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THE EFFECT OF THE ANALYSIS GRID SETTINGS ON DAYLIGHT SIMULATIONS WITH CLIMATE-BASED DAYLIGHT MODELLING

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Abstract

The recent development of climate-based daylight modelling (CBDM) practice led to various methodologies to perform daylighting evaluations, while its insertion in new guidelines created the need of common procedures and verified frameworks.

This paper aims to give an insight into the relation between the analysis grid and time-step settings and the reliability of an annual climate-based daylight simulation performed with distinct methods. CBDM is a rapidly evolving practice, and the evaluation reflects that by including several different state-of-the-art software tools in the overall comparison. The space under analysis is a real case study classroom where the monitoring of the luminous environment is being conducted for a parallel research.

The results, expressed as annual exposure, Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA), show a good agreement between most of the tools and delineate some minimum requirements on the input accuracy for the considered space, in terms of grid resolution, time step and sky vault discretisation.

Keywords: Analysis Grid, CBDM, Daylight, Simulation.

1 Introduction

1.1 Background

Daylight modelling practice has recently experienced a leap forward from the traditional methods introduced decades ago. The building performance in terms of light access and redistribution is influenced by a very high number of parameters which can now be taken all, or almost all, into account thanks to computer simulation. At the same time, fenestration technologies are evolving quickly, moving on from the "simple" transmission of light of the clear glazing windows.

With climate-based daylight modelling (CBDM) it is possible to represent both the instantaneous and the cumulative behaviour of daylight during a complete reference year, providing a feeling and a realistic evaluation of how a building design will perform through the daily and seasonal changes. The existing methods have been based primarily on the Daylight Coefficients theory developed by Tregenza (Tregenza et al., 1983) and implemented with the use of the physically accurate rendering engine called *Radiance*, which simulates the light distribution in a view-dependent manner (Ward Larson et al., 1998) and constitute the most scientifically validated state-of-the-art software for the purposes of daylight modelling (Ochoa et al., 2011). After the engine and the DC method validations (Mardaljevic, 2000), the discipline has been gradually associated with the use of the Perez-all-weather luminance distribution, especially after the contribution of Reinhart (Reinhart, 2001) and the introduction of DAYSIM as a *Radiance*-based back-end engine for various building modelling software. Furthermore, there have been validations of *Radiance* performance for Complex Fenestration System (CFS), such as translucent panels (Reinhart et al., 2006), and of a new simulation method that could be used for example to evaluate "light-pipes" light redistribution, the 3-phase method (McNeil et al., 2013).

However, all these advances in the modelling practice have not been accompanied by any new standard or structured procedure to perform them. Few rigorous analyses have been carried out in this sense: these include a work on the weather file time step to be used when calculating possible energy savings due to a combined use of daylight and lighting controls (Iversen et al., 2012) and a recent comparative work on standard weather tapes from different sources for several European cities (Bellia et al., 2015), both focusing on the metrics that have been derived from CBDM.

New metrics have been made necessary by the vast amount of data that a single CBDM simulation can produce and by the need of expressing these data in simple representative figures when comparing different design options. The two most used metrics are currently Daylight Autonomy (DA), or its variant Spatial Daylight Autonomy (sDA), and Useful Daylight Illuminance (UDI). Given an occupancy schedule for the analysed space, the first expresses the number of hours when the illuminance levels are above a certain threshold over the total number of occupied hours, while the latter expresses the number of hours when the illuminance levels fall within certain ranges, both in terms of percentage. Recently, some of these new metrics have been inserted in building simulation guidelines, as an Illuminating Engineering Society (IES) approved method in the USA (The Daylight Metrics Committee, 2012) and as a mandatory requirement for the Priority Schools Building Programme (PSBP) by the Education Funding Agency (EFA) in the UK, creating the case for a better definition of input quality and uniformity throughout the existing workflows.

1.2 The sensor grid

One of the first steps in preparing a model for daylight simulation is to set a grid of points, i.e. virtual sensors that correspond to a 'real-world' positioning of measurement instruments in the space. Given that in the simulation there are naturally no restrictions in its placement due to the room occupants, the grid is usually built on an horizontal plane at an height related to the task that is performed in that space. When checking the literature and the main guidelines however, almost all the specifications for grid settings are given with regard to lighting systems, for which the working plane height and a boundary between grid and walls are usually enough (CIBSE/SLL, 2012). The spacing between sensor points, i.e. the grid resolution, is not a common specification, as the grid would follow the lights arrangement. The same is for the Daylight Factor (DF) calculation, where the space distribution of light coming from an overcast sky is relatively smooth, therefore requiring a limited number of points to trace contour lines on the working plane.

