A methodology to integrate advanced lighting and thermal analyses for building energy simulation

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Abstract

It is well known that an appropriate daylighting design can influence the global energy performance of a building as well as the visual and thermal comfort for the occupants. Furthermore the increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions can have on the daylighting condition within a space, in relation with the architectural features. This kind of analysis is becoming more and more requested, during all stages of the design process.

The purpose of this paper is to describe a reliable simulation approach to consider daylight when assessing the energy performance of a building. The methodology is based on the use of both Daysim and EnergyPlus which were employed in synergy for a parametric study to assess lighting and energy performances of rooms with different architectural features: orientation, window size and glazing visible transmittance, room depth, external obstruction angle and site. Daysim was chosen to perform daylighting analyses since it allows us to accurately estimate the annual amount of daylight in a space and calculating climate-based daylight metrics as well as the annual electric lighting use for different lighting controls. The Daysim output file that describes the status of all lighting and shading groups in the space during the year was then used as input in EnergyPlus to estimate the influence of the daylighting and artificial lighting design on the global energy performance of a space.

The paper presents some considerations on the simulation approach adopted in the study and the most important results that were obtained in terms of daylighting conditions and energy demand for lighting, heating and cooling, to demonstrate the substantial influence of daylight harvesting on the reduction of the global energy performance.

1. Introduction

Recent directives and legislation aimed at reducing energy consumption in private and public buildings (EN 15603, 2008; COM 772, 2008; Directive 2010/31/CE, 2010) have noticeably changed the focus on the building design approach over the last decade. In the lighting sector, a substantial reduction in electricity consumption for electric lighting could be obtained through a greater use of daylight, together with the use of the most energy efficient lighting technologies, such as LEDs or lighting controls. At the same time daylight harvesting in indoor spaces can influence the global energy performance of a building also in terms of heating and cooling loads. In fact the internal gains from lighting can be affected by the solar radiation that enters through the openings and by the electric lighting systems' load. For this reason it is always necessary to consider a balance between daylighting benefits and energy requirements, as shown in some recent studies (Chan et al., 2013; Didonè et al., 2011; Shen et al., 2011; Tzempelikos et al., 2007). Daylight has to be studied according to its dynamic behaviour over a period of time to accurately predict illuminance levels within a space. In this context, the 'Climate-Based Daylight Modelling (CBDM)' approach was recently proposed (Reinhart et al., 2006). CBDM allows daylighting to be studied taking into account the contribution of both direct and diffuse solar radiation and the variation due to local climate conditions over a period of time. This approach involves the calculation of the indoor illuminances at predefined time-steps, usually for a full year period. In order to summarize the huge number of illuminance data that can be obtained, new metrics have been proposed, the so-called climate-based daylight metrics (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance and Annual Light Exposure) (Nabil et al., 2005; Reinhart et al., 2001; Reinhart et al., 2006; Rogers, 2006). Recently, two new daylight metrics have been defined and adopted by the Illuminating Engineering Society of North America, IESNA (IES, 2012). The spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and the Annual Sunlight Exposure (ASE), which expresses the annual glare potential risk. In more detail, $sDA_{300/50\%}$ is defined as the percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year, while $ASE_{1000,250h}$ is defined as the percent of an analysed area that exceeds a direct sunlight illuminance level of 1000 lx for more than 250 hours per year. It is important to note that the above metrics have been adopted in the rating system of the 'LEED Reference Guide for Building Design and Construction' (USGBC, 2014) as possible options to obtain the credit concerned with the quantity of daylight.

This kind of dynamic analysis implies the need for climate-based simulation tools. Software such as Radiance, Daysim and EnergyPlus are available for daylighting and energy simulations. Radiance and Daysim are validated dynamic daylight programs specifically developed for the analysis and visualization of lighting in a space (Ward et al., 1998; Reinhart, 2006) while EnergyPlus is a whole building energy simulation program that models heating, cooling, lighting, ventilation and other energy flows, taking the daylight contribution into account (US-DOE). These tools are based on different simulation approaches and algorithms. EnergyPlus calculates daylight through the split-flux method. Radiance is a simulation program that employs a backward ray-tracing algorithm based on the physical behaviour of light in a three-dimensional model. Daysim allows illuminance values to be accurately calculated, through the integration of the Radiance algorithm with the Daylight Coefficient method (Reinhart, 2006).

