Applicability of Climate-Based Daylight Modelling

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1. Introduction

Lighting technologies are evolving rapidly and becoming increasingly cheap and affordable. Consequently, improving the access to daylight in buildings is no longer a primary strategy to decrease energy consumption. Yet, daylight's unique character cannot be substituted so easily; more and more research points to how people need regular and sufficient amounts of daylight to boost their mood and wellbeing [1], [2].

Designers need guidelines and tools that not only specify a minimum acceptable daylight level, but that can help them in creating healthy/comfortable spaces to live in. In the UK, the Education Funding Agency first addressed this issue by introducing Climate-Based Daylight Modelling (CBDM) metrics – Useful Daylight Illuminance (UDI) and spatial Daylight Autonomy (sDA) – as a mandatory evaluation requirement for the design of 261 schools within the Priority School Building Programme (PSBP) launched in 2013 [3]. In the same year, the LEED v4 energy rating system introduced two optional CBDM metrics sDA and Annual Sunlight Exposure (ASE) [4], following the advice contained in the Illuminating Engineering Society of North America (IESNA) recommendations [5].

CBDM enables designers to evaluate realistic measures of the luminous environment of a space over a full year, taking into consideration the locale-specific daily and seasonal variations. It was first introduced in the late 90s [6], [7], and built on the simulation capabilities of the *Radiance* system [8]. It has evolved since then to account for new materials, new window system technologies and to improve computational efficiency, largely from the efforts of a handful of enthusiasts. Due to this particular mode of development, several techniques are now available and used side-by-side, or sometimes interchangeably, even though they differ quite significantly in the way they represent, for example, the sun and sky conditions. This work aims at analysing each of these techniques and find out their strengths and weaknesses, thus giving guidance to designers on the right tools to choose for robust and reliable annual performance evaluations.

2. Methodology

The analysis presented in this paper focuses on the comparison of five state-of-the-art techniques to perform CBDM evaluations: the benchmark Four-Component method; DAYSIM; the Two-phase, Three-phase and Five-phase methods. Their main characteristics are described in Section 2.1.

In Section 2.2, the four real classrooms from two English schools that were chosen as case study are presented. CBDM evaluations were carried out for each of them, with all the five techniques under analysis. The rooms were chosen because they cover a wide range in space types for daylight performance – as identified by the users in a companion study that is investigating the relationship between the subjective impression of interior daylight conditions and the objective measures of luminous quantities through long-term monitoring with High Dynamic Range (HDR) images [9].

The annual simulation results were expressed with several CBDM metrics, used for the PSBP and in LEED v4, and compared to each other to determine if there is an agreement between methods or not; the Four-Component method was used as benchmark, as it was validated against measurements recorded simultaneously for a year inside and outside a test room. The calculation procedures used for each of the metrics adopted are described in Section 2.3.

2.1 CBDM simulation techniques

Most of the techniques were applied using their command-line form, i.e. writing custom UNIX scripts to run the basic *Radiance* commands, to facilitate the automation of the analyses. Prototype end-user tools currently under development were also tested but some were considered ‘beta’ versions not yet ready for rigorous benchmarking. Note however that ‘end-user’ tools invariably embed one of the tested *Radiance* CBDM techniques – thus the findings have direct relevance for CBDM software developers.

The methods considered for the current analysis were:

I. Four-Component method (4CM): Created to validate *Radiance* against the BRE-IDMP dataset of sky luminance measurements [6], it served here as a benchmark for the inter-model comparison. It uses the Daylight Coefficients (DC) method with a Tregenza subdivision (i.e. 145 patches) and blended CIE luminance models for the stochastic calculation of skylight, while sunlight is calculated deterministically from 2056 light point sources evenly distributed over the hemisphere. An *rtrace* run is performed for each of the patches.

II. DAYSIM (DAY): One of the most widespread back-end tools to perform CBDM. It implements a modified version of *rtrace* for the light redistribution simulation. The publicly available version uses the Tregenza patches scheme for skylight and up to 65 points over the sun path as sunlight sources, with the sun luminance interpolated between the closest four points to the actual sun position. The luminance distribution is derived from weather files data using the Perez All-Weather model.

III. Two-Phase method (2PM): Instead of the classic *rtrace* command to simulate light behaviour, a new *rtcontrib* command was specifically introduced for annual simulations. This method was the first one to employ such command. The sun luminance is assigned to the three sky patches closest to the actual sun position and the sky subdivision can be assigned finer resolution than the Tregenza scheme [10]. The sun and sky contributions can therefore be accounted for in a single run and the computational cost can noticeably diminish.