For CBDM the grid may assume a deeper importance on the final results and on the initial settings, mostly due to the fact that it takes into account the direct sun, which is a strongly directional and concentrated source of light. This is inevitably bound together with the time step chosen for the series of instantaneous simulations and with the sky description resolution set by the used method. The first one is generally one hour (during which the sun moves about 15°) or sub-hourly shorter time steps, while the latter can follow a Tregenza division, in 145 patches (Tregenza et al., 1983), or smaller subdivisions that follow Reinhart description (577 or 2305 patches); moreover, the direct sun component can be assigned to a sky patch or can have its own independent position assignment.

This paper will discuss how, given a room geometry, the choice of the grid settings, combined with the simulation time step and with the sky subdivision, can influence the annual results obtained with several methods and presented through different metrics among the most common ones.

2 Methodology

The modelled space represents one in a series of classrooms that are the object of a wider research study that is being carried on by the authors and others, in which the luminous performance of the rooms will be assessed through measurements and simulations, and then related to the occupants' perception of the same spaces. Schools environments have been specifically chosen for the relevance that they assumed for daylighting regulations since the PSBP has been approved in the UK. During this stage, the study concentrates on inter-model comparisons, therefore the 3D model has been built in a simplified version. Later on, when data from real measurements and monitoring will be made available by a parallel research, the model will be refined and the accuracy increased.

The model has been created in Rhinoceros® and then converted in the formats required by each of the methods or built from the beginning in case of Tool B (with an accuracy of ± 1 cm), following the same measured dimensions and recreating the detail as similar as possible to the original model. The room orientation was chosen based on the real configuration of the classroom, while the climate file selected and maintained for all the simulations does not correspond exactly to the real location. The file is of the EPW IWEK type, sourced from the EnergyPlus website database (U.S. Department of Energy), for London (Gatwick). The space represents a double-aspect classroom with windows looking towards North-East and South-East. For Tool A and Tool B the model has been built with a rotation of 45° to the East, causing the rotation of the sensor

grid too, while for the other methods the model was kept orthogonal to the coordinate axes and the sky luminance distribution was rotated instead.

The representation of the model and its main dimensions are reported in Figure 1. The optical properties assigned to the surfaces in all the methods are reported in Table 1.

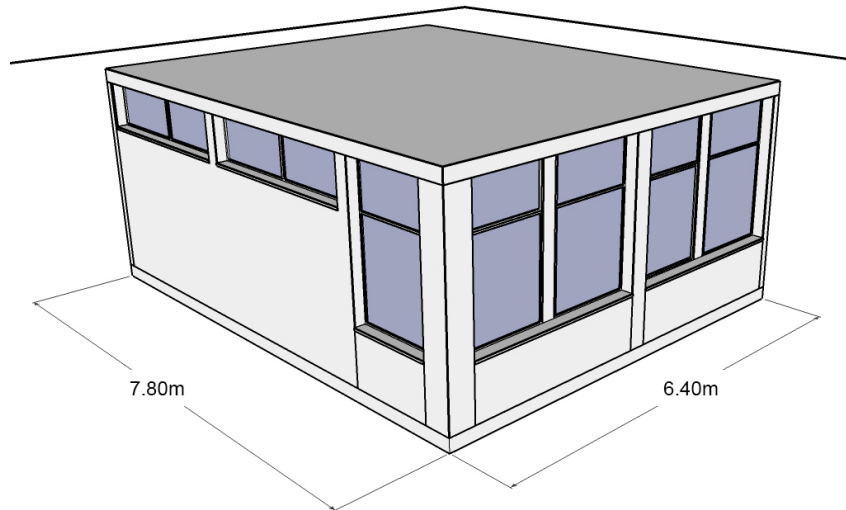


Figure 1 – The model of the classroom chosen as a case study for all simulations in this work.

Table 1 – Surface reflectances and glazing transmittance assigned to the model surfaces

Floor	Walls	Ceiling	Frames	External Ground	Glazing
0.2	0.5	0.7	0.5	0.2	0.87

Due to different calculation algorithms used for the sensor grid, the points coordinates are not exactly the same through all methods. Where possible, the same grid description was used, otherwise care was taken in order to create similar grids. The height have been set at 0.80 m and a minimum boundary between the edge of the sensor grid and the walls have been specified to about 0.50 m. The resolution has been analysed in four different variants, with the spacing between points set to 0.10 m, 0.25 m, 0.50 m and 1.00 m ; Figure 2 shows the plan view of the respective configurations created in Rhinoceros, in a way that would collocate the external points as close as possible to the 0.50 m boundary edge (indicated with a red line in the Figures). These exact coordinates were used in the simulations run with Tool A, with the 2- and 3-phase methods.

