Effective Simulation of Spatial Daylight Autonomy and Annual Sunlight Exposure

Sergey Ershov[1], Vadim Sokolov [1,2], Alexey Voloboy[1], Vladimir Galaktionov[1]

[1] *Keldysh Institute of Applied Mathematics RAS, Miusskaya sq. 4, Moscow, 125047, Russia*
[2] *ITMO University, Kronverksky pr. 49, St. Petersburg, 197101, Russia*

Abstract

Nowadays the daylight analysis is widely used by architects because it influences on the room usage and comfortability. The natural daylight has a lot of benefits. There are many issues related to the daylight which affects the function and perception of the illuminated area. The issues are direct sunlight and discomfort glare, illumination level and distribution on the working plane. The correct building design that takes into account the daylight analysis aspects leads to decrease of the artificial light usage and energy saving. So simulation of the metrics used in daylight analysis is an important task. The paper considers the simulation of two main standard characteristics widely used in the modern daylight estimation: spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). The calculation of both metrics is regulated by the Illuminating Engineering Society (IES) standards. The metric calculation provides daylight illumination data for whole year with one hour step. This means that several thousand simulations have to be run. So effective light simulation methods must be elaborated and used here. The paper presents the methods which deal with rather complex and precise building models under daylight illumination and realistic environment. Spatial Daylight Autonomy metric is calculated considering blinds control that opens or closes them depending on the over-exposure by the direct sunlight. Thus, simulation of sDA involves an optimization procedure defining blinds configuration at each hourly moment. The sDA and ASE calculations for architecture scene are provided as examples.

Keywords

Daylight simulation, daylight autonomy, spatial Daylight Autonomy, Annual Sunlight Exposure, Perez sky model, blinds control, Typical Meteorological Year.

1. Introduction

The spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) are the two widely used metrics in the modern daylight analysis. They are included into the *Leadership in Energy and Environmental Design* (LEED) — a green building certification program used worldwide. These characteristics are explained in IES LM-83-12 standard [1] and in short terms can be defined as:

- Annual Sunlight Exposure (ASE) is a metric that describes the potential for visual discomfort in an interior work environment. It is defined as the percent of an analysis area where the direct sunlight illuminance exceeds certain threshold for more than a specified number of hours per year. ASE standard thresholds are: illuminance level is 1,000 lx and time fraction is 250 hours ($ASE_{1000,250h}$).
- Spatial Daylight Autonomy (sDA) is a metric describing the annual sufficiency of ambient daylight levels in interior environments. It is defined as the percent of the analysis area (where illuminance is calculated) that meets a minimum daylights illuminance level for a specified fraction of the operating hours per year. The standard sDA thresholds are 300 lx illuminance and 50% time fraction ($sDA_{300,50\%}$).

GraphiCon 2022: 32nd International Conference on Computer Graphics and Vision, September 19-22, 2022, Ryazan State Radio Engineering University named after V.F. Utkin, Ryazan, Russia
EMAIL: ersh@gin.keldysh.ru (S. Ershov); sokolovv1969@gmail.com (V. Sokolov); voloboy@gin.keldysh.ru (A. Voloboy); vlgal@gin.keldysh.ru (V. Galaktionov)
ORCID: 0000-0002-5493-1076 (S. Ershov); 0000-0002-1719-5102 (V. Sokolov); 0000-0003-1252-8294 (A. Voloboy); 0000-0001-6460-7539 (V. Galaktionov)

Both these metrics allow to estimate how good is the design of the examined object (say, a hall or a room in the building), i.e., roughly, whether the windows are large enough and whether they open to the right side and so on [2].

The more ratio of the ASE to its threshold means the worse the situation with direct sunlight illumination which can be source of discomfort. Typically, acceptable level of ASE is below 10%. The situation with the sDA metric is the opposite: the greater its value means the better, since less artificial light is needed which decreases the energy consumption.

Simulation of ASE operates illuminance from direct sunlight only, ignoring skylight and interreflections. Simulation of sDA operates full illumination (direct and indirect, sun and sky). So, the lighting engine used for calculations must separate these components.

