < 1$ and by the different values of $SSLE_{dir}$ and $SSLE_{dir}$*. These influences produce a different regulation of the internal shading devices, when present, and of the artificial lights, altering energy consumption. All the other cases (bigger dimensions of the shading device for South, great influence of direct radiation in non-relevant hours, from 5.00 to 8.00, for East) present instead an opposite tendency for energy consumption. For what concerns West orientation, FET situation can be assimilated to the East case, as it presents the same tendency, with curtains in off position (and artificial light on) during the last afternoon hours, to avoid occupants' glare; there will be different results for the FNT case instead, due to the absence of internal curtains, although the problem exists only in the winter period, when the sun is at the lowest altitude, and in the very last hours of summer days; anyway, it cannot be considered a real case. For South, lower approximations happen in the cases of 1.0m overhang, 0.3% and 0.7%, respectively for FET and FNT situations; for East, the case with 1.5m vertical fins is the best, with percentage errors of about 4.9% (FET) and 4.2% (FNT).

Anyway, all approximations can be considered negligible, as they vary in a range between –2.9% and 5.1% for South, and between 4.2% and 8.6% for East, that is on the whole a 8.0-8.6% approximation, really acceptable for integrated energy analysis evaluations.

Partial behaviors follow the story of overall energy requirements: East orientation presents the highest percentage errors, with a maximum of 2.7% for H, -10.9% for C and 17.9% for L. Maximum errors for South are 1.2% for H, 8.1% for C and 11.4% for L. East orientation is always characterized by positive L and H percentage errors, while C is always negative: this means that non-exact simulations tend to have a lower use of electric light and heating due to a higher utilization of solar radiation, and this explains C results; H percentage errors vary between 1.3% and 2.7%, C in the range –5.4%÷ –10.9%, L between 9.3% and 17.8%. Minimum percentage errors are for East 1.3% (H) and –5.4% (C) for the case 0.6m vertical fins FNT, 9.3% (L) for the case 0.6m vertical fins FET.

South orientation instead presents negative H and L percentage values for small overhangs (between 0.4m and 1.0m for H, 0.4m and 0.8m for L) and positive values for the remaining cases, while C is always positive: this means that passing from short to bigger overhangs, equation (2) and equation (1) tend to underestimate first, and then to overestimate the effect of the direct radiation. H percentage errors vary between –1.1% and 1.2%, C in the range 1.9%÷8.1%, L between –6.8% and 11.4%. Minimum percentage errors are –0.2% (H), cases 1.0m overhang, FNT and FET, 1.9% (C) for the case 1.6m overhang FET, 1.2% (L) for the case 1.0m FET. Overall variations are 3.8% for H, 16.3% for C and 24.6% for L and can considered a acceptable, also considering that C approximations tend to balance H and L variations.

CONCLUSIONS

Comparisons on energetic basis of simple calculation procedures for a quick assessment of the indoor minimum illuminance on the working plane when external shadings are present are here presented. An equation, previously studied for visual calculations and used with *SSLEs* referred to cases of no external shading devices, has been proposed and here investigated from an energetic point of view. Energy requirements obtained with this simplified equation have been compared with exact simulations developed using correct *SSLEs**. Results are encouraging, as overall variations on partial behaviors, heating, cooling and artificial lighting, range from 3.8% to 24.6%, with cooling showing a balancing effect on heating and lighting variations. By the same way, approximations on overall energy demand are sensibly low, guaranteeing a sufficiently accurate building energy analysis.

Anyway, some steps are still to be done to assure a good approximation and at the same time a sensible simplification in calculations: a more accurate evaluation of the role played by the reflected component of solar radiation should increase the precision without increasing the complexity of this simplified method, a hypothetical parameterization of *SSLEs* curves could improve the simplicity of the method; moreover, an analysis of the variation of approximation accuracy varying the illuminance requested on the working surface must be done. Experimental measurements should also be completed to definitely validate the approximation introduced by the equation.

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NOMENCLATURE

I_{dir}: Horizontal direct solar radiation.
I_{dif}: Horizontal diffuse solar radiation.
$SSLE_{dir}$: Efficacy referred to 100 W/m^2 of outdoor horizontal sun direct irradiation
$SSLE_{dif}$: Efficacy referred to 100 W/m^2 of outdoor horizontal sun diffuse irradiation.
A_D: Window sunlit area.
A_T: Total window area.