The 4-component method make use of the *stencil method* to create a sensor grid, meaning that the user should define a certain resolution in pixels for the image of the working plane that is first rendered, then the sensor points are assigned to the centre of the image pixels. Figure 3 takes as example the plots that result from the direct sun component of the Total Annual Illumination (TAI) to show how the working plane is subdivided depending on the chosen number of sensors. This was set to be as close as possible to the number of sensors used in the other methods for each resolution. As a matter of fact, for spacing values higher than 0.25 m it is difficult to maintain an exact boundary for all space geometries. For this method in particular, the increment of the resolution does not result in a very long additional computational time, therefore it is usual to keep the number of pixels on the high side.

Radiance ambient parameters have been set accordingly to the room geometry and to each of the chosen methods, given that their simulation approach differs sometimes radically from each others. Table 2 reports the main parameters assigned and, when not inserted directly, the default parameters that *rtrace* (for the *4-component method* and Tool A) and *rcontrib* (for all the other methods) adopt are written in brackets. Tool B does not allow the user to change parameters for CBDM evaluation, using instead a predefined set specific for *rcontrib* runs.

For all simulations, the produced illuminance data have been post-processed by external

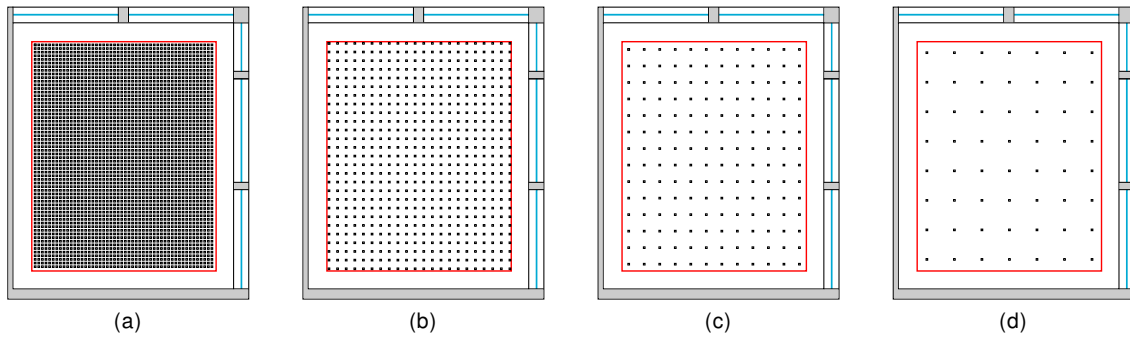


Figure 2 – The four different grid configurations used in Tool A, 2- and 3-phase methods. The set spacing between points is equal to 0.10 m in Figure (a), 0.25 m in Figure (b), 0.50 m in Figure (c) and 1.00 m in Figure (d).

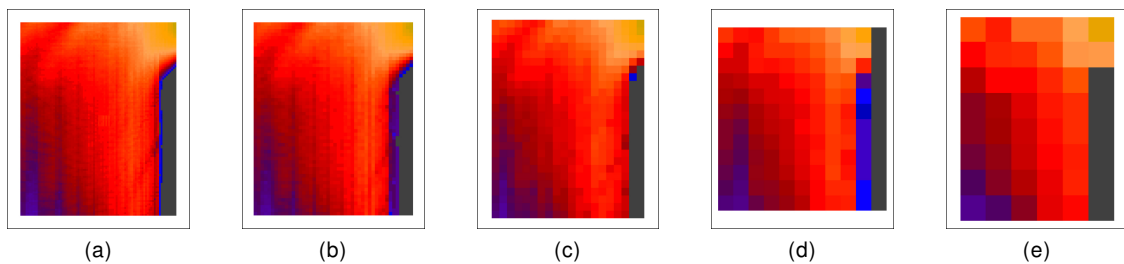


Figure 3 – Results plots obtained with the 4-component method that show the difference in grid resolution. The set pixel resolution is equal to 84x120 in Figure (a), 46x56 in Figure (b), 20x26 in Figure (c), 11x12 in Figure (d) and 6x8 in Figure (e).

data analysis software (IDL[®] or IPython (Pérez et al., 2007)) to calculate the final metrics. The occupancy schedule applied for all days of the year is 8:00 - 16:00. The derived metrics are: UDI, with thresholds at 100 lx, 300 lx, 3000 lx; DA with threshold at 300 lx; sDA with threshold at 300 lx for 50% of the time; and annual exposure in klx hr. The DF values calculated directly by the commercial software are reported, together with the ones derived by command-line *Radiance*.

All the investigated methods employ *Radiance* as the simulation engine, but they are characterised by fundamentally different procedures. Some of the main differences can be found in the description of the sky luminance and the sun positioning, as summarised in Table 3. The various techniques to define the sensor grid have been explained previously and the effects of those will be the focus of the analyses reported in the next section. The description of other characteristics specific to each method is addressed hereafter.