IV. Three-Phase method (3PM): This method was introduced on top of the Two-Phase method, in order to add capabilities to simulate the behaviour of Complex Fenestration Systems (CFS, i.e. redirecting shading devices such as venetian blinds or prismatic films). It uses the same *rcontrib* command, but splitting the raytracing process in two, one run for the exterior scene and one for the interior [11], [12]. The results matrix can be then multiplied to the matrix that describes the window Bi-directional Scattering Distribution Function (BSDF) material [13]. This kind of function is generally used to spatially relate the luminous flux coming from the exterior to the one transmitted by the window system itself towards the interior.

V. Five-Phase method (5PM): To increase the accuracy of the Three-Phase method when evaluating the performance of CFS, the direct sunlight contribution only is re-simulated using 5185 point-like sources evenly distributed over the hemisphere and applying a variable resolution BSDF material; in this way, peaks of light can be traced more reliably from the sun position and then accurately accounted for at the window transmission step [14].

2.2 Case study classrooms

The four case study classrooms chosen for the present work were characterised by different period of construction, size, orientation and fenestration systems. The code names assigned to the four classrooms are L3, L7, M1 and M5; Fig. 1 shows, for each classroom, an interior and an exterior view of the 3D model created in SketchUp for the analyses presented herein. L3 is a side-lit space with a glazed curtain-wall facing approximately North-West direction; L7 is a multi-aspect room with the major windows oriented towards North-East and others towards South-East; M1 is a deep plan space with the aperture on the smaller side that faces South; M5 is characterised by a sloped ceiling and has apertures on opposite sides, with the main window towards North and an additional clerestory window on the South side, where the ceiling is higher. For the choice of these spaces, one of the requisites was that 'traditional' taught classes were the main activity held in them; the choice of an horizontal plane (h = 0.8 m) for the simulated illuminance records was therefore deemed appropriate for this type of tasks.

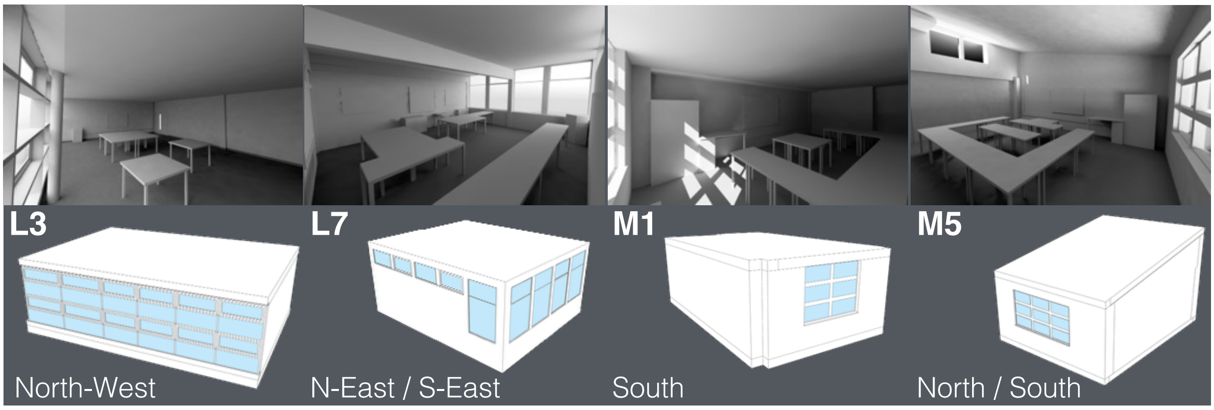

Figure 1: Interior and exterior views of the four case study classrooms, simulated using SketchUp and Radiance. The windows orientation for each classroom is reported at the bottom

The average and median Daylight Factor (DF) for each classroom were derived too, running simulations with a CIE overcast sky. Fig. 2 presents the DF results and shows how the four classrooms cover a wide range of daylight access levels, from a very dark one (room M1) to a potentially overlit one (room L7).

