EFFECTS OF WINDOW SIZE IN DAYLIGHTING AND ENERGY PERFORMANCE IN BUILDINGS

Jose Manuel Almodóvar Melendo
University of Seville
Avda. Reina Mercedes, 2
41012 Seville, Spain
e-mail: jmalmodovar@us.es

Pablo la Roche
California State Polytechnic University, Pomona
3801 West Temple Avenue
Pomona, CA 91768
e-mail: pmlaroche@csupomona.edu

ABSTRACT

The design of buildings is a complex process in which decisions are taken during the design stage that critically affect the habitability and energy performance. In this sense, large window areas allow more daylight into a space, but they may also allow excessive heat gains or losses which increase the air-conditioning cooling or heating load, and the energy consumption.

For a correct selection of window size it is advisable to consider the combined effect of daylight and temperature. In this paper a typical office space in Los Angeles, 4 x 4 x 3 m. high (13.12x13.12x9.84 ft.) was used as a base case to analyze this question and provide guidelines on appropriate glazing ratios in the façade. To determine this ratio the daylight availability and energy consumption are identified as the major criteria and an energy analysis software HEED (Develop by the Energy Design Tools Group of UCLA and CTG Irving Energetics. California) has been used together with a daylighting computer software based on configuration factors.

The results can serve as reference for similar spaces and show that a suitable design of fenestration, in which it considers the combined effect of illumination and temperature, could significantly reduce peak cooling load and energy consumption of HVAC, while maintaining good thermal and illuminance indoor conditions.

1. INTRODUCCIÓN

Electric lighting systems are responsible for a high percentage of the energy consumption, specially in no-domestic buildings. In this sense it has been stated that around 31% of the total electricity used in the commercial sector is consumed in lighting systems (1).

Lighting consumption levels vary considerably from one countrie to another, due to not only the different climatic conditions or types of design but also to cultural habits. For example in China, the lighting consumption in commercial buildings is 15% (2), in the USA, 39% (3), whereas in the UK (4) varies in a range from 30% to 60%. This energy consumption contributes significantly to climate change and global pollution because of the dirty energy production processes.

On the other hand, the control of daylight can produce benefits in terms of improvements in the productivity of workers and reduction of absenteeism (5). We must also consider that lighting has a decisive influence in the perception of the space and its visual comfort. As historian Sigfried Giedion once pointed out, “In utter darkness, there is no significant difference between a rift and the Sixtine Chapel” (6). That said, it easily follows that if we want to understand the interior space we must understand its lighting qualities in advance.

In this sense, one of the main problems of environmental sciences applied to the architecture has been to determine how the built environment is transformed due to the phisionomy of the constructions and how the design should be adjusted to obtain a better climatic performance, in other words, how to optimize the architectural design to obtain a satisfactory and coherent distribution of the natural energy.

Nevertheless the energy impact of the design of windows and solar protection elements is not being considered by most of architects in the decision-making process. This is because the great number of subjective factors and formal possibilities that often exist. Even with the improvements in energy and daylighting simulation software, detailed building, climate and site data must usually be input to even make a simple simulation for each of these design schemes. As a consequence, we thought that it would be useful to establish guidelines that could be used by practicing architects, homeowners, builders or designers to make proposals that integrate the necessities of lighting and the energy efficiency on buildings.

2. PREVIOUS STUDIES

The importance of daylight in architecture is demonstrated by the great number of studies on this topic that have been developed in the last years. These have contributed to the development of new high performance windows and glazing types.

Daylight research ranges from predictive models of the luminance of the sky, to the detailed quantitative methods for the prediction of lighting levels in a closed space. Several daylighting and electrical lighting simulation programs have been developed that are frequently used at the present time, such as Radiance, Superlite, Lumen-Micro, etc.

Resarch has also demonstated that the excess of glazed surfaces in the building envelop exclusively for views must be reviewed carefully to reduce energy consumptions (7), since they have a very important repercussion in the heating and cooling demand (8). As a consequence, the necessity to relate daylighting simulations to software of energy analysis has been stated. Different forms exist to approach from this question and also different types of errors. Some of the more commonly used software that relates in an integrated way daylighting and energy demand are ESP-r and Energy Plus. Other programs such as WIS (9) and Parasol (10) permit to analyze a great variety of glazing and solar protection systems. Authors like Citherlet and Scartezzini (11), have also analyzed of integrated way the behaviour of different glazing systems.