Table 1
Equation (1) approximations, December

hour	***D [%]***					
	S1	*S2*	*S3*	*E1*	*E2*	*E3*
8	4,42	3,51	1,15	0,04	0,02	0,01
9	10,00	6,64	3,39	0,05	0,03	0,01
10	8,83	6,14	2,96	0,04	0,04	0,02
11	8,22	4,39	2,39	0,04	0,04	0,04
12	5,55	4,51	2,41	0,04	0,04	0,04
13	8,22	4,39	2,39	-	-	-
14	8,83	6,14	2,96	-	-	-
15	10,00	6,64	3,39	-	-	-
16	4,42	3,51	1,15	-	-	-

Table 2
Equation (1) approximations, June

hour	***D [%]***					
	S1	*S2*	*S3*	*E1*	*E2*	*E3*
5	0,09	0,07	0,07	10,57	5,05	0,98
6	0,11	0,09	0,08	2,96	3,57	1,16
7	0,12	0,10	0,09	0,93	0,45	0,39
8	0,08	0,06	0,06	0,00	0,00	0,00
9	0,22	0,12	0,10	0,01	0,01	0,00
10	2,28	1,76	1,27	0,01	0,01	0,01
11	2,95	2,27	1,38	0,01	0,01	0,01
12	0,37	0,17	0,09	0,01	0,01	0,01
13	2,95	2,27	1,38	-	-	-
14	2,28	1,76	1,27	-	-	-
15	0,22	0,12	0,10	-	-	-
16	0,08	0,06	0,06	-	-	-
17	0,12	0,10	0,09	-	-	-
18	0,11	0,09	0,08	-	-	-
19	0,09	0,07	0,07	-	-	-

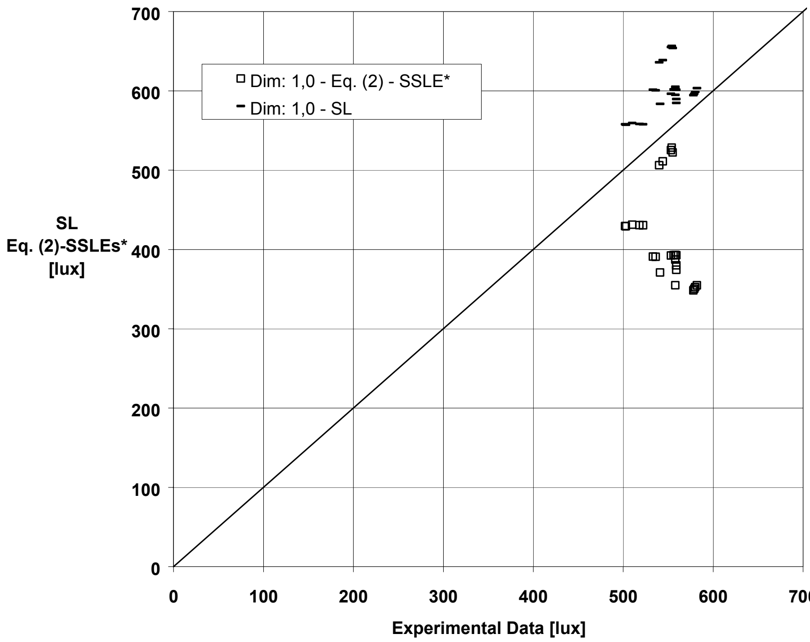

Figure 1: Scale model measurements versus Superlite (SL) and Equation (2) with SSLEs calculations, 1.0m external overhang.*

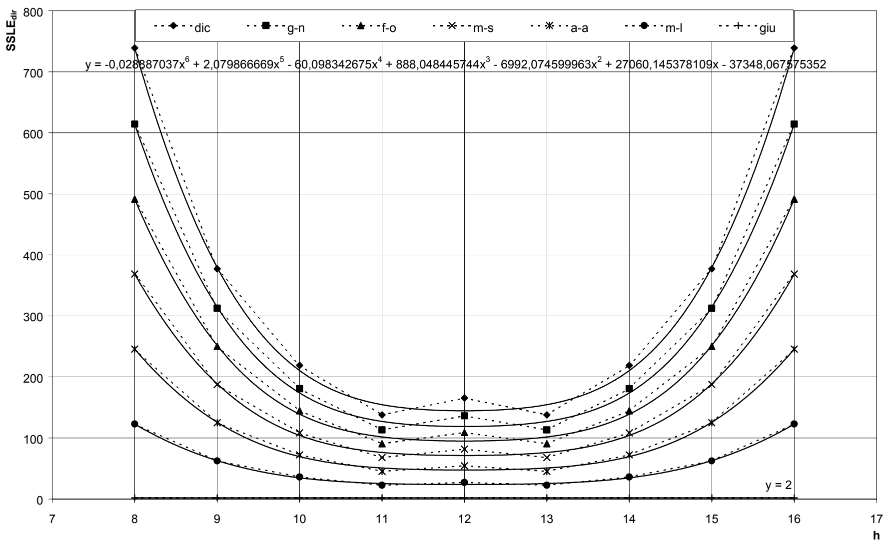

Figure 2. $SSLE_{dir}$ for South orientation, 1.0m external overhang.