Some studies demonstrated that EnergyPlus tends to overestimate the contribution of daylight. Ramos and Ghisi (Ramos et al., 2010) analysed the difference in the calculation of internal illuminance and external horizontal illuminance between EnergyPlus, Daysim and TropLux simulation programs using three different models. The most relevant difference between EnergyPlus and Daysim was found with regard to the calculation of internal reflections: the greater the importance of reflected light, the greater the difference in illuminances calculated by the two programs.

In 2010, Versage (Versage et al., 2010) examined the difference of modelling daylight using EnergyPlus and Daysim and the consequent influence on the simulation of the global energy consumption. They found that the availability of daylight during a year has similar values only within the first three meters from the window, presenting huge divergences at the points further away from the window. The higher lighting levels simulated by EnergyPlus reduced the energy demand for electric lighting and consequently the cooling loads due to the use of electric lighting.

In this context, it is evident that there is a need to couple different software for daylighting and global energy simulation to reach more accurate building energy analyses.

The purpose of this paper is to describe a reliable, integrated simulation approach to consider daylight when assessing the energy performance of a building, highlighting potentials and drawbacks of the entire simulation process.

Results related to the daylight available in a space (in terms of spatial Daylight Autonomy) and annual energy demand for lighting, heating and cooling are presented to highlight the substantial influence of a proper daylighting design approach on the global energy performance.

2. Methodology

The method is based on a parametric study to assess through simulations how the daylight availability and the consequent energy demand for lighting, heating and cooling vary as the building/room architectural characteristics vary. Simulations were performed using a 2-step process. In step 1, Daysim 3.1 was used to calculate the annual illuminance profile of each space configuration. Starting from these profiles, Daysim calculates the spatial distribution within a room of climate-based daylight metrics (DA, DA_{con}, DA_{max}, UDIs), as well as the corresponding annual electric lighting demand for different lighting controls based on available daylight. Besides, a program in Matlab was specifically written to elaborate the annual illuminance data and to calculate the $sDA_{300/50\%}$. This paper focuses on $sDA_{300/50\%}$ since this is the most recent dynamic daylight metric that has been proposed by the scientific community and is the only one for which target values were defined to assess the lighting performance of a space.

Among the simulation results, Daysim also provides a Comma Separated Value (CSV) file which contains hourly schedules of the status of all lighting and shading groups within the model.

In step 2, this output was directly used as input in EnergyPlus. The parametric analysis in EnergyPlus was conducted using jEPlus, a graphical interface that allows us to set alternative values for all the parameters and simultaneously run multiple simulations calling EnergyPlus.

As a final output of the 2-step process, annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room configuration.

Some considerations were than drawn comparing $sDA_{300/50\%}$ and primary energy demand results.

2.1 Definition of the model

A single office room was used as a 'case study' and the analysis was carried out changing its characteristics in terms of orientation, Room Depth (RD), window area (expressed in terms of Window-to-Wall ratio, WWR), external obstructions (γ) and visible glazing transmittance of the window system (τ_{vis}). The room was assumed to be located in three different sites. All the design variables are summarized in Table 1. The results presented in the paper refer to a sub-dataset highlighted with a grey background.

The room width and height were kept constant at 12 m and 3 m respectively. The effect of an automated shading system, consisting of a venetian blind, was considered in the simulations to dynamically control glare and overheating. The control strategy used for the venetian blind is explained in the following section.

The room was considered to be continuously occupied Monday through Friday from 8:30 a.m. to 6:30 p.m. over a whole year.

Table 1 – Design variables used in the overall parametric study

Site	Orientation	RD [m]	WWR [-]	γ [°]	τ_{vis} [%]
Turin (45.1°N)	South	4.5	0.2	0	35
Catania (37.5°N)	North	6	0.3	15	50
Berlin (52.5°N)	West	7.5	0.4	30	70
		9	0.5	45	90
		10.5	0.6	60	
		12		75	

2.2 Lighting input parameters

In this section the input data used in Daysim simulations are introduced.