2.1 4-component Method

The 4-component method has been created by Mardaljevic and validated against real measurements from two simultaneous datasets of interior illuminance and sky luminance (Mardaljevic, 2000). It uses a Tregenza division of the sky vault for the indirect light calculation and 2056 points evenly distributed over the hemisphere for the sun position assignment. For each of the

Table 2 – *Radiance* calculation parameters

	-ab	-ad	-ar	-as	-aa	-lr	-lw	-dr	-dp
Tool A	5	2048	256	512	0.1	6	4e-2	2	na (512)
4-component	5	2048	128	256	0.2	10	5e-2	2	0
Tool B	5	32768	1024	0	0	0	1e-5	3	512
2-phase	5	100000	na (256)	0	na (0)	na (-10)	1e-5	na (3)	na (512)
3-phase (vmx)	12	50000	na (256)	0	na (0)	na (-10)	2e-5	na (3)	na (512)
3-phase (dmx)	2	5000	na (256)	0	na (0)	na (-10)	2e-4	na (3)	na (512)

Table 3 – Main differences in the sky description of the different investigated methods

	Sky discretisation	Sun positioning	Luminance distribution
Tool A	MF:1	65 points	Perez-all-weather
4-component	MF:1	2056 points	Blended CIE
Tool B	MF:2	In the sky patch	CIE Standard
2-phase	MF:[1, 2, 4, ...]	In the sky patch	Perez-all-weather
3-phase	MF:[1, 2, 4, ...]	In the sky patch	Perez-all-weather

patches, a single *rtrace* command is used to find the Daylight Coefficients (DC), while the direct calculation is deterministically solved. The sky luminance is defined as a blend of CIE Standard Overcast, Clear and intermediate skies, determined by the climate conditions read in the weather files (Mardaljevic, 2008).

2.2 Tool A

Tool A is a commercial tool based on DAYSIM, therefore using a modified version of the *Radiance rtrace* command to calculate all DC in one single run. The sky is divided in 145 patches and the ground in further 3 concentric patches. The Perez-all-weather model is used to derive the luminance distribution to be assigned to those patches, taking the direct normal and diffuse horizontal illuminance data from the representative weather file. The sun position is derived from azimuth and altitude calculations and assigned to one of the 65 points laying on the solar paths in a fixed position (Reinhart et al., 2001).

All modifications to the standard settings that should be done through DAYSIM and that can not be accessed directly by Tool A have not been considered for this specific study.

2.3 2-phase Method

The 2-phase method has been developed for command-line *Radiance*, mainly to create a faster methodology to perform DC calculations, making use of the *rcontrib* command (or the new *rfluxmtx*). The *Radiance* renderings parameters must be set so that the indirect irradiance caching is switched off (-aa 0) and the hemispherical sampling division is high enough to compensate for it (e.g. -ad 10000). The sky vault can be divided following either the Tregenza description (145 patches) or the Reinhart one (577 patches for the MF:2 option, 2305 for the MF:4 and so on). The luminance assigned to the sky is defined by the Perez-all-weather model and the sun brightness is spread between the three or four patches closest to the actual sun position.

2.4 Tool B

Tool B is a commercial software that recently introduced a section dedicated to the annual simulation of daylight, which is however still labelled as Beta version (in the latest software distribution available to date). Also, to the authors' knowledge, it is the only publicly available software that does not use the Perez-all-weather luminance distribution over the discretised sky, applying instead a combination of CIE overcast and clear skies. The DC calculation is carried out by *rcontrib* as in the 2-phase method, with a sky subdivision in 577 patches (MF:2).

The 3D model presents some minor differences in compare with the ones used for the other methods, due to the difficulties of importing a relatively detailed geometry with thick walls, essentials in daylighting studies. The modelling of the details as inserted components created some problems in the grid assignment and the value set for the grid shrinkage (boundary between edges of the grid and walls) was not recognised by the simulation. These issues resulted in sensor points with no illuminance recorded for the whole year, which have been disregarded in the post processing of data.

The annual analysis uses only hourly data and the schedule is assigned after the simulation, with the metrics calculation. For sub-hourly time steps, the hourly results are interpolated down to a 5 minutes resolution.

