Correlating daylight availability metric with lighting, heating and cooling energy consumptions

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Abstract

This paper examines the relationship between the Daylight Availability (DAv) metric and annual energy consumption. DAv was established as a means of describing indoor daylight sufficiency both for research and practical purposes. To balance daylighting with energy concerns, the specific amount of daylight sufficiency within a space should neither be too low; nor should it be excessive. However, there is little if any notion of what the relationship between a DAv area and the energy used on-site to supply the artificial lighting, heating and cooling systems might be. The aim of this research is to determine if one or more of the DAv areas predicted on the workplane could serve as a proxy for the overall building energy consumption (lighting plus heating and cooling). The office setting is designed to offer a wide range of daylight exposures, depending on the orientation of the fully-glazed façade and that of the perforated solar screen configuration. Results indicated a strong linear relationship between the overlit area and the cooling energy use. Moreover, confining the overlit area to less than 40% at South and less than 50% at North, East and West could help limit the overall energy consumption to less than 120 kWh/m2-year.

Keywords: statistical relationships; daylight availability; low-energy projects; simulation-based design.

1. Introduction

1.1 Energy-efficient design and daylight

Façade design plays an important role as an environmental solution that should be responsive to climatic conditions. Fenestration and shading devices are essential parts of any building, influencing indoor daylight levels and enabling users to view the outside. Daylighting, admitting natural light into a room via building openings in order to replace or supplement artificial lighting, is an important strategy in modern architecture. It can, therefore, contribute to reducing the building's energy consumption [1–3]. In addition, daylight could enhance people's satisfaction and productivity, affect occupant health and promote the circadian stimulus [4]. However, not only is daylight composed of light, but also of radiation and excessive exposure to daylight can cause glare, overheating problems and thermal discomfort to a building's occupants [5].

For a favourable daylighting strategy that helps reduce energy use, the building's performance should be determined effectively and simulated at the design stage. A variety of aids and methods used for calculating the availability of daylight and the effect of sun shading have been developed [6]. These mainly refer to various 'performance indicators' developed to quantify the amount of skylight or sunlight that reach interiors. Climate-Based Daylight Modelling (CBDM) provides the framework for a complete, year-round, evaluation of the building's luminous environment [7]. According to CBDM, dynamic performance metrics have been defined for space characterisation and inserted into recent energy rating certificates, as well as mandatory design guidelines that are actively promoted by government departments. Building designers therefore turn increasingly to simulation as a means of demonstrating compliance with various schemes [8].

The most common dynamic metrics used to evaluate daylighting provision are Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA). UDI is defined as the annual occurrence of illuminances across the workplane that fall within a range that occupants consider 'useful' [9]. Based on reports and published sources [10–14], daylight illuminances in the 100 to 3000 lux range are considered to be effective, either as the sole source of illumination (300-3000 lux) or in conjunction with artificial lighting (100-300 lux). Furthermore, daylight illuminances in the 300 to 3000 lux range (UDI-autonomous, or UDI-a) are often perceived either as desirable or at least tolerable. Illuminances greater than 3000 lux (UDI-exceeded, or UDI-e) are likely to produce visual or thermal discomfort, or both [15]. With regard to standards, UDI's aim would be to maximise the occurrence of illuminances in the UDI-a range, whilst impeding undue occurrence of illuminances in the UDI-e range [16].

DA measures how often a specified illuminance is met by daylight alone throughout the year [17] and has been promoted in current daylighting evaluation standards. For example, IES LM-83 [18] has proposed the use of spatial Daylight Autonomy (sDA) which defines a point in a space to be 'daylit' if the DA for a target illuminance of 300 lux and for occupancy from 8 am to 6 pm is at least 50% (in short, sDA300,50%). Thus, sDA is expressed as a percentage of area and must meet at least 55 and 75% of analysis area for a 'nominally acceptable' and 'favorably/preferred' daylit space, respectively. These sDA targets are also required in LEED v4 [19] to receive the daylight credits. sDA300,50%, however, only addresses overall daylight levels in the test spaces, yet does not address the spatial distribution of daylight within the spaces [20].

There are, therefore, two reasons why the notion of simply achieving a threshold illuminance has restricted value for [9]. The first reason is that DA and sDA do not give significance to those daylight illuminances that fall below the threshold and which can, however, be valued by occupants and may also reduce electric lighting loads. Secondly, DA and sDA take no account of the amount by which the threshold illuminance is exceeded at any particular instant. This is significant because high levels of daylight illuminance are known to be strongly associated with occupant discomfort [15]. For another thing, DA at 300 lux is very similar to UDI-a. The main difference is that the UDI scheme includes the occurrence of exceedances of an upper illuminance limit, in this case 3000 lux. Thus, the annual occurrence of UDI-a will generally be less than that for DA300 = UDIa + UDIe [15].

A new metric termed Daylight Availability (DAv) has recently been proposed. DAv is intended to amalgamate DA and UDI information into a single one [21]. This metric represents the space area as: ‘fully daylit’, ‘partially daylit’, ‘non-daylit’ and ‘overlit’. The ‘fully daylit’ area is reported according to sDA300,50%. The ‘partially daylit’ area is measured when DA for a target illuminance of 150 lux and for occupancy from 8 am to 6 pm is at least 50% (in short, DA150,50%). One particular benefit of DA150,50% is that it shows a transition area between ‘fully daylit’ and ‘non-daylit’, thus starting to account for the subjective nature of spaces’ light evaluations [22]. Because the ‘partially daylit area’ necessarily includes the ‘fully daylit area’, the remaining area is ‘non-daylit’. Finally, the ‘overlit’ area is reported when an oversupply of daylight (e.g. 3000 lux) is assumed for at least 5% of the working year. The 5% criterion was selected as an analogue method to thermal assessments according to BS EN 15251 [23]. The ‘overlit’ area signifies the potential for heat gain [21] and glare [15].

To balance daylighting with energy concerns, a specific amount of daylight sufficiency within a space should be neither too low; nor should it be excessive. Although the previous metrics have related excessive daylight illuminances to thermal problems and glare, there is, as yet, no consensus regarding what the target values for these measures should be [15]. Moreover, there is little if any notion of what the relationship between a daylighting metric and the energy used on-site to supply the artificial lighting, heating and cooling systems of a building might be. The optimisation process often involves sacrificing daylighting performance in favour of energy performance in order to obtain an ideal energy balance [20]. At present, there is a lack of metrics that simultaneously take into account both daylighting and thermal conditions within a space. This lack of simplified metrics and evaluation tools can still be considered as one of the main reasons why building professionals are reluctant to incorporate daylighting features into their design [6].