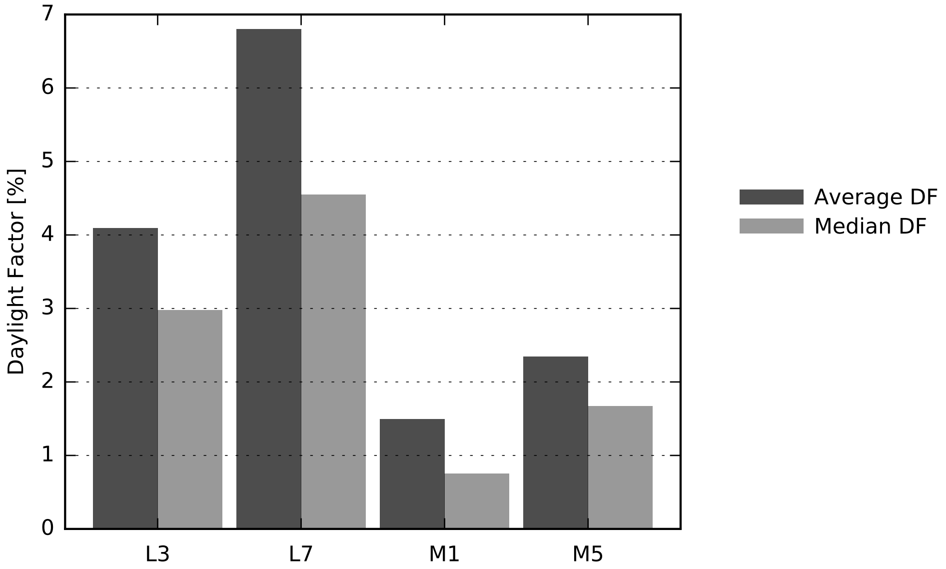

Figure 2: Average and median Daylight Factor values for each of the case study rooms

2.3 CBDM annual metrics and guidelines requirements

The metrics used in this analysis were the ones required in LEED v4 (Option 1) and in the PSBP Daylight Design Guide (Rev 2), specifically:

- Useful Daylight Illuminance (UDI): Formed by a set of values, each representing the percentage of occupied hours where the illuminance level falls into certain ranges. The concept was first introduced in 2006 [15]. The sum of all UDI results has to add up to 100% for the same space. The ranges used in all analyses are [0-100 lx] (UDI-n for *non-sufficient*), [100-300 lx] (UDI-s for *sufficient*), [300-3000lx] (UDI-a for *autonomous*) and over 3000 lx (UDI-x for *exceeded*). Sometimes the range [100-3000] is used as well, and is referred to as UDI-c, for *combined*.
- Spatial Daylight Autonomy (sDA): Represents the portion of the working plane that complies with the Daylight Autonomy (DA) requirement; DA represents the percentage of occupied hours where the illuminance level is higher than a certain threshold (300 lx) for each of the sensor points.
- Annual Sunlight Exposure (ASE): It considers only direct sunlight during the simulation and it represents the portion of the working plane where the sensor points recorded illuminances higher than a certain threshold (1000 lx) for more than a fixed number of occupied hours (250).

To obtain daylight credits from the LEED v4 energy rating system, each occupied space has to satisfy the requirements of an $sDA_{300/50\%}$ > 55% (2 credits) or $sDA_{300/50\%}$ > 75% (3 credits), as well as an $ASE_{1000/250hr}$ < 10%. The first requirement aims at providing enough light into the space and has to be verified with movable shading devices in place, if they are deemed necessary; it prescribes that more than 55% (or 75%) of the working plane has to record illuminance values higher than 300 lx for more than 50% of the occupied hours. The second requirement takes care that the amount of direct sunlight entering the building is not excessive, even when movable shading devices are not operated (i.e. are open). Only fix form shadings are modelled in this case (e.g. overhangs are, but blinds are not). The prescription considers direct sunlight only, for less than 10% of the working plane has to record illuminance values that are higher than 1000 lx for more than 250 occupied hours. For both metrics, the defined working plane has to be the same, as well as the occupancy schedule, which is set to go from 8:00 am to 6:00 pm every day of the year, for a total of 3650 hours.

For PSBP compliance, the requirements are an $\text{sDA}_{300/50\%} > 50\%$, similarly to what previously described, and a $\text{UDI-c}_{(100\text{-}3000\text{lx})} > 80\%$. The second condition prescribes that the illuminances recorded over the working plane fall within the range 100-3000 lx for more than 80% of the occupied hours. The UDI-c values are collected at each sensor points, and then their average is calculated to give the working plane overall result. Movable shading systems are not modelled, as only the designed fixed form is evaluated. The occupancy schedule is set to start at 8:30 am until 4:00 pm.