Therefore, these studies have shown that the correct design of the glazed surface in buildings, in which thermal aspects and lighting are both considered, can considerably reduce the energy consumptions while contributing to improve the environmental quality of the indoor spaces (12).

3. METHODOLOGY

In spite of the numerous studies on energy efficiency in buildings in the last decades, most of the new construction is not being designed properly with regard to the integration of daylighting with the electric lighting systems and HVAC. An efficient design not only needs an Energy-efficient equipment, but also an Energy-efficient lighting design. The effective integration of the electric lighting and daylighting can only be possible if the lighting systems are designed based on the daylighting levels reached on the work plane.

To establish criteria to answer this question, a methodology was developed that integrates thermal and daylighting analysis in commercial buildings. The objective of this procedure is to establish guidelines that can serve as a reference in the design stage to select the optimal amount of glazed surfaces as a function of the orientation.

As a reference case of study, we have selected a small space which could be an office located in Los Angeles, 4x4x3 m high. All orientations have been analyzed at increments of 45º from the north. In each direction different proportions of windows in relation to the area of the wall were studied, which range from a value of 10% for the smallest windows to 80%.

In order to select the best window dimension, each orientation has been studied to compare the dimension of the window with daylight availability and energy demand.

4. SIMULATION OF DAYLIGHTING

4.1 Procedure to estimate daylighting

In order to determine the daylight values, a software based on a configuration factors method develop by Jose Maria Cabeza (13, 14) is used. This name is due to the fact that a series of exchange ratios, known as configuration factors, are calculated and organized until the required energy balance is found. Configuration factors represent a generalized version of the form factors used in heat transfer for radiometric systems.

The model extends the radiation properties of diffuse sources to luminous exitance of all kinds of building surfaces irrespective of their shape. These surfaces are therefore treated as radiative emitters by means of the generalized law of the projected solidangle (15).

We have assumed that all the materials involved in the calculations are almost perfect diffusers or Lambertian bodies, that is a very good approximation for most office spaces. The window is assumed a uniform diffuse luminous source, as well as the envelope. If the involved surfaces are clearly not lambertian or non-diffusive, for instance mirrors, we have to use a procedure which consists of producing an symmetrical image of the space considered with the axis precisely on the mirror surface (16). We have used the irradiance model of Gillette and Pierpoint to predict beam and diffuse solar radiation on tilted surfaces (17).

When we are discussing the design of a window we should be utterly aware of how and where and especially under which conditions the light reaches the inner spaces.

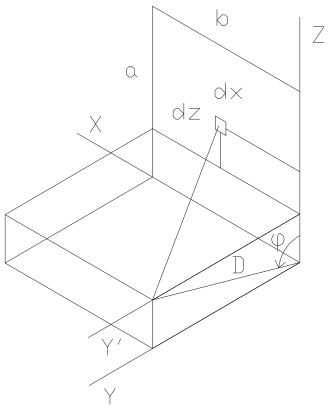


Fig. 1. Configuration factor between a rectangle and a point that belongs to a tilted plane (parallel to distance D).

With this objective expressions for the configuration factor between inclined surfaces have been integrated at several angles to be used for the simulation (figure 1). As a result we can obtain the following expression:

$$E=\frac{L}{2}\left[\begin{array}{l}\dfrac{a\cos\varphi-y}{\sqrt{a^2+y^2-2ay\cos\varphi}}\operatorname{arctg}\dfrac{b}{\sqrt{a^2+y^2-2ay\cos\varphi}}+\\+\dfrac{b\cos\varphi}{\sqrt{b^2+y^2\mathrm{sen}^2\varphi}}\operatorname{arctg}\dfrac{a\sqrt{b^2+y^2\mathrm{sen}^2\varphi}}{b^2+y^2-ay\cos\varphi}+\operatorname{arctg}\dfrac{b}{y}\end{array}\right]$$

Angle θ makes reference to the relation between the investigated point and the normal to the surface. This is the relation between the normal vector (0,1,0) and (- x, y, -z1).