Meanwhile, some indicators have been proposed to assess the role of fenestration in promoting daylighting performance and restricting solar thermal effects. The solar shading coefficient (SC), for instance, has been used to represent the solar shading performance over a glazed area. SC is the ratio of the solar radiation with solar protection to solar radiation without solar protection [24]. Clearly, a lower SC value corresponds to better solar protection. In addition, the ratio between the DA metric to SC [25] and the ratio between the actual daylit area to SC [26] have been proposed in the literature as indices of both solar shading and daylighting. High index values represent a better integrated performance of solar shading and daylighting. These indices are an approach to taking the thermal effects of daylighting into consideration, but they do not, however, account for the impacts of daylight on energy consumption.

The current evaluation procedure of building performance consists of two parts [27]: to assess the indoor daylight availability by either simulation or field measurements [28–32] and accurately to estimate potential energy saving by dynamic thermal calculations [33–36]. However, the benefits of daylighting can only be fully realised if comfort criteria are carefully considered in building design [37]. In fact, daylight could lead to a net increase in energy consumption if the additional cooling load caused by daylight exceeds the energy saved due to a reduction in electric lighting, or if net heat gains and losses due to fenestration do not compensate for the lighting energy saved [8].

Solar heat gain becomes a cooling load which will unintentionally increase the energy consumption for air-conditioning by around 28% [38]. Such situations may entail no daylight benefit in terms of displaced lighting energy of daylight provision.

Therefore, daylight in a building does not by itself lead to energy saving [6]. It has been reported that an ideal envelope design could reduce the annual cooling load by 33% without taking daylighting into consideration [39]. It appears that optimising building design for daylighting performance is addressed without regard for how this affects thermal loads. Consequently, the benefits of daylighting optimisation can be negated by large heating and cooling loads stemming from solar gains and conducted losses through windows [39]. How to balance the conflicting energy consumptions of artificial lighting and air-conditioning is a major challenge in cooling-dominant climates [40]. In order to achieve the total energy-efficient objective when optimising envelope design with regard to daylight, cooling loads and artificial lighting electricity should be considered simultaneously [41].

1.2 Aims of current research

A full consideration of daylighting's energy-saving potential should also account for daylight's thermal effects. Design solutions need to strike a suitable balance between daylighting provision and overall energy performance [42]. Within this framework, daylight performance metrics may need to be calibrated against criteria for energy use in the whole building and not just the potential to reduce the energy consumed by electric lighting [8]. The aim of this paper is to determine if there is the potential to employ one or more of the DAv areas as a proxy for overall on-site energy consumption. Using statistical techniques, this work investigates the relationship between every DAv area (actual fully daylit, actual partially daylit, overlit and non-daylit areas) and every energy usage (artificial lighting, heating and cooling systems).

2. Methodology

2.1 Setting

The space used for this study is an open-plan office with a fully-glazed façade that can change its orientation towards the four cardinal points. The dimensions are 7 m × 7 m and 3 m high, as Figure 1 shows. The space is evaluated with and without different configurations of Perforated Solar Screens (PSS) placed externally 0.05 m from the fully-glazed façade. 16 PSS configurations are selected and derived from the full combination of different values of perforation percentage, matrix and shape, as Figure 2 summarises. Thus, a total of 16 PSS × 4 orientations = 64 study cases is considered in the combined daylight and thermal analysis. The purpose of the space used is merely to offer a wide range of daylight exposures depending on the orientation of the fully-glazed façade and on the PSS configuration. The characteristics of the materials are shown in Table 1. The setting is evaluated in the warm and temperate climate of Seville (37°42′N, 5°9′W).

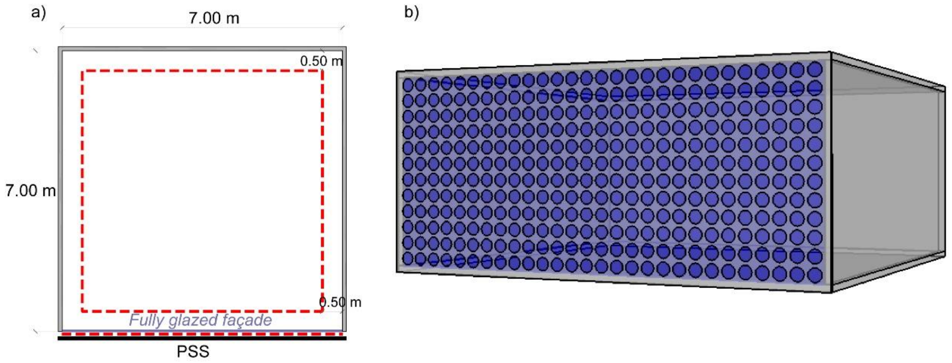

Figure 1. a) Plan view of the office space. The calculation planes used further on for the daylight and irradiation analysis are depicted in dashed lines. b) An example of PSS placed in front of the fully-glazed façade.

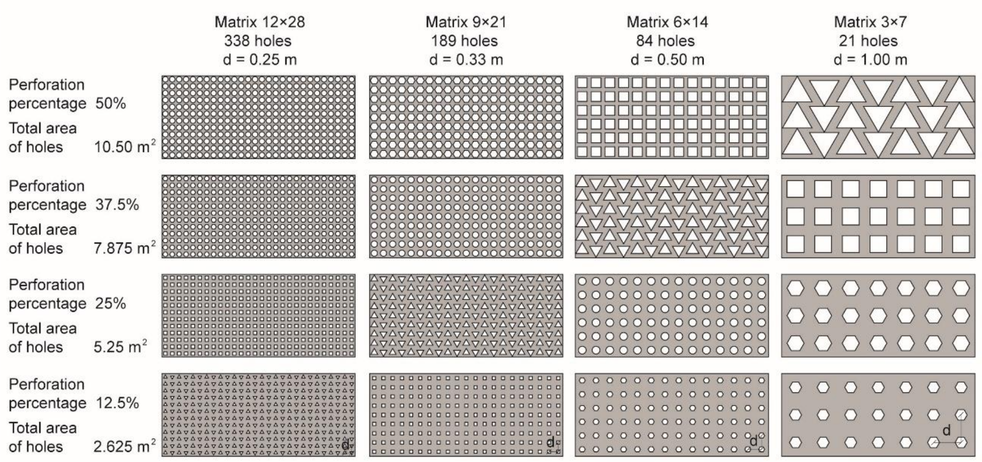

Figure 2. PSS configurations selected for this study. The orientation changes towards the four cardinal points.

Table 1. Characteristics of the materials.