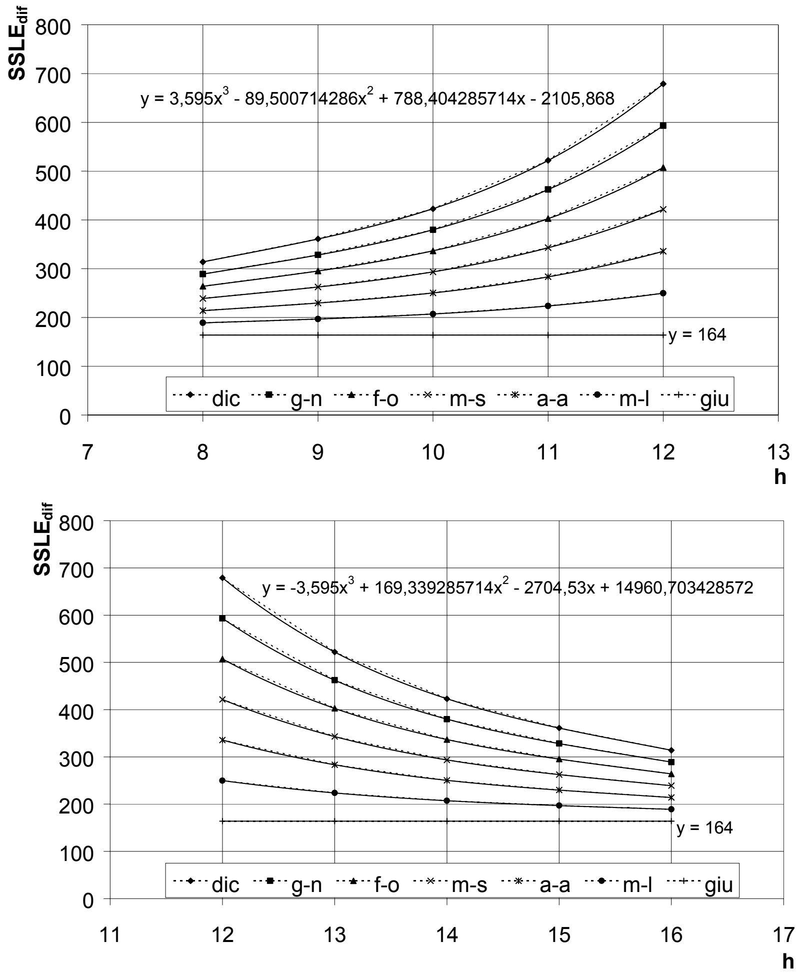

Figure 3. SSLE$_{dif}$ for South orientation, 1.0m external overhang.

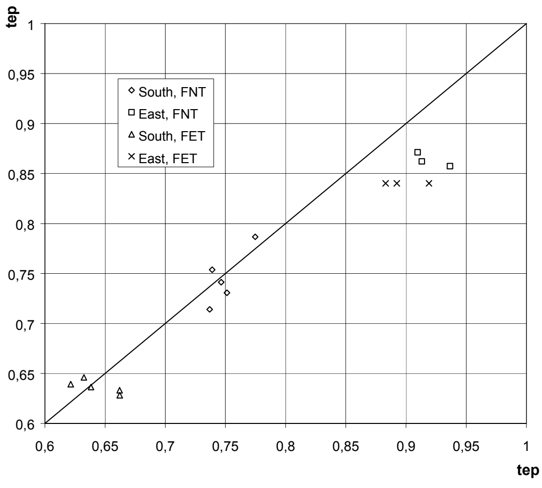

Figure 4. Approximations, tep.

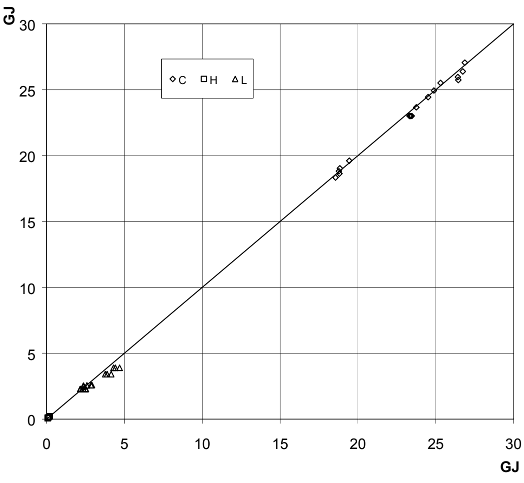

Figure 5. Approximations, GJ.