The room was modeled with all walls and window frames with a diffuse reflectance of 50%, while the diffuse reflectance values of the floor and the ceiling were set to 30% and 70%, respectively.

The daylight illuminances were calculated according to a 50 cm * 50 cm calculation grid over the whole working plane (minus a 50 cm deep peripheral stripe all along the walls, which typically is a space for furniture). The work plane was set at a distance of 80 cm from the floor.

The daylighting system included in the model to control glare is a venetian blind with a diffuse transmittance of 25% (when in closed position). The blind is a movable shading system and the control is based on the algorithm implemented in Daysim, which assumes the presence of active and/or passive users. Active users open the blinds in the morning and partly close them to avoid visual discomfort when direct sunlight above 50

W/m² is incident on the work plane calculation greed points. Passive users keep the blinds lowered throughout the year (Reinhart, 2006). The strategy adopted in this study refers to mixed behaviour, i.e. both types of users were assumed to equally influence the blind control.

The target task illuminance was initially set to 500 lx, a typical value required for office activities according to the European standard CEN 12464-1:2011 (CEN, 2011). Climate based daylight metrics have been calculated based on this value. For further development of the study and for the calculation of the $sDA_{300/50\%}$ metric the target task illuminance was then set equal to 300lx.

Two different electric lighting control systems were simulated in Daysim, namely a manual on-off switch and a daylight responsive dimming system. The first one is based on the Lightswitch algorithm (Reinhart, 2006) taking into account a user that does not turn electric lights on if there's sufficient daylight on the workplane. The daylight responsive dimming system takes advantage of the daylight availability over the working plane and reduces, proportionally, the electric light use by dimming the luminaire light output.

The analysis was carried out considering a lighting power density of 12 W/m².

The Radiance simulation parameters were set as: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05; the simulations were run using the climate files of the considered locations with a time-step of 5 minutes.

2.3 Thermal input parameters

In this section all the input data that were used in the EnergyPlus simulation program are introduced. It was assumed that the space has only one wall exposed to the outdoor environment. As a consequence interior walls, floor and ceiling were modeled as adiabatic elements.

The wall and the window facing the outdoor environment were modeled with a thermal transmittance of 0.25 W/m²K and 1.6 W/m²K, respectively. The Solar Heat Gain Coefficient of the glazing was set equal to 0.67.

The occupancy index and air change rate were fixed according to the Italian Standard UNI EN 10339:1995 (CTI, 1995) while internal loads (people and equipment) were set according to the Italian Technical Standard UNI TS 11300-1:2008 (CTI, 2008). Winter and summer setpoint temperatures are based on the Italian Standard UNI EN 15251:2008 (CTI, 2008). The latter input parameters are all summarized in Table 2.

Table 2 – Thermal input parameters

Parameter	Definition	Source
Occupancy hours	8:30 a.m. - 6:30 p.m.	
People definition	0.12 people/m²	UNI 10339
Air change rate	11 l/s·person	UNI 10339
People loads	70 W/person	UNI TS 11300-1
Equipment loads	3 W/m²	UNI TS 11300-1
Lighting loads	12 W/m²	
Winter setpoint temperature	21 °C 7:00 a.m. - 9:00 p.m. 18 °C 9:00 p.m. - 7:00 a.m.	UNI EN 15251
Summer setpoint temperature	26 °C 7:00 a.m. - 9:00 p.m. 28 °C 9:00 p.m. - 7:00 a.m.	

HVAC systems were modeled in EnergyPlus considering an ideal air load simplification. This object permits us to assess the theoretical thermal loads needed to achieve the thermal balance at any time step of the simulation.

2.4 Integrated approach

In order to evaluate the global energy demand of each space configuration and the influence of the daylighting design project on internal loads, the assumptions made for the lighting analysis needed to be coupled with the thermal analysis. In particular the control strategy used for the venetian blind and the control system adopted to automatically dim electric lighting in Daysim generate a schedule of the status of all shading and lights that has to be used for the thermal simulation.

For the present study, this connection was realized using the jEPlus tool (www.jeplus.org). jEPlus allows us to perform a parametric analysis that can be applied to all the design variables present in a model simultaneously. It can create and manage multiple simulation jobs and collect results afterwards.