Room	Width × Length × Height	7 m × 7 m × 3 m
	WWR	100%
	Glazed façade orientation	South – East – West – North
Wall	Visible reflectance	50%
	Solar reflectance	50%
	Material	adiabatic
Floor	Visible reflectance	20%
	Solar reflectance	20%
	Material	adiabatic
Ceiling	Visible reflectance	80%
	Solar reflectance	80%
	Material	adiabatic
Glazing	Visible transmittance	78.1%
	Solar transmittance	60.4%
	SHGC	0.703
	U-value	2.785 W/m^{2}K
PSS	Width × Height (no thickness)	7 m × 3 m

Perforation Percentage	50% – 37.5% – 25% – 12.5%
Matrix	12×28 – 9×21 – 6×14 – 3×7
Shape of holes	circular – hexagonal – quadrangular – triangular
Visible reflectance	90%
Solar reflectance	90%
Material	white paint finish

Note: Visible reflectances were set up for daylighting calculations; solar reflectances for annual irradiation calculations, and thermal properties for energy simulations.

2.2 Daylight and thermal assessment

Daylight simulations are performed with Diva-for-Grasshopper (version 4.0.2.24), a highly optimized daylighting modelling software [43,44]. Diva-for-Grasshopper builds on thoroughly validated and tested simulation engine for daylight: Radiance, which is an open source and trusted by the industry [21,45,46]. Daylight calculations are determined on a workplane 0.80 m above ground level, with 576 sensor points placed 0.25 m apart and 0.50 m from the walls. The ambient parameters used are summarised in Table 2. It is assumed that the space is occupied on weekdays between 8 am until 6 pm. The lighting power density is 10.6 W/m2 and the lighting control system corresponds to a manual on/off switch [47]. The International Weather for Energy Calculations (IWEC) provided the climate data used [48]. The daylighting criteria used for assessment are based on Daylight Availability (DAv) metric [21] and consists of overlaying the following daylit areas [31]:

- Non-daylit area includes illuminances of under 150 lux for at least 50% of occupied hours (UDI<150, ≥50%).
- Actual partially daylit area is measured when daylight illuminances fall within the range 150-300 lux for at least 50% of occupied hours (UDI150-300, ≥50%).
- Actual fully daylit area includes only those useful illuminances within the ranges of UDI300-3000, ≥50% + UDI>3000, <5%.
- Overlit area includes illuminances of over 3000 lux for at least 5% of the occupied hours (UDI>3000, ≥5%).

Here, the term 'actual' is used to differentiate these areas from the original DAv areas grounded in DA150,50% for the partially daylit area and in DA300,50% for the fully daylit area. As mentioned above, the DA metric has no upper limits in their illuminance targets, so it necessarily includes the occurrence of exceedances of 3000 lux. Since the excessive illuminances are related to problems of thermal discomfort and glare [15], the 'actual' areas reported here do not quantify them. The aim for DAv is, therefore, to maximise the 'actual fully daylit' area and minimise the 'overlit' area. This design goal is used as an evaluation basis for the relationship between the DAv areas and overall energy consumption.

Table 2. Radiance ambient parameters set for daylight and solar irradiation calculations.

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold
7	1500	100	0.1	300	0

Energy calculations are conducted in Archsim Energy Modeling for Grasshopper that supports EnergyPlus. While there are many study validations that have demonstrated that Radiance (the simulation engine that is used for DIVA) is capable of modelling interior illuminances for a wide range of real-world materials and complex façade geometries [17,46,49], it is questionable whether EnergyPlus can describe accurately the energy transfer phenomena that occur in complex geometries [50]. However, EnergyPlus has been validated thoroughly for assessing the energy performance of conventional building systems or of whole buildings [50]. EnergyPlus is one of the most accessible professional energy simulation tools available and thus is the simulation environment of choice.

To model the thermal performance through the complex geometries of PSS, a specific calculation process that both takes advantage of the daylight software's capabilities and limits the energy calculation engine's drawbacks is used [26]. First, DIVA-for-Grasshopper is used to calculate the annual solar irradiation on a vertical grid with 2,201 sensor points placed 0.10 m apart and directly behind the PSS. The ambient parameters used are summarised in Table 2. Hourly shading coefficients are then generated by determining the ratio of the solar irradiation with and without PSS. The resulting 'hourly transparency schedule' for each PSS configuration is directly set as input for the dynamic energy simulations performed with Archsim via EnergyPlus version 8.8.

In order to focus on studying the impact that daylight has on heating/cooling load as well as on electric lighting usage, the modelling of a specific HVAC system is avoided by selecting the EnergyPlus software option of using "purchased air" (An Ideal Loads Air System) . Moreover, with the exception of the fully-glazed façade, the thermal transmittance from all walls, the ceiling and the floor, are set to be adiabatic. The glazing system consists of clear double glazing (6mm), separated by a 13 mm air gap, with a U-value of 2.785 W/m2-K and SGHC of 0.703. The zone conditioning is based on Spanish standards for office buildings [51]: the heating and cooling set points are 21°C and 25°C, respectively; the minimum and maximum relative humidity are 45% and 50%, respectively; the fresh air for mechanical ventilation is set at 12.5 L/s/person with a sensible heat recovery of 0.64. Infiltration is not considered. The occupancy and equipment loads are 0.1 people/m2 and 12W/m2, respectively.

The lighting energy calculation is based on the output of DIVA simulation results. The 'hourly lighting schedules' previously obtained from DIVA daylighting simulations form inputs for the artificial lighting energy calculation with EnergyPlus. These are used instead of the EnergyPlus software daylight calculations in order to integrate better with this study's daylighting analysis results. EnergyPlus utilizes the split flux method to model the interior reflections of light by dividing the luminous flux into two components; then, each split component is reflected by an average weighted reflectance of the surfaces above and below the window [52]. This kind of calculation often results in substantial inaccuracies that have direct consequences on electric lighting use intensity [53,54]. This model has been surpassed by more advanced computer simulation approaches [55].

Once the thermal model is characterised within Archsim workflow, EnergyPlus is run and the total annual energy used on-site (kWh/m2) to supply the artificial lighting, heating and cooling systems are calculated for every study case.

2.3 Statistical relationship between DAv areas and overall energy consumption

As mentioned earlier, the purpose of this paper is to assess the relationship between every DAv area and every energy usage. The data are investigated visually to determine if scatter plots reveal distinct population distributions for specific energy usages when the workplane is: a) non-daylit, b) actual partially daylit, c) actual fully daylit and d) overlit. Additional variables are then displayed in the scatter plots of the overlit and actual fully daylit areas. In basic terms, the data are grouped by orientation in order to investigate the impact of that particular variable on results. Moreover, data labels linked to perforation percentages are added to explore their effect.

The scatter plots suggest various kinds of correlations between daylight and energy metrics at every cardinal point. The main interest here is to investigate if there are linear relationships between the metrics and variables studied. When the metrics increase or decrease concurrently, a positive linear relationship exists. When one metric increases while the other metric or variable decreases, a negative linear relationship exists. When the data points in plots appear to be randomly distributed, there is a very weak relationship, if indeed one exists at all [56].