2.5 3-phase Method

The 3-phase method is run through command-line version of *Radiance*. Together with the 5-phase method, not investigated in here, it has been recently introduced to deal effectively with CFSs. Either Tregenza or Reinhart divisions can be adopted and the sky luminance distribution is calculated via Perez (sky matrix *S*), while a Klems division is used to describe the light flux falling onto a window (daylight matrix *D*) and the transmitted component redirected into the space

(transmittance matrix T resulting from the Bidirectional Scattering Distribution Function (BSDF)). The light scattered within the room and reaching the sensor points is then described by the view matrix (V). The illuminance values are therefore obtained with a matrix multiplication, as in the equation:

$$E = VTDS \quad (1)$$

3 Analysis

Each of the analysed methods will be presented at first separately, focusing on the effects that the grid spacing (0.10m, 0.25m, 0.50m, 1.00m), the time step (5,10,15,30,60 minutes) and the sky resolution have on that specific process, first shown with the cumulative metric of *annual exposure* [klx hr], so that they take into account the whole simulated year without grouping the values into bins as CBDM metric do. Successively, the methods will be compared to each others, using both cumulative and CBDM metrics.

3.1 Method by Method

The 2-phase method gives the user the choice of a coarser or finer sky discretisation, starting from the Tregenza subdivision to the Reinhart ones. The *rcontrib* options MF:1, MF:2 and MF:4 have been tested for all the grid resolutions and the selected time steps. As Figure 4 shows, the results in the three cases are almost identical, meaning that for the considered geometry the simulation is not affected by the sky subdivision. The same test, limited to the MF:1 and MF:2 cases, have been run for the 3-phase method, showing again that there are no substantial differences due to the sky discretisation.

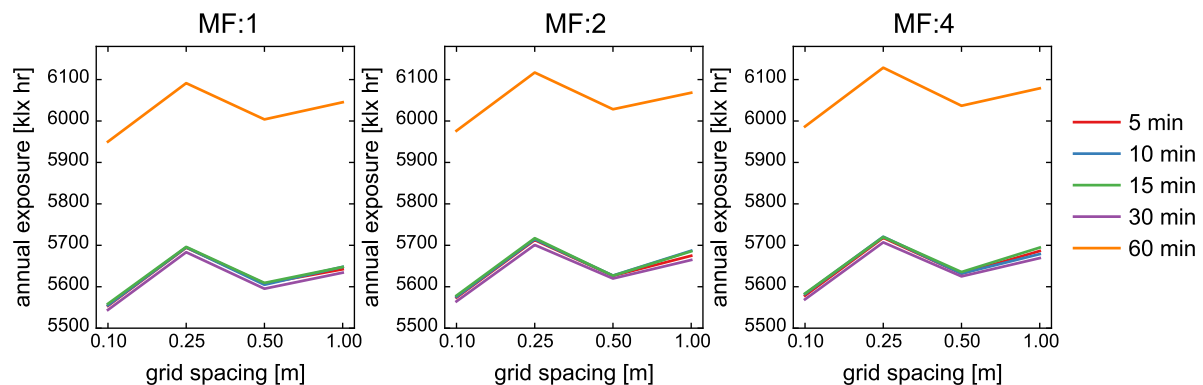


Figure 4 – Results obtained with the 2-phase method, using different sky subdivisions.

Along the grid spacing axis, the results are sufficiently stable, with percentage differences of less than 3% that could be due to a spatial alias-like effect. Each configuration requires a specific subdivision to fit in the working plane that leads to a different placement of the sensor points and a bigger or smaller distance between the grid and the walls. Especially for the direct sun contribution, even a small displacement can result in a high variance of instantaneous luminance values.

The choice of different time steps, shown in Figure 4 with coloured lines, lead to a noticeable difference only stepping from 60 to 30 minutes; for shorter time steps the values remain the same as for 30 minutes. This distinct division might be caused by the use of stochastically interpolated sub-hourly weather files produced by DAYSIM for the 30 minutes and shorter time steps rather than the original EPW file with hourly steps.

The 4-component method uses instead a linear interpolation of climate files for sub-hourly time steps and that is reflected in the results in Figure 5. The values are gradually and proportionally rising as the shorter time steps allow the sensor points to capture more of the light variation, especially more direct sun straight on the virtual sensor.

For this method, the annual exposure reaches a better stability only for grid spacing below 0.50 m. The case with a spacing equal to 0.05 m has been added to verify that this stability is maintained while the resolution grows. The lower results given by the 1.00 m resolution grid might be caused by the grid points assignment method used in this case. As previously presented in Figure 3, the sensors are positioned at the centre of the pixels that form the working plane