Architects and designers often use the Radiance software [3-5] to calculate daylight illumination and then convert results into values of metrics. This is due to the wide popularity of this package and the availability of open sources. But more and more designers would like these calculations to be improved in speed and incorporated into commercial systems.

This paper concerns the problems related to the efficiency (acceleration) of calculation of illumination and also the method of deciding which blinds to close and which to open to meet the ASE requirements.

2. Daylight model

The important factor for the correct and precise calculation of the sDA and ASE characteristics is the proper daylight model which should be based on Perez sky model according to the standard. The Perez formulas of the sky luminance distribution (sky goniogram) can be found in [6, 7] and our simulations are based on them.

There are several main parameters determining Perez sky model, the first part of them is related to sun position (sun azimuth and elevation angles). The definition of these parameters is well-known [8, 9] and can be defined based on geography location and specific date and time. The next portion of parameters is related to the values measured in particular date/time: the Direct Normal Illuminance (DNI) and Diffuse Horizontal Illuminance (DHI).

These data are provided with metrological stations around the whole world and represented in different formats. They are called Typical Meteorological Year. The EnergyPlus Weather (EPW) format [10] of the data is used in the paper. The file with ".EPW" extension contains tabular data in the ordinary CSV format.

3. Methods of lighting simulation for ASE and sDA calculation

3.1. Direct sunlight

ASE is calculated on the base of illuminance created with *direct* sun light, so the ray does not change its direction. Attenuation (for example, by a tinted glass) is taken into account. Illumination of an observer cell is calculated as follows: we take at random a point in this cell; then fire from it the ray "towards the sun". If the ray undergoes reflection or diffuse scattering, this ray makes no contribution. If it undergoes only specular transmission or no event, its contribution is equal to an attenuation factor. The error of illuminance estimation is calculated as sample variance because different rays (points) are independent. When the error drops below the desired tolerance, we go to the next cell etc.

The calculation goes for all target time moment (i.e. annually with 1 hour step), skipping only those when the sun is below the horizon. We do not use "interpolation" like we do for the indirect sunlight (see below) to have better accuracy, and also because this part of calculations is relatively fast.

sDA calculation is based on the full illumination including light scattered diffusively. Such calculation can take significant time. The whole annual period consists of 365 days and a dozen calculations have to be run for each day. Thus about four thousand calculations should be run to get annual result. To accelerate sDA calculation several approximations are used.

3.2. Indirect sunlight

It is calculated with the classical Forward Monte Carlo ray tracing (FMCRT) just setting observers to ignore the direct rays (which had been calculated as described in section 3.1). Indirect illumination is not very sensitive to the sun direction. This allows to reduce amount of calculations: unlike the direct sunlight, here we do calculations not for all target time moments but for distinct sun positions.

Namely, we first collect the set of all sun positions above horizon. For an annual period, polar angles of the sun form a spiral (Figure 1):

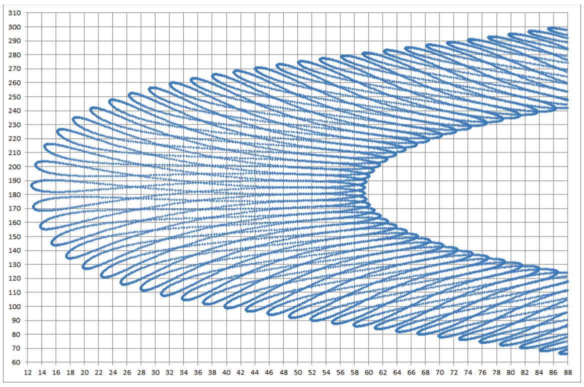

Figure 1: Sun position in the hemisphere during a year; azimuth is vertical and polar angle is horizontal

Then, we take a *Klems grid* (subdivision of hemisphere in approximately equal square cells) of 31 cells in polar angle and corresponding (to make them quadratic) number in azimuth for each polar angle. Totally there are about 1000 cells and 1000 vertices. This reduces the number of calculation about fourfold as compared to processing of all target time moments.