3. Results

3.1 Assignment results

Daylighting results are expressed as percentages of the workplane (% wp) according to the DAv targets. Since the 'actual fully daylit area' is grounded in UDI-a, their values will generally be less than that for the 'fully daylit area' (sDA300,50%) [31]. Thus, a target of ≥50% wp for the actual fully daylit area is used here as an approach for daylight sufficiency in the space. Energy results are quantified annually and normalised by floor area (kWh/m2). Total energy use takes into account lighting plus heating and cooling. In this study, the total energy to be used for heating, lighting and cooling is limited to ≤120 kWh/m2-year following the Passive House Institute (PHI) certification criteria for low-energy projects. PHI is a well-established standard, focusing on providing a high level of occupant thermal comfort with low levels of energy use [57]. All simulation results are summarized in Table 3.

Table 3. Simulation results.

Orientation	Perforation percentage	Matrix	Shape	Non-daylit [% wp]	Actual partially daylit [% wp]	Actual fully daylit [% wp]	Over lit [%wp]	Lighting energy [kWh/m2]	Heating energy [kWh/m2]	Cooling energy [kWh/m2]	Total Energy [kWh/m2]
North	50%	12×28	circular	0	1	93	6	13.01	2.56	58.10	73.67
	50%	9×21	hexagonal	0	1	92	7	13.05	2.68	55.38	71.11
	50%	6×14	quadrangular	0	0	95	5	13.70	2.57	57.93	74.19
	50%	3×7	triangular	0	0	93	7	12.73	2.23	55.09	70.05
	37.5%	12×28	hexagonal	0	34	66	0	15.18	2.17	57.66	75.00
	37.5%	9×21	circular	0	39	61	0	15.23	2.41	55.04	72.68
	37.5%	6×14	triangular	0	36	64	0	15.83	2.17	55.93	73.92
	37.5%	3×7	quadrangular	0	33	67	0	16.33	2.21	54.17	72.72
	25%	12×28	quadrangular	30	40	30	0	20.69	1.84	56.73	79.26
	25%	9×21	triangular	31	36	32	0	22.03	1.83	58.07	81.93
	25%	6×14	circular	34	35	31	0	22.03	1.87	56.33	80.24
	25%	3×7	hexagonal	26	34	40	0	20.69	1.84	55.28	77.81
	12.5%	12×28	triangular	80	17	3	0	25.76	1.75	55.74	83.25
	12.5%	9×21	quadrangular	80	17	3	0	25.62	1.72	56.80	84.15
	12.5%	6×14	hexagonal	76	19	5	0	26.02	1.71	57.02	84.75
	12.5%	3×7	circular	66	22	11	0	25.67	1.72	56.18	83.57
South	50%	12×28	circular	0	0	43	57	13.39	1.50	138.71	153.61
	50%	9×21	hexagonal	0	0	42	58	21.24	1.27	134.11	156.62
	50%	6×14	quadrangular	0	0	43	57	21.96	1.55	143.11	166.62
	50%	3×7	triangular	0	0	45	55	13.07	1.34	131.98	146.39
	37.5%	12×28	hexagonal	0	0	49	51	23.59	1.05	126.25	150.88
	37.5%	9×21	circular	0	0	49	51	24.78	0.81	116.67	142.27
	37.5%	6×14	triangular	0	0	47	53	16.89	0.79	112.62	130.29
	37.5%	3×7	quadrangular	0	0	50	50	14.92	0.64	103.81	119.37
	25%	12×28	quadrangular	0	36	23	41	26.24	0.54	98.85	125.63
	25%	9×21	triangular	0	34	23	43	25.82	0.56	99.85	126.24
	25%	6×14	circular	0	35	20	44	26.35	0.50	94.00	120.85
	25%	3×7	hexagonal	0	31	29	40	26.30	0.49	93.24	120.02
	12.5%	12×28	triangular	50	15	5	31	27.26	0.56	72.69	100.51
	12.5%	9×21	quadrangular	47	23	8	22	27.23	0.49	76.35	104.07
	12.5%	6×14	hexagonal	48	24	13	14	27.44	0.51	76.45	104.40
	12.5%	3×7	circular	44	16	13	27	27.42	0.55	74.40	102.37

East	50%	12×28	circular	0	0	40	60	13.27	1.40	121.82	136.50
	50%	9×21	hexagonal	0	0	40	60	12.11	1.21	110.77	124.09
	50%	6×14	quadrangular	0	0	37	63	13.12	1.38	119.37	133.87
	50%	3×7	triangular	0	0	39	61	12.56	1.27	113.71	127.54
	37.5%	12×28	hexagonal	0	18	31	51	13.05	1.16	108.02	122.23
	37.5%	9×21	circular	0	20	34	45	14.74	0.96	98.83	114.54
	37.5%	6×14	triangular	0	16	34	50	14.30	1.00	100.75	116.05
	37.5%	3×7	quadrangular	0	15	39	46	14.16	0.90	92.73	107.79
	25%	12×28	quadrangular	10	43	14	33	16.88	0.80	86.02	103.70
	25%	9×21	triangular	9	43	19	30	17.14	0.81	87.52	105.47
	25%	6×14	circular	12	43	12	34	16.81	0.76	80.93	98.50
	25%	3×7	hexagonal	3	44	17	36	15.04	0.75	79.00	94.79
	12.5%	12×28	triangular	64	23	1	12	22.20	0.83	66.15	89.17
	12.5%	9×21	quadrangular	64	16	6	15	22.30	0.79	70.26	93.35
	12.5%	6×14	hexagonal	63	17	7	14	22.54	0.78	70.27	93.59
	12.5%	3×7	circular	57	16	10	18	20.91	0.81	66.81	88.53
West	50%	12×28	circular	0	0	60	40	14.91	1.40	104.31	120.62
	50%	9×21	hexagonal	0	0	60	40	14.43	1.15	95.20	110.77
	50%	6×14	quadrangular	0	0	61	39	14.89	1.33	101.53	117.76
	50%	3×7	triangular	0	0	60	40	13.98	1.23	98.00	113.21
	37.5%	12×28	hexagonal	0	29	38	33	16.02	1.08	92.66	109.76
	37.5%	9×21	circular	0	33	36	31	16.85	0.90	85.31	103.07
	37.5%	6×14	triangular	0	29	40	32	16.95	0.93	86.78	104.66
	37.5%	3×7	quadrangular	0	27	39	35	16.35	0.81	80.12	97.28
	25%	12×28	quadrangular	22	42	16	20	20.21	0.82	75.56	96.59
	25%	9×21	triangular	23	41	18	19	23.47	0.81	78.68	102.96
	25%	6×14	circular	27	37	13	24	21.71	0.78	72.45	94.94
	25%	3×7	hexagonal	15	42	17	26	22.80	0.80	72.80	96.40
	12.5%	12×28	triangular	76	16	1	8	26.65	0.97	60.59	88.21
	12.5%	9×21	quadrangular	75	15	4	6	26.75	0.94	63.58	91.28
	12.5%	6×14	hexagonal	71	16	2	10	26.24	0.95	62.99	90.17
	12.5%	3×7	circular	64	19	9	8	26.56	0.96	61.63	89.15

Figure 3 shows the relationship between the four DAv areas and the different energy usages. It is apparent here that cooling energy use is more prominent in terms of the total energy consumption than both lighting and heating. It is also observed that many study cases achieve less than 120 kWh/m2-year for the total annual energy consumption. The cases exceeding that total energy limit also tend to exceed 50% wp as an overlit area. Additionally, only some cases exceed 50% wp as an actual fully daylit area.