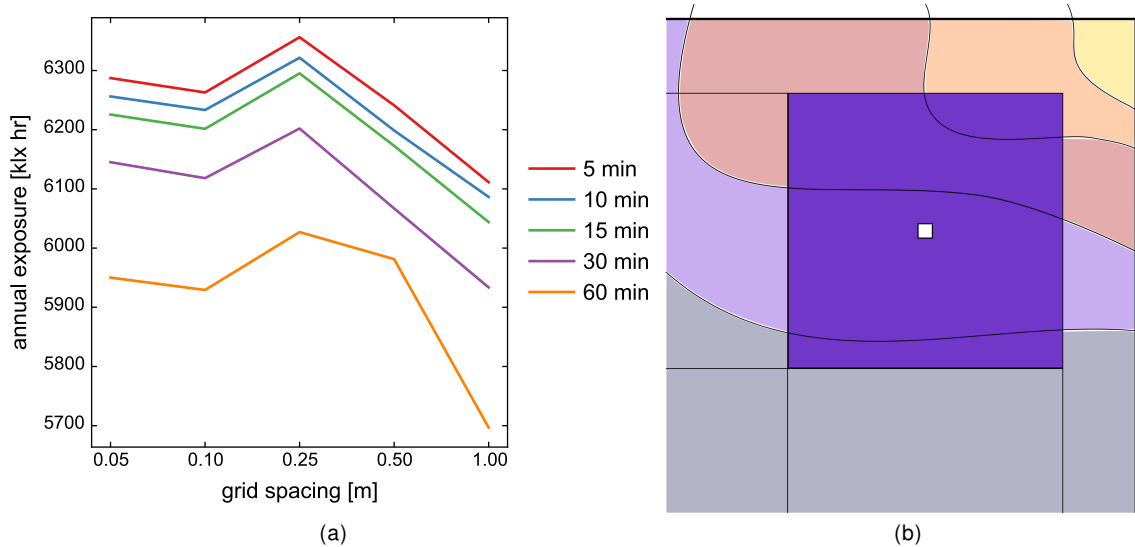


Figure 5 – Results obtained with the 4-component method (a) and illustration of a possible alias effect when showing the results measured at one single point over the whole pixel area (b).

image. The pixel distribution is constrained by both the room dimensions and the square shape of the pixels themselves. When displaying the results, the values recorded at one sensor point are adopted for the whole pixel area that surrounds the point, leading to an alias-like effect, as explained in Figure 5. The apparent surface of the working plane might have a distance from its edge to the walls similar to the required one (i.e. 50 cm), but in reality the measurement was taken slightly further away. The further from a window, the less direct contribution the sensors receive and lower cumulative values are recorded.

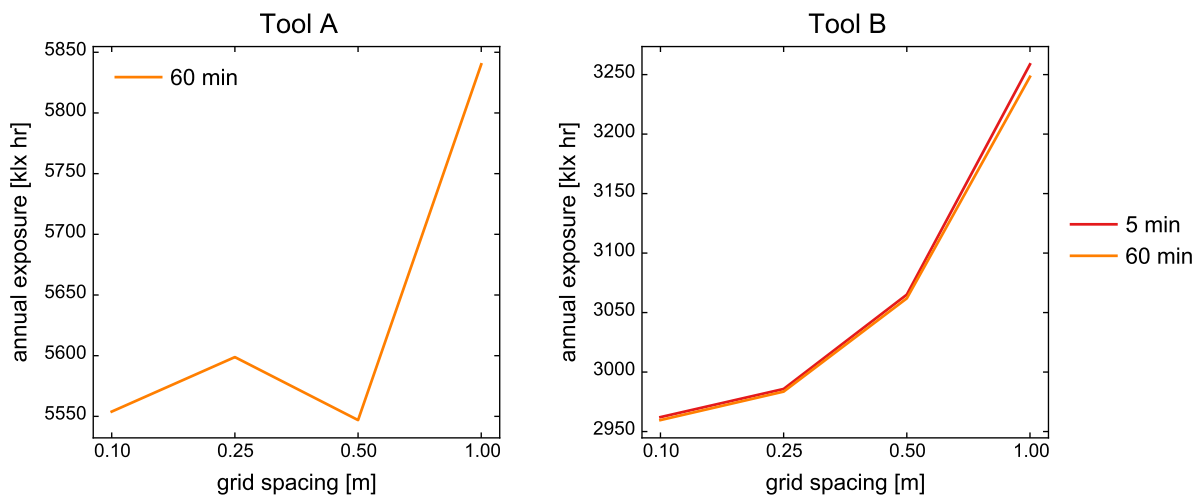


Figure 6 – Results obtained from Tool A and Tool B.

Tool A and B do not offer the same flexibility as the other methods, so the investigated combinations of grid resolution and time steps are consequently reduced. Tool A can only produce hourly results and, as shown in Figure 6, it stabilises for resolutions of 0.50 m or finer; the result obtained using 1.00 m spaced grid cannot be considered reliable and the cause might be again conducted to the points placement strategy. Tool B clearly shows a convergence toward a value with the refinement of the grid resolution for both the 60 and 5 minutes time steps. The shorter time step is obtained from the hourly one by interpolating the final results, rather than the input climate file, and consequently shows an almost perfect match in this case. On the whole, Tool B produces results that are significantly lower than all the other methods, therefore all

considerations about it should account for the fact that this specific tool is still under development and not completely reliable.