Now we calculate illuminance for a parallel light source with **unit** flux and each of these about 1000 directions (vertices of the Klems grid). To be precise, we calculate only for vertices of those cells which contain at least one of the target sun positions (Figure 1). This reduces their number to about 600.

Then for each of the target sun position (Figure 1) we can approximate illuminance as follows. Take a cell of the Klems grid which the target sun point belongs to. Illuminance of each observer cell for the target sun position is bi-linear interpolation over the four "bracketing" directions times the sun flux (and color) at the target moment and then take CIE sum. Do this for all target time moments, for all cells of all observers.

3.3. Full skylight

It is calculated with Forward MCRT. It is not calculated for all target sun configurations but uses a sort of "interpolation" like it is done for indirect sunlight.

Illumination by the sky is determined by the skylight goniogram, and due to the linearity of the problem, illumination of an observer cell is a linear functional over the goniogram. In case goniogram is a tabulated function, this functional has the form like

$$I_i = \sum_j R_{i,j} L_j \tag{1}$$

where i is the index of the observer cell and I_i is the target illumination of this observer cell, j is the index of the goniogram vertex, L_j is sky luminance in this vertex and $R_{i,j}$ is "the response function", i.e. illumination of the i-th observer cell from the sky goniogram which is 0 in all vertices but the j-th one where it is 1.

We therefore cycle over all the vertices of sky goniogram, setting 1 for this vertex and 0 otherwise, then run the usual FMCRT and calculate all observer cells. This gives us $R_{i,j}$. After that for each target moment we calculate sky goniogram from the Perez model, and apply (1) for each observer cell.

Obviously calculation of the response function requires time proportional to the number of the vertices of sky GD, and thus one needs to reduce its resolution as much as possible. But in the meanwhile for an accurate representation of the sky goniogram its resolution must be as high as possible. By experience, a due compromise is to use Klems grid of about 150 vertices.

4. Blinds control

The calculation of sDA metric requires support of blinds control. If the illuminance distribution meets the "overexposure" condition, some blinds have to be closed and this state to be used in the sDA calculation. The default overexposure condition is that more than 2% of the analysis area has illuminance greater than 1,000 lx under direct sunlight.

Usually there are several blinds which can be open or close independently. Closing all the blinds solves the problem with overexposure but it becomes too dark in the rooms because all the light is blocked. Opening all of them lets the light in but at the expense of discomfort from overexposure.

We must find their optimal configuration (which blinds have to be open and which blinds have to be closed) that provides the best daylight illumination: as high illumination as possible but without overexposure from the direct sun. This is obviously achieved by closing as few blinds as possible. State of blinds is calculated independently for each target time moment and it is calculated from the direct sunlight ignoring the rest components.

4.1. What blinds to close

The idea is simple. First we open all the blinds. Then we try to close just one of them: maybe this will be enough. We cycle over all the blinds denoting their index as k and close only the k-th blind while open all the rest. Then we calculate illumination of observers as described in the Section 3.1 and calculate the fraction of overexposed area f_k. If $f_k \leq 2\%$ for some k then it is enough to close just the k-th blind and we have found the optimal configuration for this time moment. After this procedure we have a full array $\{f_k\}$ where f_k is the overexposed fraction when only the k-th blind is closed!

Otherwise single blind is not enough and we have to close at least two of them. A natural choice is to close those two blinds for which the overexposure fraction f is the smallest (i.e. these are the most efficient blinds). We cycle through the array of $\{f_k\}$, find the two smallest elements and close corresponding blinds k_1 and k_2 and calculate the fraction of the overexposed area. If it is below 2% then we finish with this time moment deciding that blinds k_1 and k_2 are closed while other are open.

Otherwise we see that closing two blinds is not enough and we must close at least three of them. We cycle through the array of $\{f_k\}$, find the three smallest elements. Obviously, two of them are the above k_1 and k_2 from the previous iteration and k_3 is new. Then we calculate the fraction of the overexposed area. If it is below 2% then we finish with this time moment deciding that blinds k_1, k_2, k_3 are closed while other are open.