The parametric analysis starts with the use of jEPlus graphical interface, which allows us to specify a search string with all alternative values for each parameter that has to be varied: site, orientation, Room Depth, Window-to-Wall Ratio, external obstruction angle and visible glazing transmittance. Then jEPlus allows us to open one single EnergyPlus IDF model and put search strings in the places of each parameter. Then the software picks the set of values that were specified, and it puts them in every search string in the IDF model and then calls EnergyPlus.

Two specific search strings were elaborated to pick up for each room configuration the output provided by Daysim related to the use of electric lighting and blinds as a function of daylight availability.

This kind of approach can represent a reliable method to evaluate a building's whole energy performance exploring multiple design options, starting from a detailed climate-based daylighting analysis.

3. Results

A synthesis of the results that could be obtained after this integrated approach is presented in this section, with reference to the sub-dataset of configurations highlighted in Table 1.

Results are divided in two different subsections. The first subsection refers to the simulations conducted in Daysim and presents a comparison between $sDA_{300/50\%}$ values and energy demand for electric lighting (Q_{EL}) results.

The second subsection refers to the simulations conducted in EnergyPlus using the jEPlus interface analyzing the overall energy performance of each room configuration compared with the amount of daylight available in the space.

In order to correctly sum lighting (Q_{EL}), heating (Q_H) and cooling (Q_C) energy, the primary energy equivalent demand has been considered and calculated as follows:

$$E_P = Q_H/\eta_H + (Q_C/EER)\cdot\eta_{el} + Q_{EL}\cdot\eta_{el} \quad (1)$$

where η_H is the mean thermal energy generation efficiency, EER is the Energy Efficiency Ratio of a "reference" air-to-air chiller and η_{el} is the mean National electricity generation efficiency. For the present study the following values were assumed: η_H = 0.85; EER = 3; η_{el} = 2.17.

3.1 Daylight availability and energy demand for electric lighting

The parametric analysis conducted in Daysim generated results about the influence that different architectural features have on daylight availability and, consequently, on the energy demand for electric lighting. In this section, results obtained for a daylight responsive dimming system are shown in comparison with a "base-case" in which lights are always turned on.

Figure 1 shows the results for room configurations without external obstructions (γ=0°). It could be noted that $sDA_{300/50\%}$ values are on average lower for South-facing than North-facing rooms (sDA_m=60.8% and 78% respectively). This is mainly due to the presence of the movable shading device which avoids direct sunlight on the workplane and admits 25% of diffuse light only into the space.

As a consequence the mean annual energy demand for electric lighting is higher for south-facing than north-facing rooms ($Q_{EL,m}$= 21.7 kWh/m^2·a and 18.8 kWh/m^2·a respectively).

Room Depth and Window-to-Wall Ratio also have a massive influence on daylight availability and energy demand for electric lighting: a progressive increase in the RD and a decrease of WWR result in a decrease of $sDA_{300/50\%}$ values and an increase in the energy demand.

In order to compare with a more effective approach the daylight amount in a space and the consequent energy demand for electric lighting, the sDA performance criteria suggested by IESNA were used as a reference (IES, 2012). Two levels of criteria were identified to assess the luminous performance of a space: spaces with $sDA_{300/50\%}$ that meets or exceeds 55% of the analysis area and spaces with $sDA_{300/50\%}$ that meets or exceeds 75% of the analysis area. According to these criteria a space can be rated respectively as "neutral" and "favourable" with regard to the sufficiency of the available ambient daylight. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

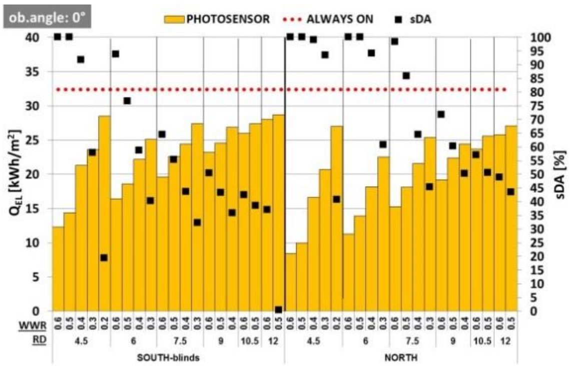

Fig. 1 – Annual energy demand for electric lighting (Q_{EL}) and $sDA_{300/50\%}$ values for all room configurations with γ=0°.