3. Inter-model comparison results

The results that are obtained from a CBDM evaluation, used to comply with either LEED or PSBP requirements, should be independent from the choice of the simulation method, so that they are equivalent to any possible collaborator's or competitor's own analysis. But what happens when the available methods are systematically analysed and compared?

Table 1 and 2 illustrate the results obtained for each room when assessing the compliance to LEED and PSBP respectively, by using different methods. DAYSIM was not tested for the PSBP compliance check, as it was not possible to obtain sub-hourly time steps with the interface employed herein.

	4CM	DAY	2PM	3PM	5PM
L3	3	3	3	3	3
L7	3	0	0	0	0
M1	0	0	0	0	0
M5	2	2	3	3	3

Table 1: LEED credits obtained for the four classrooms when using different methods (blinds were not modelled)

	4CM	2PM	3PM	5PM
L3	yes	yes	yes	yes
L7	no	yes	yes	yes
M1	no	no	no	no
M5	yes	yes	yes	yes

Table 2: PSBP compliance check for the four classrooms when using different methods

For rooms L3 and M1 there is a full agreement that they are respectively a well daylit space and a badly lit space. For the LEED assessment of room M5, the differences are due to the sDA results, which are slightly lower than 75% when calculated with the Four-Component method or with DAYSIM, therefore giving only 2 credits instead of 3. More interesting is the analysis of the results for room L7, which is the one that receive most daylight throughout the year, due to its double aspect. Not only different methods bring to different answers, but also the two compliance systems give contradictory evaluations of the same space.

When looking in more detail at L7 results, it can be noticed that the UDI-c results are the reason of the disagreement between methods when complying with PSBP requirements, but this is due to a relatively small difference in values. Using the Four-Component method, UDI-c is equal to 78%, while with the Two- and Three-phase methods it is 80%, and 82% if obtained with the Five-Phase method. Indeed, when using annual metrics such as UDI, sDA, DA, the variations in results due to the method choice are remarkably small, with relative differences always below 12% for all the analyses carried out during this work. The same applies for the results calculated for LEED. While sDA values are very similar, independently of the chosen method, ASE results are affected by a huge variability and, in room L7 case, led to scores of 0 credits for all the methods but the Four-component one. This uncertainty in ASE values is highlighted in Figure 3(b), which shows the results obtained following LEED requirements for all the rooms, obtained with each of the studied method. An ASE value obtained with the Three-Phase method (43.8%) can be as much as five times higher than one obtained with the Four-Component method (6.5%).

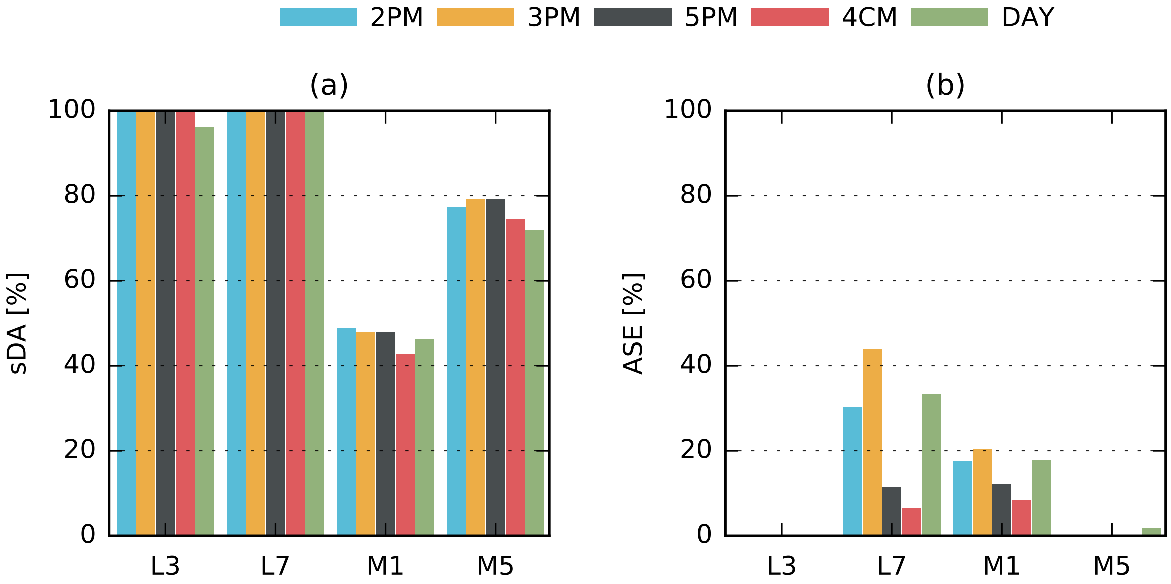

Figure 3: sDA and ASE results as required by LEED v4

The difference between ASE results can be explained better by looking at the instantaneous direct sunlight illuminance conditions represented in Figure 4. The horizontal plots obtained with the five investigated methods for the 1st March at 8:00am are shown, together with the number of virtual sensors that are hit by direct light at that instant. The different methods produce very different pattern, depending on how they treat the sunlight contribution. Consequently, the number of sensors that record illuminances higher than 1000 lx is very different at each time step of the year, leading to different ASE final values.