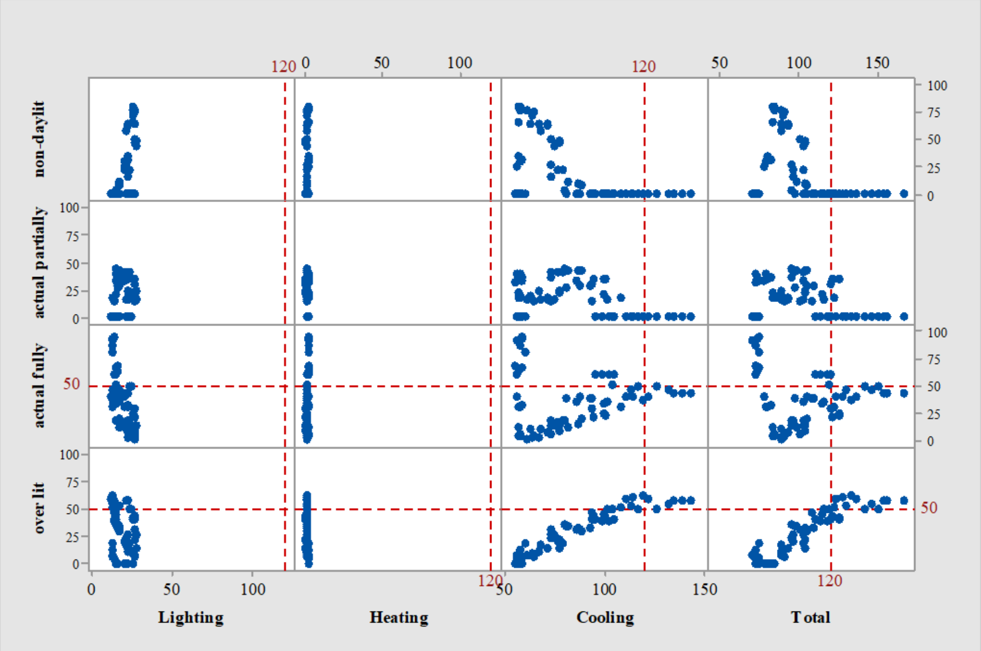

Figure 3. Scatter plot for DAv areas (% wp) versus annual energy usages (kWh/m2).

Figure 4 depicts a negative relationship between the actual fully daylit area and the electrical lighting use. For instance, maximizing the aforementioned area can contribute to minimizing the lighting use. However, only some study cases exceed 50% wp with low lighting use – those having perforation percentages of 50 and 37.5% facing North and those having perforation percentage of 37.5% facing West. This trend excludes the South and East oriented cases where there is no further increase in the actual fully daylit area from perforation percentage 37.5% upwards.

South is characterized by its high levels of direct solar radiation entering space throughout the year. East receives a large amount of solar radiation during the morning hours that, in the study case, coincide with many hours of the occupancy schedule (See Figure 4). Therefore, there is a considerable increase in the excessive illuminances and, at the same time, a significant decrease in the useful illuminances, at both orientations. In contrast, North receives mostly diffuse solar radiation throughout the year, so the excessive illuminances are less frequent than in the other orientations. West receives solar radiation in similar amounts to East, although at different times, so it quantifies less excessive areas during the occupancy time of this study (See Figure 4).

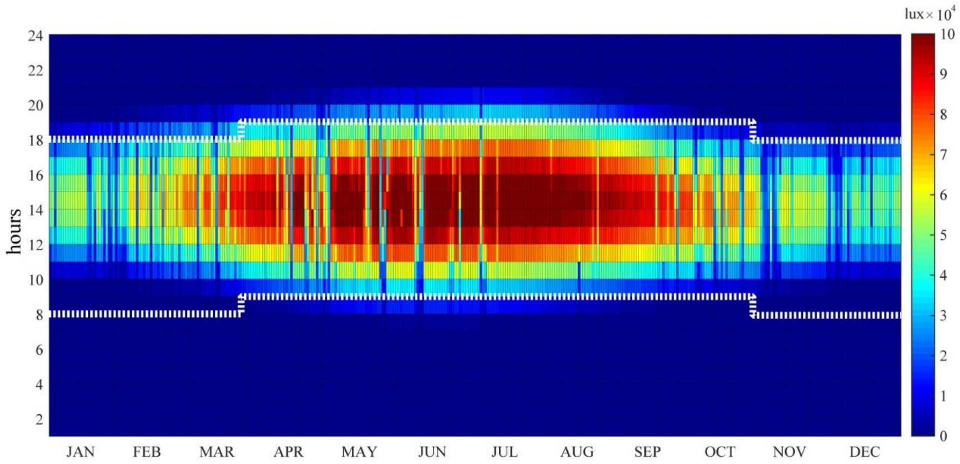

Figure 4. Occupancy time throughout the year.

Additionally, when data are grouped by orientation, the actual fully daylit area rises concurrently with perforation percentage, but the lighting energy use decreases as perforation percentage increases. This is due to the fact that increasing the area of the holes increases the illuminances of daylight in the interiors. In addition, the lighting control system (Lightswitch) used in the study case involves a user who turns off the electric lighting when 300 lux is reached [47]. This fact contributes to the reduction of the artificial lighting use. In brief, the negative linear relationship between the actual fully daylit area and electrical lighting use is markedly conditioned by orientation. This negative relationship is stronger at North than at West or East whilst it is nonlinear at South.

Figure 5 also shows that there is a strong positive linear relationship between the actual fully daylit area and the cooling energy use for South, East and West orientations, even with concurrent increases in the perforation percentage. On the other hand, North data show a weak relationship between the two metrics since the actual fully daylit area rises from 5% wp to 95% wp but the cooling energy use remains around 56 kWh/m2 in all cases. At this cardinal point the actual fully daylit area does, however, rise as perforation percentage increases. This behaviour is attributed to the notion that cooling energy results of this work are derived exclusively from the transmitted solar radiation energy through holes and glazing to indoors. Also, to the notion that sun reaches to North façades only early morning and late afternoon during the summer months in the locality studied. Consequently, excessive illuminances are lower at this orientation but autonomous illuminances are higher.