If even that was not enough we continue closing blind k_4 and so on, until either the overexposed area fraction drops below 2% or all blinds are closed, whichever happens first.

4.2. Fast calculation of the blind effect

As explained above, we may try about N^2 combinations for N blinds. For each trial we must calculate illumination and then overexposed area fraction. Since calculation of even the direct sunlight illumination is not too fast, this can be very expensive. But utilizing the linearity of the illumination problem it is enough to calculate only N combinations (only one blind is closed the rest being open). Indeed, illuminance of an observer cell is the average over these rays from the cell to the sun:

$$I = const \times \left(\underbrace{\sum_i \mathcal{I}_i}_{through\,\mathfrak{E}} + \underbrace{\sum_i \tau_i^{(1)} \mathcal{I}_i}_{through\,\mathfrak{B}_1} + \underbrace{\sum_i \tau_i^{(2)} \mathcal{I}_i}_{through\,\mathfrak{B}_2} + \underbrace{\sum_i \tau_i^{(3)} \mathcal{I}_i}_{through\,\mathfrak{B}_3} + \cdots \right) \quad (2)$$

where $\mathfrak{E}$ is the area which cannot be blinded (i.e. it is outside of all blinds), $\mathfrak{B}_k$ is the k-th blind, i is the index of ray, $\mathfrak{I}_i$ is the contribution of this ray to average cell illuminance and τ_i is attenuation for the i-th ray through the k-th blind area. It can be written as

$$\tau_i^{(k)} = (1 - \chi_k)\tau_i^{(o)} + \chi_k \tau_i^{(c)}$$

where $\chi_k = 1$ when the k-th blind is close and $\chi_k = 0$ otherwise, $\tau_i^{(o)}$ is attenuation when the blind is open and $\tau_i^{(c)}$ is attenuation when this blind is closed.

The expression (2) can be identically re-written as

$$I = I^{(open)} - \sum_k \chi_k \left(I^{(open)} - I^{(k)}\right)$$

where $I^{(open)}$ is illuminance when all the blinds are open and $I^{(k)}$ is illumination when all blinds are open but the k-th blind is closed.

Therefore, we can instantly calculate illumination for an arbitrary configuration of blinds (determined by the set of $\{\chi_k\}$) if we know illumination for the "base" configurations when only one blind is closed.

5. Full scheme of calculation with blinds

Section 4 describes how we find the optimal blind configuration for each target time moment. Since it is based upon the overexposed area fraction we also calculate illuminance under the direct sunlight for all observer cells. Notice it is not the ASE because this latter is for all blinds open.

After completion of this phase we know blinds configuration for all time moments. The two rest illumination components: skylight and indirect sunlight must be calculated for this state of blinds. It is not very trivial because these calculations are not performed at the target time moments but they are performed for the set of sun/sky states from which illumination for sun position and sky goniogram for the target model are interpolated (Sections 3.2 and 3.3). What to do with the blinds then?

5.1. Skylight

As explained in Section 3.3, illumination is calculated from the response matrix, see eq. (1). This response matrix is illumination of the i-th observer cell when the luminance of sky is 0 at all the vertices but the i-th one where it is 1. Naturally this vertex contributes for all target time moments and therefore we must know its $R_{i,j}$ for each used blind configuration. We cycle over all the time moments and gather all the different configurations of blinds because several time moments may use the same state of blinds. For each of them we calculate response matrix as described in Section 3.3.

5.2. Indirect sunlight

The situation is much similar to the skylight. Now we have a grid of directions. We calculate illumination for a parallel light with unit flux from each direction and remember the results. After that we cycle over all target time moments. For each of them we find 4 grid directions that bracket sun position at this time moment. The target illumination is the weighted sum over illuminations for these 4 directions. The weights are equal to ones used in interpolation the target sun position and times the target sun flux, see Section 3.2.