3.2 Inter-model Comparison

Focusing only on the hourly step, it is possible to compare together the results from all the methods encountered before, using also more metrics than the annual exposure alone. The CBDM metrics that are currently used in various guidelines are mostly DA and UDI; sDA was calculated too, but for the analysed room it always resulted in 100% in most of the cases.

Figure 7 compares the results obtained from the five methods when using different grids and a time step of either 5 (dashed lines) or 60 minutes, expressed in TAI and in DA. It is noticeable how Tool B produces low illuminance values. The rest of the software is more comparable and lead to values that all fall within a range of about 600 klx hr. All of them can be considered constant below a grid spacing of 0.50 m. Looking at the DA the variation range is even reduced to 3%.

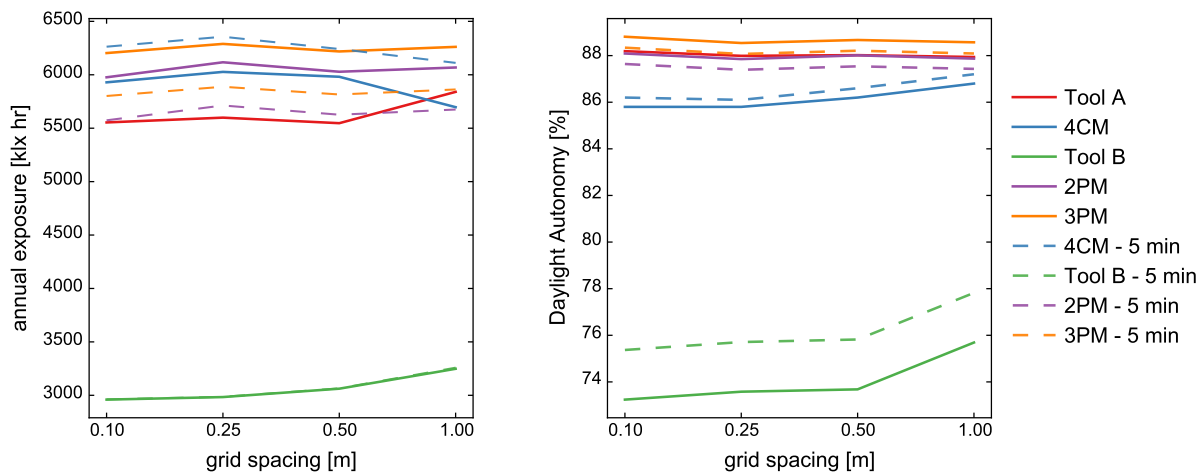


Figure 7 – Comparison between results from all methods for time steps of 60 and 5 minutes, expressed in annual exposure (left) and DA (right).

The same can be seen in Figure 8, where the four UDI ranges obtained using hourly time steps are presented as stacked bars, with the UDI-n range (i.e. $E < 100lx$) at the bottom, followed by UDI-s ($100lx < E < 300lx$), UDI-a ($300lx < E < 3000lx$) and UDI-x ($E > 3000lx$). Apart from Tool B, the other methods differ from each other for few percentage points, with a maximum of 5% between the 4-component method and the 3-phase method UDI-x values when using 1.00 m spacing.

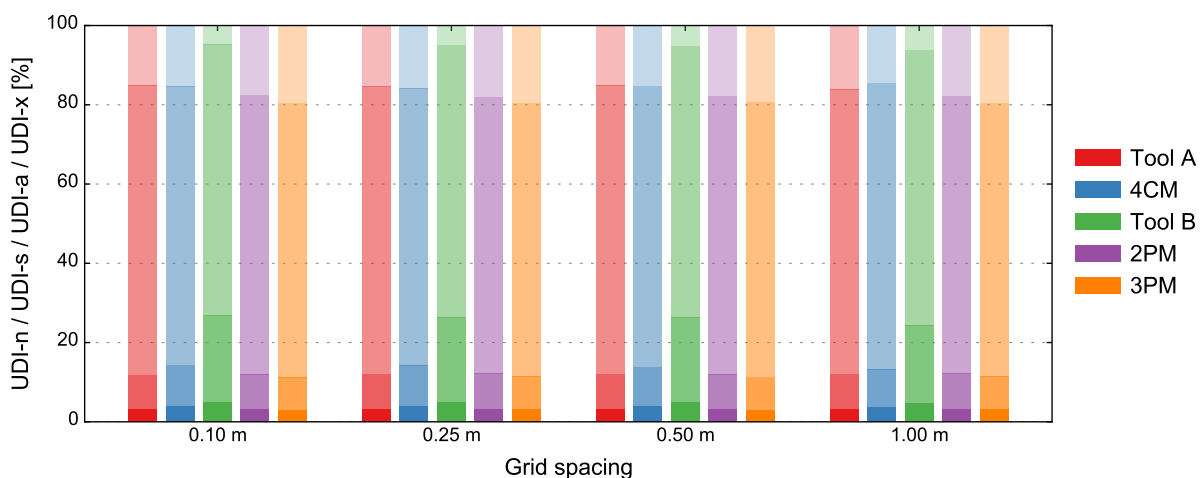


Figure 8 – Comparison of UDI results obtained with the five methods using hourly time steps.