On the other hand, angle φ defines the relation with the normal to the considered work plane. It is easy to notice that if φ = 90º, this would give cosine φ = 0 and sine = 1, substituting these values in the former equation:

$$E=\frac{L}{2}\left[\begin{array}{l}\dfrac{b}{\sqrt{b^2+y^2}}\operatorname{arctg}\dfrac{a}{\sqrt{b^2+y^2}}+\\+\dfrac{a}{\sqrt{a^2+y^2}}\operatorname{arctg}\dfrac{b}{\sqrt{a^2+y^2}}\end{array}\right]$$

This expression represents the exchange between parallel surfaces. If φ = 90º, cosine is 0 and the expression equates the above-stated formula for perpendicular rectangles.

$$E=\frac{L}{2}\left[\operatorname{arctg}\frac{a}{y}-\frac{y}{\sqrt{b^2+y^2}}\operatorname{arctg}\frac{a}{\sqrt{b^2+y^2}}\right]$$

The radiative transfer procedure allows us to quantify the effect of inter-reflection in the limiting surfaces (18). The involved mathematics are summarized as follows: the total component is made of the direct light plus the reflected light.

$$E_{tot}=E_{dir}+E_{ref}$$

Thus, If we are able to create two matrixes F_d and F_r with the elements described:

$$F_d=\begin{bmatrix}1 & -F_{12}\rho_2 & -F_{13}\rho_3\\ -F_{21}\rho_1 & 1 & -F_{23}\rho_3\\ -F_{31}\rho_1 & -F_{32}\rho_2 & 1\end{bmatrix}$$

$$F_d=\begin{bmatrix}0 & F_{12}\rho_2 & F_{13}\rho_3\\ F_{21}\rho_1 & 0 & F_{23}\rho_3\\ F_{31}\rho_1 & F_{32}\rho_2 & 0\end{bmatrix}$$

Where Fij are the corresponding configuration factors from surface I to surface j and ρ_i is the coefficient of reflection of surface I.

Then we could easily establish a relationship between reflected and direct illuminances.

$$F_r * E_r = F_d * E_d$$

And through matrix operations we arrive at the final expression which gives the reflected light as a function of direct light (19).

$$F^{-1}{}_r * F_r * E_r = F^{-1}{}_r * F_d * E_d$$

$$E_r = F_{rd} * E_d ; F_{rd} = F^{-1}{}_r * F_d$$

However this expression gives the values only as an average and therefore, minor corrections have to be applied in each particular case.

4.2. Daylight availability.

The daylight availability is defined as the fraction of working time in a year during which sufficient daylight is available on the work surface. As the analyzed space has a commercial use it has established 500 lux as the reference value from as the use of additional artificial illumination is considered necessary**.**

In the study case, the daylight availability has been calculated for each point of a grid of 50x50 cm (1.64x1.64 ft), being the work plane located 0.6 m (2ft.) from the floor. The ground reflectance is assumed equal to 20% (not snow), the floor reflectance 30%, the ceiling reflectance 80% and the reflectance of all sidewalls 70%. The windows are assumed as double-glazed windows. In order to calculate the transmitance of the window the formula of Rivero has been used. It is expressed as a function of the incidence angle of the sun (20).

$$T_\theta = T_o(\cos\theta + \sin^3\theta\cos\theta)$$

Daylignting was calculated hourly during working hours, from 8:00 AM to 4 PM solar time (symmetrical around noon). For all hours the ratio of existing daylight in relation to the minimum established (500 lux) has been calculated. When this value is surpassed the percentage is considered 100%.

Then the monthly and annual daylight availability distribution on the work plane was calculated. Figure 2 indicates the average value of all the points of the grid as a function of the orientation (45º intervals) and window-to-wall ratio from a range of values from 80% to 10%.

