

CLIMATE BASED DAYLIGHT MODELLING IN  
THE DANISH BUILDING INDUSTRY



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**Synopsis:**

This report investigates how to perform a rapidly and accurately climate-based daylight model (CBDM) evaluation in the Danish building industry in the early design.

The findings are that no program is available for making rapidly and accurately determined and only a program combination based on the tendency are suitable for early design. Different combinations of programs will suit the various complexities, objects involved and design phases. For compliance check in the Danish building regulation the recommended combination of programs is; Accelerad, Radiance, Daysim, Diva4Rhino. Three typical room where testing to see if they fulfil the Danish building regulation requirement where 2 out of 3 fulfilled the 300lux-rule.

As a result of this project, a guide made to make uniformity CBDM evaluation in the Danish construction industry.

*By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for the all contents of the project.*

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# Abstract

This report examines how daylight provision through a climate-based daylight model (CBDM) simulation can be rapidly and accurately determined in the Danish building industry in the early design. Moreover, how to make uniformity in the way of calculating annual daylight in the Danish construction industry.

To accomplish this goal, an investigation of industry's needs, literature of useful information regard climate-based daylight modelling (CBDM) and a comprehensive review of daylight design tools for annual daylight evaluation were found through state-of-the-art literature review. Here 45 tools are compared to 5 different categories developed based on various aspects involved in a daylight design tool.

The findings are that no program is available for making rapidly and accurately determined in the Danish building industry in the early design. Different combinations from programs will suit the various complexities, objects involved and design phases. For compliance check in the Danish building regulation recommendation goes to following combination of programs; Accelerad, Daysim, Diva4Rhino and these program are verified in this report based on SBI daylight calculation in practices and thereafter an annual daylight evaluation of 3 typical room were tested to see if they fulfil the Danish building regulation requirement and 2 out of 3 fulfilled the 300lux-rule.

A program combination based on the tendency are suitable for climate-based daylight modelling in early design in a Danish context: The GPU for Parallelism and Accelerad as computation for Radiance as calculation engine with photo mapping bi-directional capabilities. Suitable for 2-phase to 6-phases CBDM techniques and has a graphic user interface like Velux daylight visualiser. Plugin with honeybee+ capability and Diva4Rhino interface and graphical algorithm editor in Dynamo that work as a direct plugin to Revit.

Another key finding is that no benchmark of which state-of-the-art CBDM techniques used for annual daylight evaluation and the different techniques show a deviation up to 39% from the benchmark CBDM techniques in calculation ASE. The direct and diffuse illuminance metrics show to be more robust results of  $\pm 15\%$  within the benchmark. Furthermore, the report shows when to use CBDM techniques in terms of simplification, accuracy and parameter included in the daylight simulation and it illustrates a study of which CBDM techniques the different programmers use. Based on the test of the three typical room and literature a guide is work out of how to make CBDM evaluation.

To conclude no simple solution was found to solve the CBDM simulation in early design in the Danish building construction industry given none of the programs fulfil the need to rapidly and accurately determined. The most promising available program a combination of: Accelerad, Radiance, Daysim and Diva4Rhino and then wait for the future development of new better programs.

# Table of Abbreviations

ADF	Average Daylight Factor
ALE	Annual Light Exposure
API	Application Programming Interface
ASE	Annual Sunlight Exposure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BDPT	Bidirectional Path Tracing
BIPV	Building-Integrated Photovoltaics
BIM	Building Information Modelling
BPS	Building Performance Simulation
BR	Building Regulations
BRDF	Bidirectional Reflectance Distribution Function
BSDF	Bidirectional Scattering Distribution Function
BTDF	Bidirectional Transmittance Distribution Function
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CBDM	Climate-Based Daylight Modelling
CFS	Complex Fenestration System
CIE	Commission Internationale de l'Eclairage
CPU	Central Processing Unit
DA	Daylight Autonomy
cDA	Continuous Daylight Autonomy
sDA	Spatial Daylight Autonomy
DC	Daylight Coefficients
DDS	Dynamic daylight simulation
DF	Daylight Factor
DGNB DK	Sustainability Certification Scheme in Construction Industry for Danish Industry
DGP	Daylight Glare Probability
DK-GBC	Green Building Council for Danish Industry
DRC	Daylight redirecting components
DRY	Design Reference Year
DS/EN	Danish and European Standards
EDP	Early Design Phase
GPU	Graphics Processing Unit
GUI	Graphical user interface
G-BDPT	Gradient-Domain Bidirectional Path Tracing
HDR	High Dynamic Range
IES	Illuminating Engineering Society
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
LT	Light Transmittance
MLT	Metropolis Light Transport
NIR	Near Infrared