The entire database of results was then divided according to these criteria. For each performance class the mean annual energy demand for electric lighting ($Q_{EL,m}$) value was calculated and compared to the base-case. Figures 2-3 show the results for south and north-facing rooms.

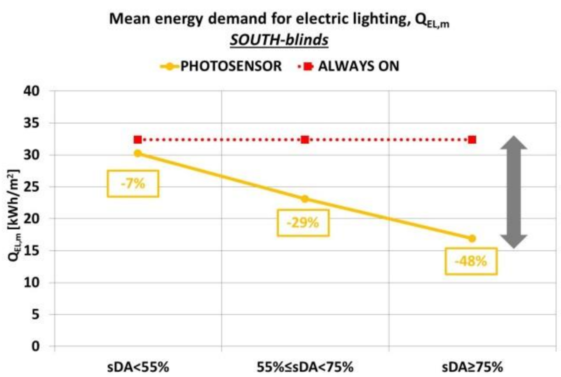

Fig. 2 – Mean annual energy demand for electric lighting ($Q_{EL,m}$) for each $sDA_{300/50\%}$ performance class (South-facing spaces)

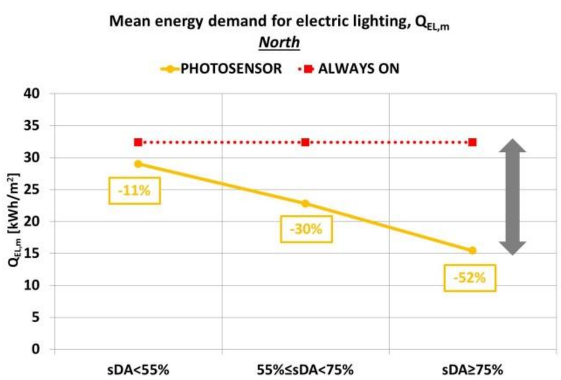

Fig. 3 – Mean annual energy demand for electric lighting ($Q_{EL,m}$) for each $sDA_{300/50\%}$ performance class (North-facing spaces)

As might be expected, the higher the daylight availability ($sDA_{300/50\%}$≥75%), the lower the energy demand for electric lighting, especially in presence of a daylight responsive dimming system. This was observed for both orientations: the mean percentage difference with respect to the case with lights always on can reach -48% for south orientation and -52% for north orientation.

Values of $sDA_{300/50\%}$ below 55% (showing that the amount of daylight is not sufficient) result in a lower reduction in the energy demand for electric lighting, even in the presence of a daylight responsive dimming system (-7% for south orientation, -11% for north orientation).

Furthermore it was observed that the glare potential risk, assessed by the Maximum Daylight Autonomy metric, is very low for all simulated case studies. DA_{max} values are always below 5%, even for cases with sDA≥75%. This is mainly due to the lack of direct solar radiation for north-facing rooms and to the presence of movable shading devices for south-facing rooms.

3.2 Overall energy performance

The parametric analysis conducted in EnergyPlus using the jEPlus interface allows the global energy performance of a room with multiple design options to be analyzed. This section focuses on the effect on cooling and heating loads concerned with an advanced daylighting analysis.

Figure 4 shows the results for south and north-facing rooms without external obstructions (γ=0°) considering a daylight responsive dimming system. In the graph, the Room Depth was shown on the x-axis in terms of S/V ratio (surface which is exposed to the outdoor environment to the space volume ratio).

For each room configuration the corresponding $sDA_{300/50\%}$ values are also shown. The data shown in the figure demonstrated that spaces with $sDA_{300/50\%}$≥75% are not only well daylit environments but they can achieve a better energy performance.

Figures 5 and 6 show that, for both south and north-facing rooms, the mean global primary energy demand ($EP_{glob,m}$) is lower for spaces rated “favorably” daylit ($sDA_{300/50\%}$≥75%) than for spaces not enough daylit ($sDA_{300/50\%}$≤55%).