Last, a comparison between methods when calculating the DF is displayed in Figure 9. The 4-component, 2- and 3-phase methods are all procedures specific for annual CBDM calculations; the DF produced by *Radiance* with the *rtrace* command is presented instead. Tool A and B are able to calculate the DF within their interfaces, making also use of *Radiance* as their back-end simulation engine. For Tool A the Average DF is reported here as it was displayed by the software to the user, while for Tool B the tabulated values at each sensor point were used to calculate the average (null values were excluded during this post-process).

The DF values from Tool B follow the same behaviour as the annual exposure was following for this tool. This might indicate that the used tabulated values were calculated through *rcontrib* instead of *rtrace*. Tool A and *Radiance* show a better agreement and a similar behaviour when using different sensor grid resolutions, even though *Radiance* has a wider variation.

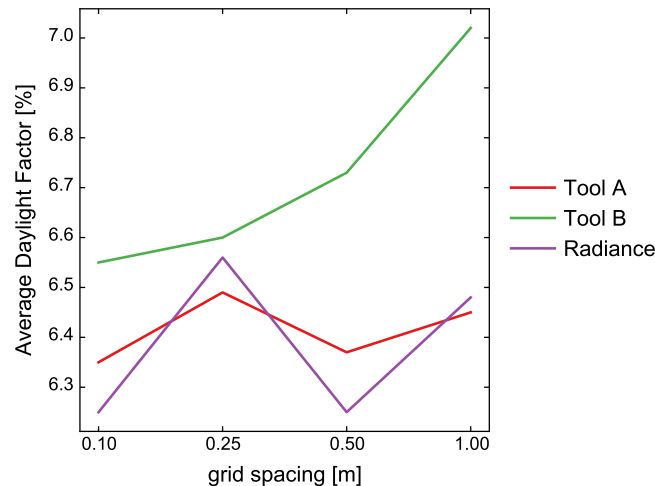


Figure 9 – Daylight Factor values calculated with three different tools.

4 Discussion

All the results presented herein are inevitably relative to the chosen space, its orientation and its geometrical characteristics. Rather than being an abstract simplified model, it has been chosen to recreate a realistic space that is currently being monitored for a parallel research. This choice could potentially lead to an evaluation that is affected by several simultaneous effects and too complex to analyse. Nonetheless, it is believed that some of the features of the investigated tools and the results obtained with them when studying the horizontal grid resolution have been brought to attention and explained. The discussed outcomes will be then expanded by applying the same analysis to more spaces, different in size and properties.

Considering the exception of Tool B, it is possible to see a general agreement between the results obtained by the different methods, even though they make use of dissimilar approaches. While looking at the instantaneous results at any hour of the year and point in the space would show greater discrepancies, the combination of counter-acting effects during a whole year lead to an overall evaluation of the space performance that does not strictly depend on the chosen software or methodology. This is even more accentuated by the use of CBDM metrics, that smooth out the singularities of the initial settings.

The choice of grid settings, as well as of the sky vault subdivision, do not bring to radical differences in results for a space like the considered one. It is probably best to choose a grid finer than 1.00 m, so that the required working surface can be filled with sensor points in an accurate way. The results appeared to be more sensitive to the distance between the grid edges and the room walls rather than to the spacing between points within the grid. One solution would be to increment the resolution so that the points at the edges are positioned as close as possible to the boundary. In case the number of points is limited by the computational requirements, the grid construction algorithm should be optimised to give the priority to the set boundary distance over the grid spacing.

5 Conclusion

The analysis presented the comparison between several CBDM methods and their results when changing the sensor grid characteristics, combined with the time step and the sky subdivision.

For the selected space, which represents a real classroom undergoing a monitoring study on its luminous environment, the results showed that the most of the tools used for the evaluation agree on the general assessment of the room performance. The sky vault discretisation is not affecting the outcomes, while the grid construction and the time step chosen can have some minor effect on the annual results. When using a grid spacing equal or smaller than 0.50 m and a time step equal or shorter than 30 minutes, all the methods show a stabilisation of the results and the increment in input accuracy does not produce any significant effect.

Further work will include the analysis of more spaces with different characteristics.

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