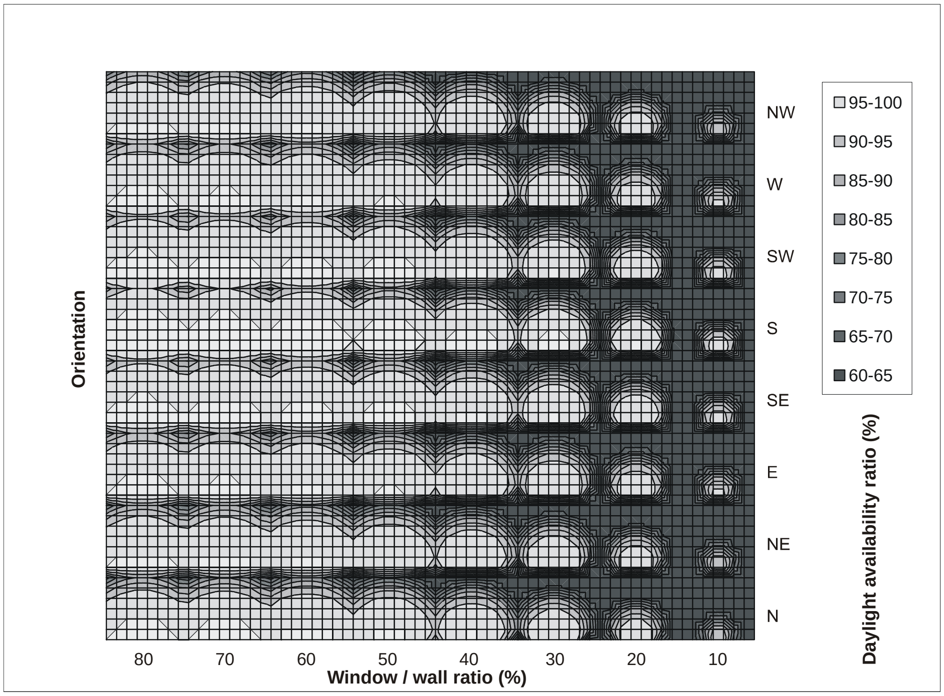
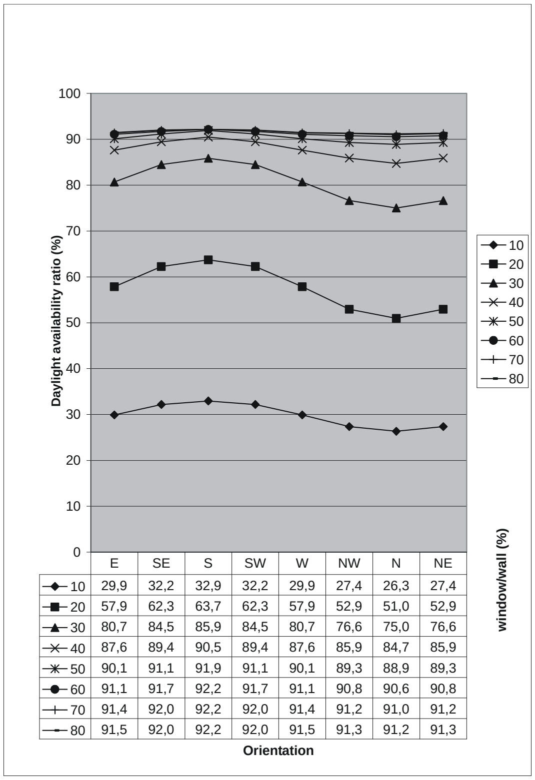


Fig. 2: Distribution of annual average daylight availability.

Finally the total average of the space has been determined in each direction (Figure 3).