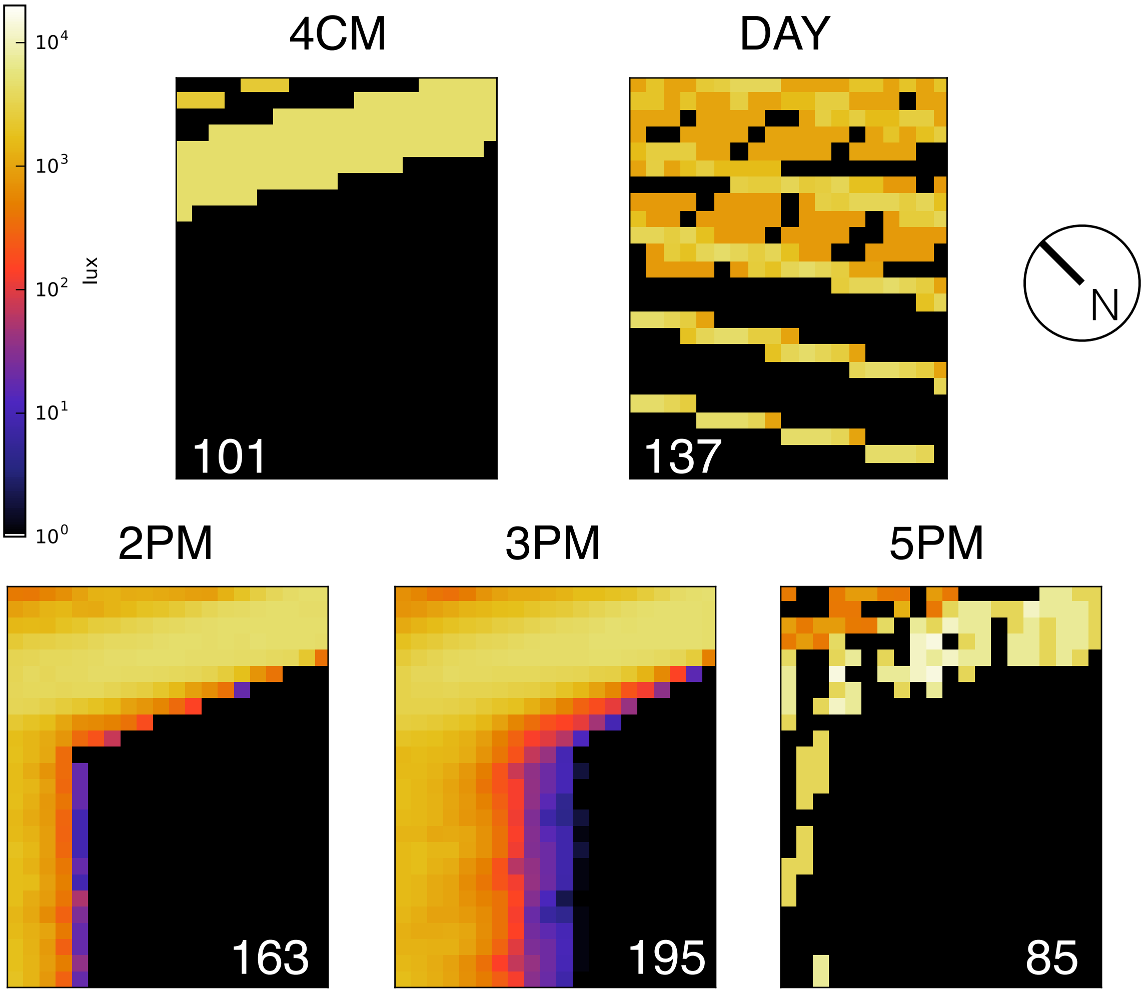

Figure 4: Illuminance plots on the horizontal plane for the 1st March at 8:00am. The numbers at the bottom of the plots indicate the virtual sensors that are hit by direct sunlight in each method