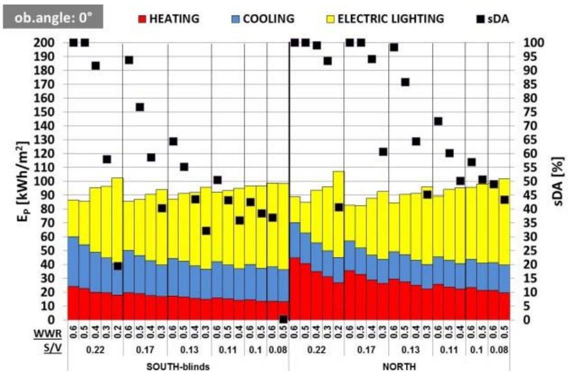

Fig. 4 – Global primary energy demand and $sDA_{300/50\%}$ values for all room configurations with γ=0°.

For south-facing rooms the mean annual global primary energy demand is 112.4 kWh/m²·a when $sDA_{300/50\%}$ is below 55% and 89.7 kWh/m²·a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 20% (Fig. 5).

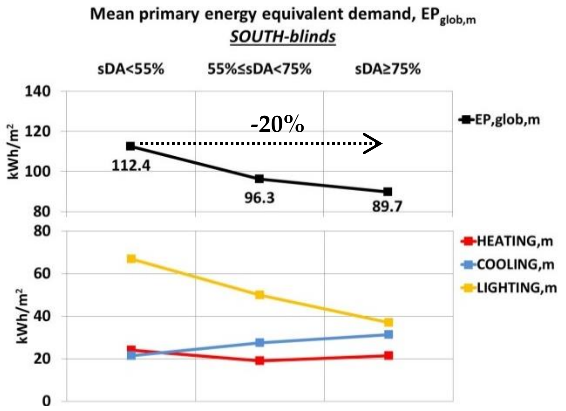

Fig. 5 – Mean annual global primary energy demand for each $sDA_{300/50\%}$ performance class (South-facing spaces).

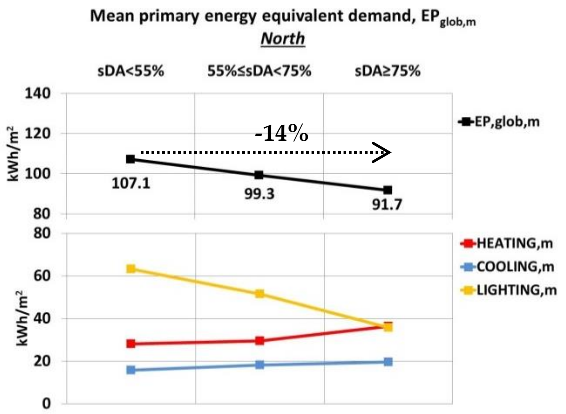

Fig. 6 – Mean annual global primary energy demand for each $sDA_{300/50\%}$ performance class (North-facing spaces).

For north-facing rooms the mean annual global primary energy demand is 107.1 kWh/m²·a when $sDA_{300/50\%}$ is below 55% and 91.7 kWh/m²·a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 14% (Fig. 6).

4. Discussion and conclusion

The purpose of this paper was to describe a reliable simulation approach to consider daylight when assessing energy performance in buildings, in order to demonstrate the substantial influence of daylight harvesting on the global energy performance.

The methodology was based on the use of both Daysim and EnergyPlus which were employed in synergy for a parametric study to assess the lighting and energy performance of rooms with different architectural features.

The results presented proved that a building design based on the optimization of daylight (i.e. $sDA_{300/50\%}$ over 75%) could achieve a reduction in the global energy demand of a space. However, it has to be highlighted that results refer to a sub-dataset that includes data on north and south-facing rooms located in Turin with a visible glazing transmittance of 70%. Furthermore these results were obtained using specific software and input data. If different software and input data were used to run the dynamic simulations, the results might be different.

One important consideration about the simulation approach which was presented is that this 2-step process could be a big effort for a design team, especially during the first stages of the design process when a parametric analysis could be useful to base the first decisions about the building shape and orientation, window sizes and characteristics of glazing and shading systems. In general, it could be said that there is a lack of sufficiently accurate prediction tools for a design team to optimize a project integrating advanced daylighting analysis into energy analysis.

One further problem could be the right choice of all the input data needed for an advanced simulation. There is increasingly the need for extensive libraries which can fill in all required inputs automatically when a model has to be handled.

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