Now each direction of the grid can be used at several target time moments. Thus we must calculate illumination from it for blind configurations from all the target time moments that use this direction. Usually there are not many of them because the grid of directions is rather dense and so each grid cell contains not many target moments. Moreover, the blind state is a function of sunlight direction (Section 4.1) and since for all the moments inside this small cell directions are close, their blind configurations usually coincide. This reduces their number.

We then cycle over all target time moments, for each one we find the 4 grid directions that bracket it. Then we go through array of blind states stored in each of them, and if the current one is different, add it to the set. After completion for each grid direction we have all the blind states needed for it.

Then we go through all these directions skipping those that are not used for any target time moment (Section 3.2) and calculate illumination for a unit parallel light from that direction for all blinds configurations saved at this grid vertex.

Eventually we cycle over the target time moments, for each we find the 4 bracketing directions and take weighted sum of illumination calculated for them for the target blind configuration.

The overall simulation can be subdivided into the following steps:

- **Step 1**. It starts with calculation of illumination created by the direct sunlight throughout the annual period with hourly step. This phase ends with array of the desired state of blinds for each time moment and with illumination by the direct sunlight under these blinds for each moment.
- **Step 2**. Illuminance by the indirect sunlight is calculated for all time moments and the target blind configuration for each moment is obtained.
- **Step 3**. Illuminance by skylight is calculated for all time moments.
- **Step 4**. The sum of illumination under the target blind configuration by the direct sunlight (step 1), indirect sunlight (step 2) and skylight (step 3) gives full illumination for all time moments.

These time arrays are saved and used to calculate sDA. The direct sunlight illumination under all blinds open (step 1) is also saved and is used to calculate ASE.

6. Simulation example

To verify efficiency of the proposed method of the cDA/ASE calculation the Lumicept [11] program complex was extended with a special plug-in utility aimed for Daylight Autonomy calculation. The model scene is presented on Figure 2.

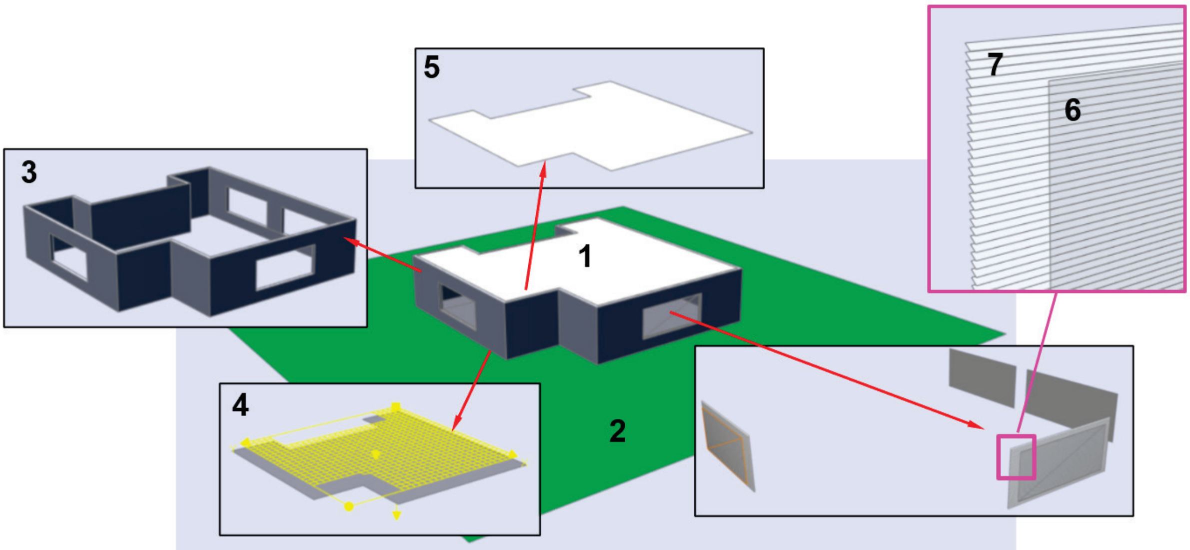

Figure 2: A scheme of simulated model

The model scene consists of:

- building part (marked by *1*)
- ground plane (marked by *2*)
- windows (marked by *6*) with “Venetian” blinds (marked by *7*)

The geometry of building includes walls (marked by *3* on Figure 2). All wall surfaces have diffuse reflectance 50%, floor (marked by *4*) has diffuse reflectance 20% and ceiling has diffuse reflectance 70%. Notice the optical properties are set according to the IES recommendations. The grid is specified automatically based on “floor” geometry and satisfies the standard requirements: elevation above the floor is 30”, size of cells 24”, offsets from the walls 12”.