Similarly, the relationship between the actual fully daylit area and the total energy use is positive and linear at South, East and West orientations since both metrics increase concurrently with perforation percentage. However, the North cases indicate both a slight reduction of the total energy use (from 85 kWh/m2 to 70 kWh/m2) and a significant increase in the actual fully daylit area which occurs concurrently with perforation percentage increases.

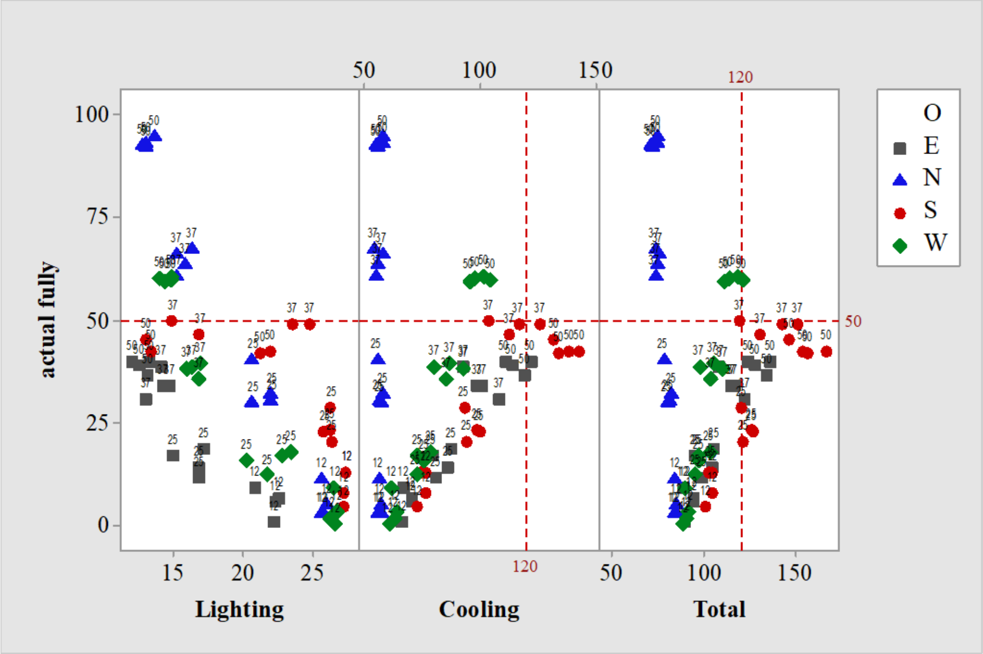

Figure 5. Scatter plot for the actual fully daylit area (% wp) versus lighting, cooling and total energy use (kWh/m2). Data labels are linked to perforation percentages.

Figure 6 shows the scatter plots for the overlit area versus different energy usages. Particular inferences for every cardinal point can be drawn with regard to the overlit area and electrical lighting use. Among the four orientations, South-facing façades achieve the highest values for the over lit area while the North cases obtain the lowest. At the locality studied, solar radiation can quantify up to 1147 kWh/m2 on the unprotected façade at South, while it only achieve 270 kWh/m2 on the unprotected façade at North [58]. Thus, South orientation maximizes the excessive illuminances throughout the year. Instead, the lighting energy obtains similar consumes in the four orientations (respectively to the perforation percentage) due to the notion of 300 lux in Lightswitch.

In short, a negative nonlinear relationship between the overlit area and the lighting use is observed at South, that is to say, the former metric increases as the latter decreases, although not at the same rate. Furthermore, a negative linear relationship between both metrics is observed at East and West while a weak relationship between both metrics is noticed at North since the overlit area barely changes while the lighting use increases. It is also observed that, as perforation percentage increases at the four orientations, the overlit area increases while lighting use decreases.

With respect to the overlit area and the cooling energy use, a strong positive linear relationship is clearly observed at orientations South, East and West. Moreover, both metrics increase concurrently with perforation percentage. On the contrary, North-facing cases achieve small overlit areas and low cooling energy consumptions that remain around 6% wp and 56 kWh/m2, respectively. This behaviour is due to the aforementioned differences for the solar radiation at the specific orientations. Thus, South quantifies higher values for the transmitted solar radiation energy and, consequently, higher values for the cooling energy use.

Similarly, the relationship between the overlit area and the total energy use is strong positive linear for orientations South, East and West. The North cases, however, obtain only minor changes between the overlit areas and total energy consumptions. Here, it should be noted that cooling energy use is more prominent in the total annual energy consume than lighting electrical use. As mentioned previously, it is also observed that the cases exceeding 120 kWh/m2-year tend to exceed a certain percentage of the workplane as overlit area - around 50% wp at East, West and North and around 40% at South.

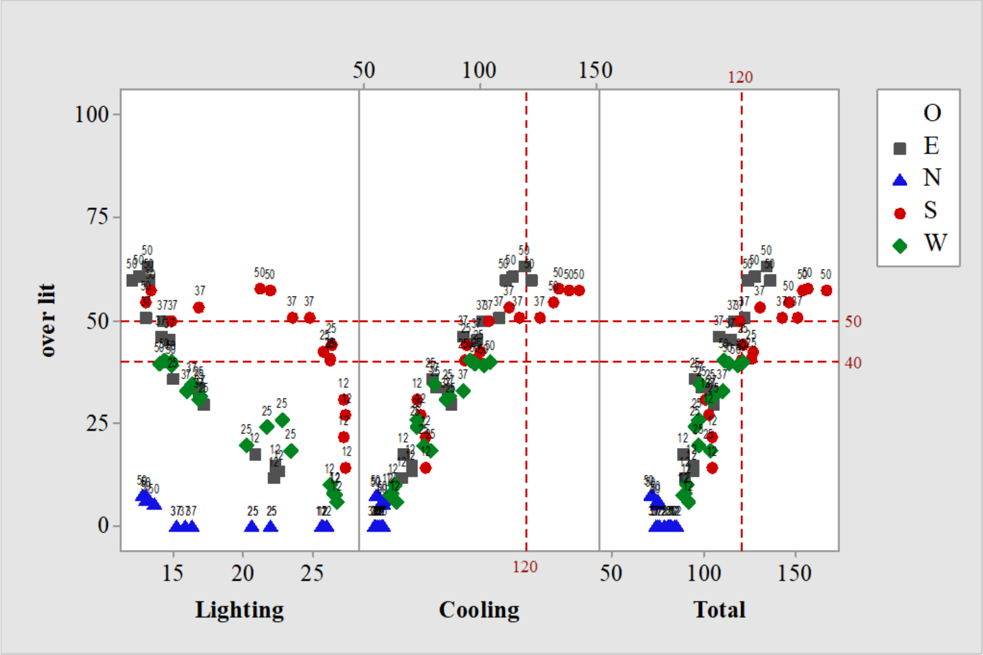

Figure 6. Scatter plot for the overlit area (% wp) versus lighting, cooling and total energy use (kWh/m2). Data labels are linked to perforation percentages.