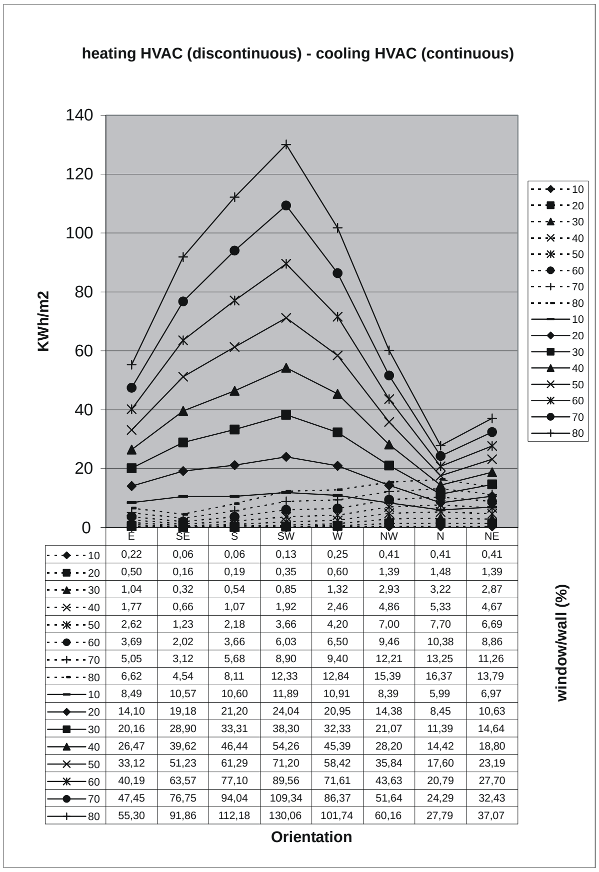
	E	SE	S	SW	W	NW	N	NE
—◆— 10	29,9	32,2	32,9	32,2	29,9	27,4	26,3	27,4
—■— 20	57,9	62,3	63,7	62,3	57,9	52,9	51,0	52,9
—▲— 30	80,7	84,5	85,9	84,5	80,7	76,6	75,0	76,6
—✕— 40	87,6	89,4	90,5	89,4	87,6	85,9	84,7	85,9
—✳— 50	90,1	91,1	91,9	91,1	90,1	89,3	88,9	89,3
—●— 60	91,1	91,7	92,2	91,7	91,1	90,8	90,6	90,8
—+— 70	91,4	92,0	92,2	92,0	91,4	91,2	91,0	91,2
—▬— 80	91,5	92,0	92,2	92,0	91,5	91,3	91,2	91,3

Fig. 3. Energy Annual average daylight availability ratio.

5. ESTIMATION OF ENERGY DEMAND

The energy demand through the year has been calculated with HEED, for the space with the same orientations and window-to-wall ratios previously used for daylighting.

The model input in the software has the envelope designed according to the California Title 24 energy code (2005) for climate zone 9. It consists of glass and aluminum frame with a U value of 0.67, insulation of wall R=13, roof R=30 and floor R=19. For infiltration, a standard construction has been selected (4.9 SLA). High natural ventilation (up to 20 air changes per hour) and high thermal mass, 3.5" ground of concrete and 0.62" plaster walls and ceiling are proposed. A double-glazed window with clear glass is used. Of course the reflectances are the same as for the daylight mode. The ground reflectance is 20% (not snow), the floor reflectance 30%, the ceiling reflectance 80% and the reflectance of all side walls 70%. The study plane is located 0.6 m (2 ft.) from the floor. In figure 4 we can observe the energy demand as a function of the orientation and window-to-wall ratio.



	E	SE	S	SW	W	NW	N	NE
- -◆- - 10	0,22	0,06	0,06	0,13	0,25	0,41	0,41	0,41
- -■- - 20	0,50	0,16	0,19	0,35	0,60	1,39	1,48	1,39
- -▲- - 30	1,04	0,32	0,54	0,85	1,32	2,93	3,22	2,87
- -✕- - 40	1,77	0,66	1,07	1,92	2,46	4,86	5,33	4,67
- -✳- - 50	2,62	1,23	2,18	3,66	4,20	7,00	7,70	6,69
- -●- - 60	3,69	2,02	3,66	6,03	6,50	9,46	10,38	8,86
- -+- - 70	5,05	3,12	5,68	8,90	9,40	12,21	13,25	11,26
- -▬- - 80	6,62	4,54	8,11	12,33	12,84	15,39	16,37	13,79
—▬— 10	8,49	10,57	10,60	11,89	10,91	8,39	5,99	6,97
—◆— 20	14,10	19,18	21,20	24,04	20,95	14,38	8,45	10,63
—■— 30	20,16	28,90	33,31	38,30	32,33	21,07	11,39	14,64
—▲— 40	26,47	39,62	46,44	54,26	45,39	28,20	14,42	18,80
—✕— 50	33,12	51,23	61,29	71,20	58,42	35,84	17,60	23,19
—✳— 60	40,19	63,57	77,10	89,56	71,61	43,63	20,79	27,70
—●— 70	47,45	76,75	94,04	109,34	86,37	51,64	24,29	32,43
—+— 80	55,30	91,86	112,18	130,06	101,74	60,16	27,79	37,07

Fig. 4. Energy demand – high mass and ventilation.