Perez sky gonio diagram model was specified for simulation. TMY file was taken from the EnergyPlus data set [10].

The graphical user interface dialog specifying parameters of daylight autonomy is presented on Figure 3. Most of parameters are default and corresponds to standards of ASE/sDA calculation. It is the entire annual period from 1 January to 31 December, 08:00 thru 18:00 each day with an hourly step (marked by *4* on Figure 3). Accuracy set as stop criterion to interrupt calculation is 5% for the main “floor_obs” area. Blinds are to be closed automatically (marked by *6* on Figure 3) according to the standard values of overexposure (2% area for 1,000 lx). All the partial blinds are combined in the three groups “South”, “East” and “North” (marked by *1*, *2*, *3* on Figure 3). Blinds within each group are open/closed only together, i.e. effectively the scene has three blinds. As it was mentioned blind control runs automatically.

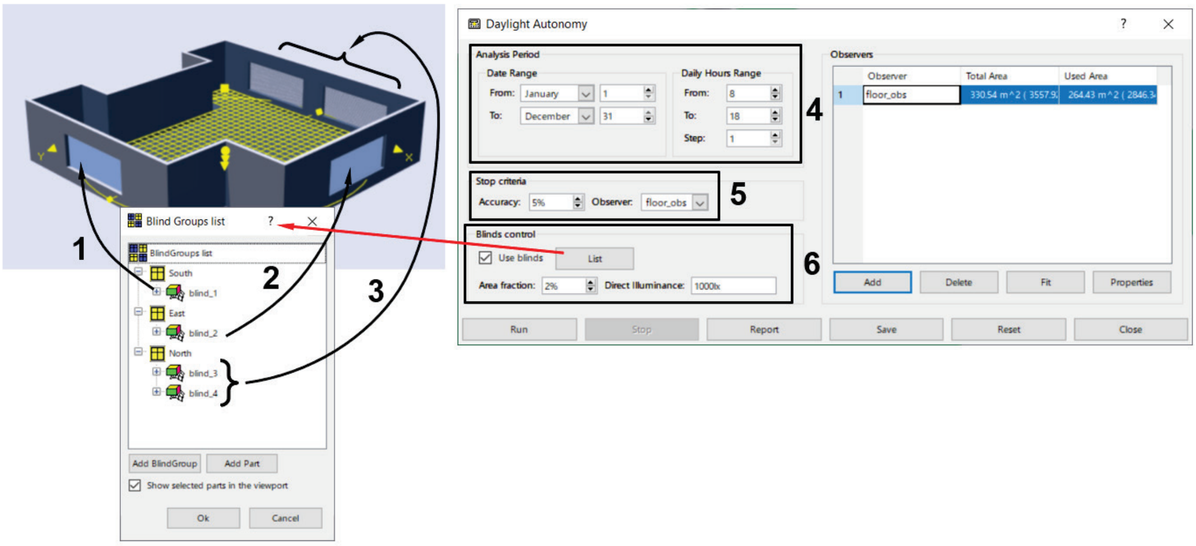

Figure 3: Parameters of Daylight Autonomy simulation

The calculation of such configuration takes 2 to 3 hours on conventional PC (processor i7 or i9, 32 Gb RAM). The output results are presented on Figure 4. They can be seen in the form of a general report, where ASE, sDA values are presented in the table (marked by *1* on Figure 4). An arbitrary number of analysis areas can be specified. In case of several ones the ASE and sDA values are presented for each one individually together with the total value (over all of them).