The benchmark Four-Component method, which is based on the use of the *rtrace* command, produced clearly defined sun patches coming in through the windows; DAYSIM results were characterized by a multiplicity of patterns, due to the existence of four sunlight sources at the same time in the interpolated mode; the Two-Phase method led to the spreading of light over big solid angles as the sun was assigned to three of the Reinhart sky patches; similarly, the Three-Phase method shown very spread light patterns, but the cause in this case has to be attributed to the BSDF Klems basis used at the window plane; lastly, the Five-Phase method resulted in a lower number of sensors hit by direct sunlight, but not as clearly defined as with the Four-Component method, as here no proxy geometries were used, but only the Tensor-Tree based BSDF.

4. Discussion

The methods investigated in this paper are all *Radiance*-based but they differ in many aspects of the annual simulation techniques employed. From the analyses presented in Section 3, it is noticeable that the most influential distinction is in the representation of direct sunlight. When the simulation involves both sky and sun sources, and indirect contribution from the two is considered (i.e. the light inter-reflections within the space), the final annual metrics shows a remarkable agreement between all methods, regardless of the sky model used and other dissimilarities in the process. The Two-Phase method (noticeably faster than all the others) could be therefore successfully applied for Total Annual Illumination (TAI), Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) calculations; that is, if the model presents only clear glazing. In this simpler case, it was found that even the coarser sky subdivision, following the Tregenza scheme, would suffice. Similarly, if Complex Fenestration System (CFS) are adopted in the design and those same metrics are required, the Three-Phase method is deemed to be suitable, but further studies with more complex materials applied to the model's apertures would be necessary.

On the other hand, when the final results need to represent the influence of directional light coming from a small source, as the sun is, not all the methods should be considered reliable. The same applies for analyses related to specific viewpoints, e.g. glare analysis, or any simulation that necessitates of the exact sun position at the specified time steps. In these cases, choosing CBDM methods that apply different strategies for sky and sun contributions looks advantageous, such as the Four-Component and the Five-Phase methods, and ideally DAYSIM. DAYSIM however did not lead to the same Annual Sunlight Exposure (ASE) results obtained with the benchmark method, likely because of the Interpolated mode used in its sunlight simulation. To understand if the method is comparable to the benchmarks for higher precision purposes, the comparison should be repeated using the Nearest Neighborough (NN) or the Shadowing Test modes, available within DAYSIM original source code, but none of the commercial interfaces employs that at present.

Further work is also planned to compare the results gained from all simulations with the luminous values collected in the real spaces, so that the CBDM methods investigated would not only be verified against a benchmark technique (the Four-Component method here), but with measured data too, increasing the robustness of the study.

5. Conclusion

The research presented in this paper compared five of the most commonly used methods to perform CBDM evaluations. The annual metrics currently used for energy rating certification (e.g. LEED) or other compliance checks (e.g. PSBP) were adopted as term of comparison; namely, UDI, sDA and ASE were used. The results showed how some of those metrics agree remarkably well, independently of the chosen simulation techniques, such as UDI and sDA. ASE however, being based on the direct sunlight contribution only, led to very high variability in results, which undermines the validity of this specific metric for compliance purposes. These findings highlighted also the need for guidelines that would help designers in choosing the appropriate method for each daylight evaluation. The research will be expanded further with a comparison between simulated and measured data.

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Glossary

Bidirectional Scattering Distribution Function (BSDF): Function of solid angles and directional variables that define the relationship between an incoming light flux and the resulting outcoming flux, sampled on each respective hemisphere. In daylight simulation, this function replaces the geometry of complex fenestration systems that would be too computationally demanding if modelled realistically. When it is built on a Klems basis (as for the Three-Phase method), each hemisphere is composed by 145 patches, while when the Tensor-Tree scheme is used (for the Five-Phase method), the resolution varies depending on the light peaks direction.

Daylight Coefficients (DC): Mathematical function that relates that relate the luminance distribution at the sky with the illuminance at a point in a room [16].

Daylight simulation engines: Packages of programs that usually run in the background and that simulate the light behaviour by means of mathematical and statistical functions. Depending on the functions that each engine uses, they can be classified as forward or backward raytracers, radiosity based, or analytically based. *Radiance* is a backward raytracer.

Virtual sensors: Coordinate points usually defined and evenly placed over a planar surface (e.g. the working plane). These points are used in a simulation to collect luminous data, whether for a point-in-time analysis or for an annual one.

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