Additionally, Figure 7 examines the relationship between the actual fully daylit area and the total energy consumption where each bubble's size/label represents the overlit area. In this manner, it is observed that many study cases can consume less than 120 kWh/m2-year with an acceptable daylight provision (actual fully daylit area ≥50% wp). North-facing cases can achieve actual fully daylit areas of 75-100% wp with less than 8% wp as the overlit area and actual fully daylit areas of 50-75% wp with 0% wp as the overlit area. Furthermore, West-facing cases can reach actual fully daylit areas of 50-75% wp with less than 50% wp as the overlit area. All of these specific North- and West-facing cases reduce the total energy consumption to less than 120 kWh/m2-year.

However, East-facing cases can only limit the energy consumption to less than 120 kWh/m2-year if the sum of the actual fully and partially daylit areas is greater than 50% wp, as Figure 8 depicts. As an illustration, the best daylit cases reach approximately 35% fully + 17% partially. As a result, the overlit area can also be limited to less than 50% wp at East. Furthermore, only few cases at South reach around 50% wp as the actual fully daylit area with less than 50% wp as the overlit area while simultaneously consuming less than 120 kWh/m2-year. Another small number of south cases can limit energy consumption to less than 127 kWh/m2-year, but with an actual daylit area that is subdivided into approximately 24% fully + 34% partially daylit. In this way the overlit area can be limited to around 40% wp at South.

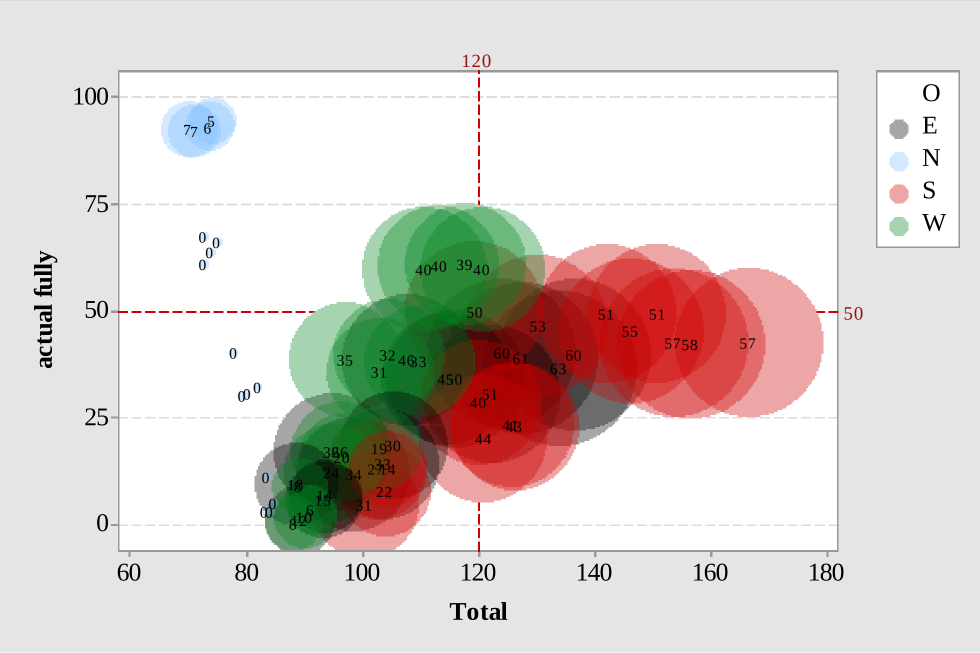

Figure 7. Scatter plot of the actual fully daylit area (% wp) vs the total annual energy consumption (kWh/m2-year). Bubble size: overlit area (% wp).

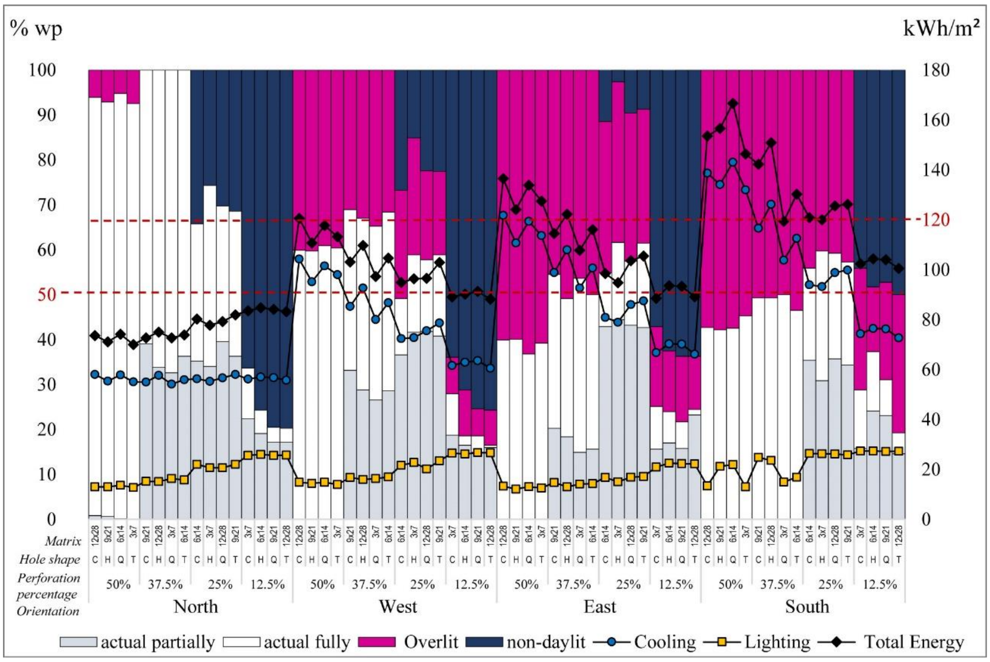

Figure 8. Simulation results.