If daylight metric is out of the range it is marked with the red font. In our case it is ASE = 12% that is out of acceptable range (≤10%). So from the viewpoint of discomfort created with daylight illumination our example is not optimal one. Meanwhile sDA = 100% which is the ideal value, i.e. the building will require a minimal artificial lighting. The report dialog contains editable characteristics such as analysis period, sDA/ASE thresholds, etc. These parameters can be modified here and new ASE, sDA values will be updated instantly without long daylight simulation.

The detailed report in the ordinary CSV format can be saved (marked by *2* on Figure 4). It contains hourly data in the tabular form. Each line contains information for one date and at certain time, see the first two columns in the table. A short string *3* descripts the blind state: for each blind group it is printed “o” if it is open or “c” if it is closed. The ASE values with blinds control *4* and for all blinds open *5* and similar values for sDA (marked by *6*, *7* on Figure 4) are presented.

In some cases investigation of the output results is more convenient in a graphical form. The scene calculated with the DA simulation keeps calculated illumination for each time moment for all calculated illumination components (Figure 5).

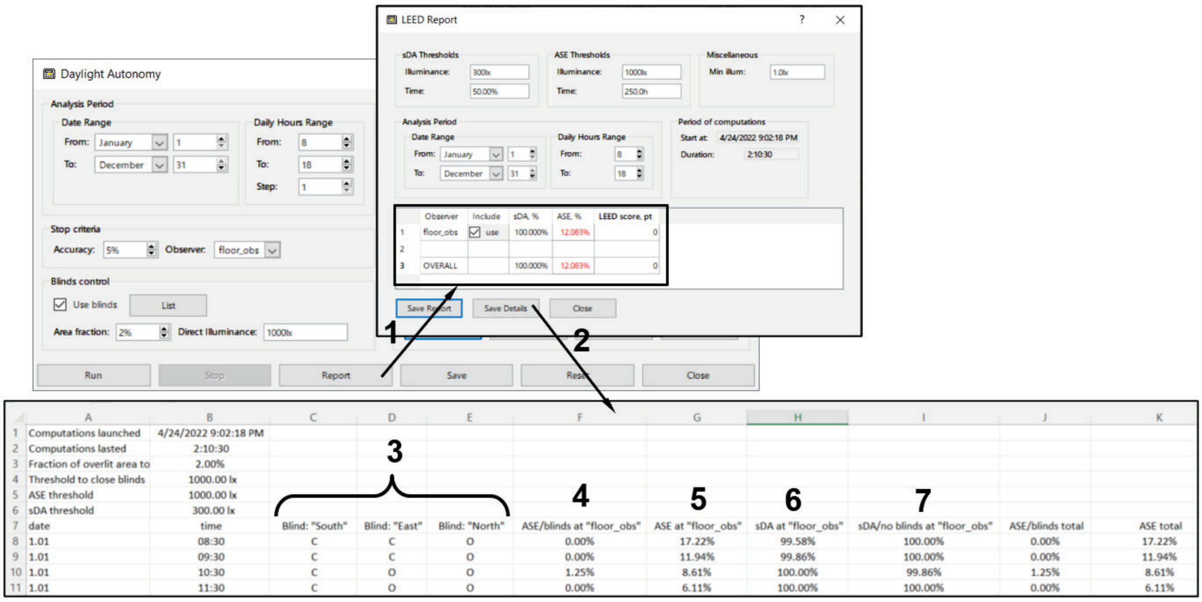

Figure 4: Output reports of Daylight Autonomy

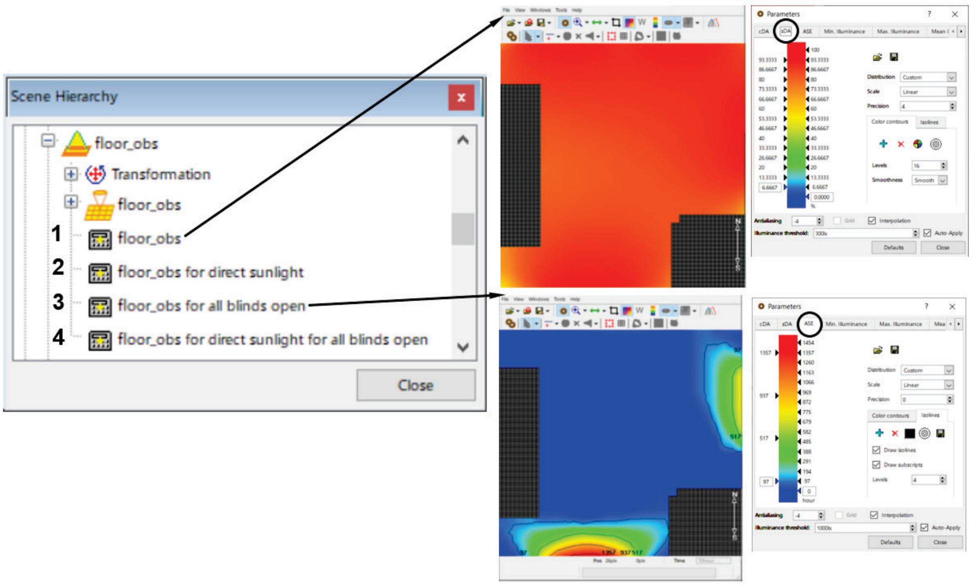

Figure 5: Graphical presentation of output data

Each analysis area is represented with four components. On Figure 5 they are marked as: *1* presents illumination data for the full illumination with blinds control, *2* is for the direct sunlight only and *3*, *4* are similar data for the case of all blinds open. These data can be visualized as color contours. Illuminance snapshots for the desired time moment can be extracted, saved to disk and examined.

7. Conclusions

In results of the given work the Daylight Autonomy tool has been developed and evaluated. It is shown, what methods of calculation for direct and indirect light components applied here are quite effective and sufficient for daylight analysis, calculation of ASE and sDA metrics for the reasonable calculation time.