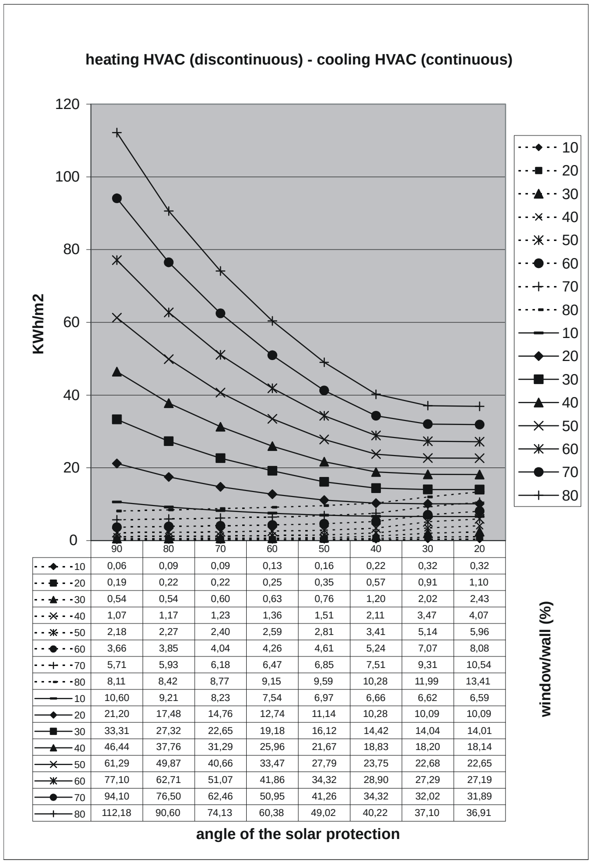
6. SHADING DEVICES

Shading devices contribute to the regulation of solar gains and therefore have a great effect on energy demand. In hot climates, or during periods of hot weather it is necessary to reduce the penetration of direct solar radiation, but when the temperature of an indoor space is below the comfort level, solar energy is a source of free heat.

In this sense the south-facing façade has well know unique features in latitudes such as Los Angeles, in which it receives more radiation in winter than in summer because the sun is lower in the sky in the winter months. On the other hand this orientation receives more daylight than other façades and it is possible to obtain solar radiation from it during most of the day.

The possibilities of energy saving on south-facing façades that can provide the regulation of solar radiation through horizontal protection elements, has been quantified with Heed. As a result in the same case study we can observe in figure 5 the variation of the energy demand as a function of different eaves sizes and window-to-wall ratio.

The obtained values indicate that increases in the depth of eaves, produce a high reduction of the cooling necessities, whereas the heating demand increases only slightly. The effect is greater in wider windows.



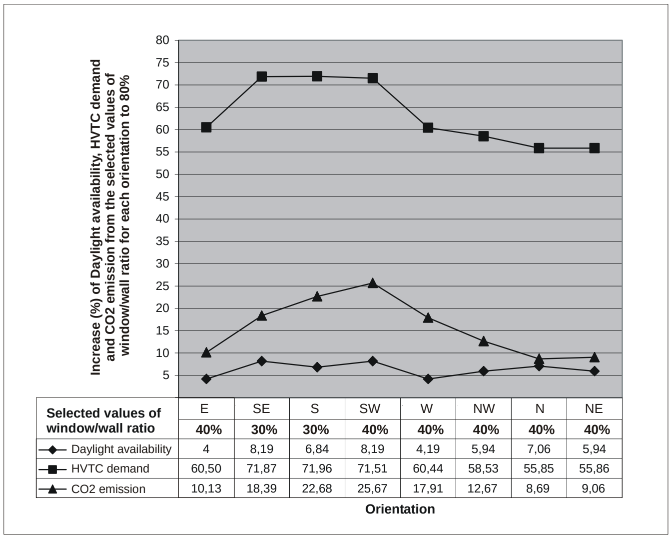
	90	80	70	60	50	40	30	20
- - ◆ - - 10	0,06	0,09	0,09	0,13	0,16	0,22	0,32	0,32
- - ■ - - 20	0,19	0,22	0,22	0,25	0,35	0,57	0,91	1,10
- - ▲ - - 30	0,54	0,54	0,60	0,63	0,76	1,20	2,02	2,43
- - × - - 40	1,07	1,17	1,23	1,36	1,51	2,11	3,47	4,07
- - ✳ - - 50	2,18	2,27	2,40	2,59	2,81	3,41	5,14	5,96
- - ● - - 60	3,66	3,85	4,04	4,26	4,61	5,24	7,07	8,08
- - + - - 70	5,71	5,93	6,18	6,47	6,85	7,51	9,31	10,54
- - - - - 80	8,11	8,42	8,77	9,15	9,59	10,28	11,99	13,41
—— 10	10,60	9,21	8,23	7,54	6,97	6,66	6,62	6,59
—◆— 20	21,20	17,48	14,76	12,74	11,14	10,28	10,09	10,09
—■— 30	33,31	27,32	22,65	19,18	16,12	14,42	14,04	14,01
—▲— 40	46,44	37,76	31,29	25,96	21,67	18,83	18,20	18,14
—×— 50	61,29	49,87	40,66	33,47	27,79	23,75	22,68	22,65
—✳— 60	77,10	62,71	51,07	41,86	34,32	28,90	27,29	27,19
—●— 70	94,10	76,50	62,46	50,95	41,26	34,32	32,02	31,89
—+— 80	112,18	90,60	74,13	60,38	49,02	40,22	37,10	36,91