3.2 Comparison to current daylight availability metrics

In accordance with the IESNA Daylighting Metrics Committee, an sDA300,50% of at least 55 and 75% wp should be attained in order to define a space as daylit [18]. These targets are also encouraged by the LEED v4 requirements for reducing the use of electrical lighting by introducing daylight into space [19]. Accordingly, Figure 9 shows these targets for sDA300,50%. It also plots the relationship between sDA300,50% and the lighting, cooling and total energy usages. It indicates that a maximisation of sDA300,50% can reduce electrical lighting use, but only at orientations North, East and West. In fact, achieving the 55 or 75% wp required in standards does not necessarily help to reduce lighting energy use at South. On the contrary, maximising sDA300,50% can increase cooling energy use at East, West and South, while it has a weak effect on cooling at North. Moreover, it is apparent that, for the locality studied, cooling energy use has more weight in the total energy consumption than lighting. As a result, maximising sDA300,50% might imply increases in total energy consumption, mostly at orientations South and East, where some cases exceed the limit of 120 kWh/m2-year. Taking this into account, it will be advantageous for designers if rating systems consider the impact that daylight has – not only on electric lighting usage but also on cooling and heating loads. Indeed, reducing total energy use is one of the priority targets when designing low-energy projects.

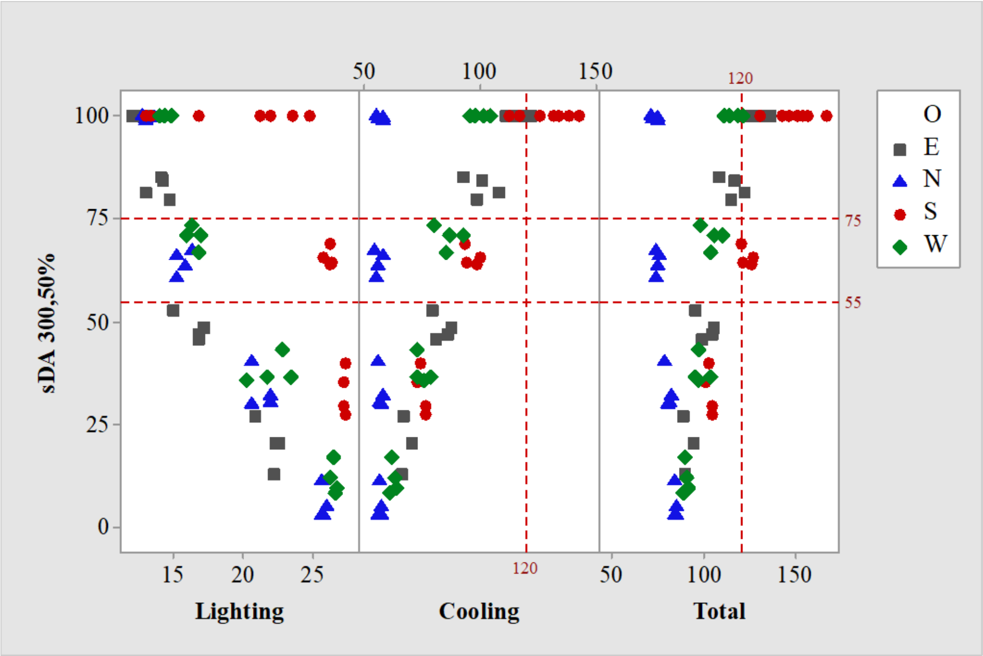

Figure 9. Scatter plots for sDA300,50% (% wp) versus lighting, cooling and total energy use (kWh/m2).

4. Discussion

In summary, scatter plots indicate that the relationship between the actual fully daylit area and lighting energy use was negative and linear at orientations North, East and West, while it was nonlinear at South. The relationship between the actual fully daylit area and cooling energy use was strong positive linear at South, East and West whilst it was weak at North. Moreover, total energy consumption was strongly correlated with cooling energy use. These trends confirmed that orientation plays a major role in the quantification of daylight sufficiency. Therefore, determining target values for daylight metrics at different orientations is a task to be undertaken.

With a sample size of a warm and temperate climate, it has yet to be determined whether these results are of a more general nature. This caveat notwithstanding, the actual fully daylit area accounted for the impact that daylighting has on total building energy use. The DAv scheme with the actual fully daylit area provided an upper threshold level for useful illuminances thereby delimiting specific areas with excessive illuminances in order to alert designers to potential problems of glare or overheating. Therefore, the actual fully daylit area according to the UDI-a metric [9] aims to be more than a mere daylight availability metric and aims to combine availability, comfort and energy concerns in one.

Conversely, the daylit area according to sDA300,50% of at least 55 or 75% wp helped to reduce the lighting energy use at some orientations only. Nevertheless, it did not contribute to reducing the overall building energy consumption. Thus, the effectiveness of the daylit area to fulfil the main goals of the sustainable rating systems becomes questionable. Since daylight is always accompanied by solar gains, it is therefore advisable to update standards, not only to achieve a high daylight sufficiency and a low electrical lighting use but also to achieve acceptable cooling energy use and a low total energy consumption.

As far as the over lit area was concerned, a strong positive linear relationship between cooling and total energy was detected. Moreover, a negative linear/nonlinear relationship with lighting energy use was clearly distinguished for every orientation. Most importantly, when the overlit area exceeded 50% wp, total energy consumption tended to exceed the limit of 120 kWh/m2-year recommended by PHI certification. Therefore, determining a target limit for the overlit area could be more effective for relating daylight to energy efficiency and a building’s sustainability. It could also help achieve more responsive results that avoid the ASE (Annual Sunlight Exposure) metric’s significant uncertainty. At present, the ASE is not robust enough to be considered for daylight performance evaluations aimed at either overheating or glare assessments [59]. Briefly, in order to estimate daylight quality and achieve the daylight credits, green building rating systems could include the use of the overlit area, together with the actual fully daylit area. Ideally, target limits for the overlit area should be linked to orientation.

As mentioned before, the test method developed in this work needs to be applied to more study cases located in different places worldwide before more general conclusions can be drawn. It is, therefore, hoped that others reproduce the test for their particular spaces and share their findings with the aim of improving the current rating standards.

5. Conclusion

This paper presented a study approach to establish relationships between the DAv and the predicted annual energy consumption for lighting, heating, cooling and total consumption. It attempted to show the impact of daylight on whole building energy use and not just its potential to reduce the energy consumed for electric lighting. The main research purpose was to determine if one or more of the DAv areas predicted on the workplane could serve as a proxy for overall building energy consumption (lighting plus heating and cooling). Having seen its strong linear relationship with the total annual energy use, the overlit area became a feasible metric. Confining the overlit area to less than 40% at South and less than 50% at North, East and West could help limit energy consumption to less than 120 kWh/m2-year. In fact, as building standards and rating systems have become increasingly stringent and far-reaching, this type of study become increasingly important in order to specify the requirements that every project must meet according to its climatic conditions. Hence, future lines of research could both deepen the target values of the daylight availability metrics, as well as lead to similar tests for other climates and for other metrics such as glare or uniformity. In order to ensure clear evaluation tools are developed, not only to guarantee proper lighting analysis but also to support energy savings strategies in complex spaces, this particular field needs to be further investigated.

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