The proposed method was compared with the other lighting simulation methods available in Lumicept [11] software – Forward Monte Carlo ray tracing. This method is precise but time consuming. The comparison was done for small time interval (a week) because simulation with the ordinary lighting engine takes huge amount of calculation time. In our opinion this time interval is sufficient for verification goals because there are not principal differences in daylight simulation for different weeks. The comparison shows good agreement with the developed approach: difference in ASE and sDA values calculated by both methods does not exceed 1%.

8. References

[1] Illuminating Engineering Society of North America (2013). IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). (IES LM-83-12).
[2] K. Van Den Wymelenberg, A. Mahic. Annual Daylighting Performance Metrics, Explained. The journal of the American institute of architects. April 12, 2016. https://www.architectmagazine.com/technology/lighting/annual-daylighting-performance-metrics-explained_o.
[3] G. Ward, F. Rubinstein, A new technique for computer simulation of illuminated spaces, Lawrence Berkeley Laboratory Report 23042, 1988.
[4] G. Ward, The RADIANCE Lighting Simulation and Rendering System, Computer Graphics, in: Proceedings of '94 SIGGRAPH Conference, 1994, Orlando, Florida, USA.
[5] U. Berardi, T.Wang. Daylighting in an atrium-type high performance house, Building and Environment, 76 (2014), pp. 92–104.
[6] R. Perez, R. Seals, P. Ineichen, R. Stewart, D. Menicucci, A new simplified version of the Perez diffuse irradiance model for tilted surfaces. Solar Energy 39 (3), (1987) pp. 221–232.
[7] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, Modeling daylight availability and irradiance components from direct and global irradiance. Solar Energy 44 (5), (1990), pp. 271–289.
[8] J. Meeus, Astronomical Algorithms, 2nd ed., (Richmond, VA: Willmann-Bell, 1998).
[9] O. Probst, “The apparent motion of the Sun revisited,” Eur. J. Phys. 23 315–322 (2002).
[10] Climate.OneBuilding.Org, URL: https://climate.onebuilding.org
[11] Lumicept – Hybrid Light Simulation Software. URL: http://www.integra.jp/en