Fig. 5. South-facing façade with eaves. Solar protection angle from 90º to 20º.

7. CONCLUSIONS

This paper presents a methodology to integrate thermal and daylighting simulation for a typical office space in Los Angeles with the objective to provide guidelines on selecting the surface of glazed areas at the early design stage. From the analysis of the results we can deduct that in all cases the increase of the window-to-wall ratio generates a significant increase of annual energy demand, but there are glazing ratios for each orientation in which the daylight availability is stabilized (figures 3 and 4). As a consequence, the reduction of window-to-wall ratio down to these values can provide adequate daylight, with a significant decrease in HVAC energy consumption which means lower CO2 emissions.

In order to quantify this question, in figure 6, increase of annual average daylight availability, total cooling and heating annual energy demand and CO2 emissions have been compared as a function of the window-to-wall ratio increase from a selected value for each orientation to 80%.



Selected values of window/wall ratio	E	SE	S	SW	W	NW	N	NE
	40%	**30%**	**30%**	**40%**	**40%**	**40%**	**40%**	**40%**
—◆— Daylight availability	4	8,19	6,84	8,19	4,19	5,94	7,06	5,94
—■— HVTC demand	60,50	71,87	71,96	71,51	60,44	58,53	55,85	55,86
—▲— CO2 emission	10,13	18,39	22,68	25,67	17,91	12,67	8,69	9,06

Fig. 6. Comparison of daylight availability, HVTC demand and CO2 emissions.

Our analysis indicates that in a south-facing façade, with a 30% of window-to-wall ratio, natural daylight provides the space with 500 lux on the work plane for 85.9% of the working time in a year. Increasing window size more than 30% will not result in significant increase in useful daylight in the room (a 6.84% increase for a 80% window-to wall ratio). Therefore 30% is identified as the daylighting saturation value in south-facing façades. With regard to the energy demand, reduction of glazed surfaces from 80% to the selected value (30%) produces a reduction of 71.96% on the energy demand in HVAC and 22.68% on the CO2 emissions.

Choosing 40% of north-facing façade to be glass only increase daylight availability by 7.06% when the window-to-wall ratio is 80%. Nevertheless, the demand of HVAC energy increases by 55.85% and as consequence CO2 emissions increase by 8.69%. On the other hand, the east facades receive a little less daylighting during the working time that the west, but both directions reach a stabilized daylighting condition for window-to-wall ratios higher than 40%. More detailed values in all analyzed orientations are shown in figure 6 that should be taken into account in Los Angeles when selecting the glass ratio of the façades.

On the other hand, It is advisable to study simultaneously shading devices and window size. In this sense we have been able to verify and quantify in Los Angeles the high energy savings that are possible to reach in south orientation by simply placing horizontal solar protections. For instance, in the case of a window-to-wall ratio of 30%, a simple eave with a solar protection angle of 60º produces the reduction of annual cooling demand from 33.31 to 19.18 kWh/m^2 (43%) while increasing the annual heating demand only from 0.54 to 0.63 kWh/m^2. Later developments of this work can be directed to analyze other types of solar protection in different orientations.

The methodology can be applied in other spaces and cities of the world to estimate optimal window dimensions that balance both daylighting and energy savings.

8. ACKNOWLEDGMENTS

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