NUV	Near Ultraviolet
NURBS	non-uniform rational B-splines
PLT	Precomputed Light Transport
RGB	Red, green, blue
TAI	Total Annual Illumination
TRY	Test Reference Year
UDI	Useful Daylight Illuminance
VDGP	Visual Discomfort due to Glare Probability
VIS	Visible
WFR	Window-to-Floor Ratio
WWR	Window-to-Wall Ratio
XML	Extensible Markup Language

*Keywords: Daylight; Daylight provision; Daylight availability; Climate Based Daylight Modeling; state-of-the-art Radiance CBDM techniques; Parametric design*

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# 1 Introduction

## 1.1 Background information, Purpose of the project

Sun light forms every form of life on our planet and make the variation between night and day between season and season [1]. Daylight is a part of basic human need and contribute to well-being, quality of life, health and work efficiency[2]. People spent 90% of the time indoor [3], daylight have a strong benefits on human, therefore it is important to provide sufficient daylight inside the rooms and buildings. Benefits of daylight can put into three categories: Human benefits, energy savings for electric lighting and environmental benefits [4]. Sufficient daylight design in building minimise the electric use and provide energy savings for electric lighting. A well daylit space have positive influencing on the human vitality, comfort and emotion in relation to a poorly daylit room.

The light has a great impact on people's experience of a room and the general building usefulness. The faced design should ensure a balance between thermal, atmospheric, visual comfort and on the same time consider architecture engineering and construction (AEC) industry wishes. Sustainability buildings set up requirement to a holistic building design where the daylight especially plays a significant role in the façade design.

Climate-based daylight calculation is new implemented in the Danish building regulation which has brought great attention form the consultant in the Danish building sector. The Danish building regulation 2018 (BR18) exam that sufficient access to daylight can be documented using the 10pct.-rule or the climate-based 300 lux - rule visualise through spatial daylight autonomy (sDA) metrics and different alternative methods that providing sufficient daylight can be used such as daylight factor. The daylight calculation in the BR18 is based on the European standard, DS/EN 17037 (Danish Standard, 2018) and the standard exam daylight factor method 2,1% and 300 lux method is equal calculation methods to documenting sufficient access to daylight [5]. Table 1.1-1 show different inclusion descriptions from DS/EN 17037 and BR18.

<b>Simulation inclusion</b>	<b>DS/EN 17037</b>	<b>BR18</b>
<b>Shading</b>	Moveable shading device [5] DS/EN 17037, section B.3.3.	Static shading [6] - SBi 272 § 379, STK.2. Building significant neighbouring obstructions.
<b>Sun and sky</b>	Hourly (or sub-hourly) sky and sun conditions [5] [5], section B.3.3.	
<b>Calculation method</b>	Equalize daylight factor and 300 lux - rule [5], section B.3	Equalize 10pct. - rule, 300 lux - rule and alternative daylight factor [5][6].
<b>Lux recommendation</b>	Minimum, medium and high [5] section A.1	Only minimum target [6][7]. SBi 272 § 379, STK.2
<b>Fraction of space</b>	50% and 95% [5], section A.2	50% [6][7] SBi 272 § 379, STK.2

Table 1.1-1 Different inclusion descriptions from DS/EN 17037 and BR18

The daylight factor (DF) calculation method used in Denmark since 2006. The daylight factor based on its simplicity rather than its capacity to describe reality as the dominant evaluation metric [8]. Daylight factor is a simple static calculate metric that only gives information about the amount of interior daylight on an overcast day and excludes façade orientation and varying sky conditions. The building location incorporated in the daylight factor calculation by adapting the requirement to the specific location [5]. Dynamic aspects such as protection from glare, sunlight exposure and dynamic solar shading cannot investigated through the daylight factor method and here the Climate based daylight calculation is useful [9][10]. The dynamic calculation is getting more specific than the static method by involving a time step of one hour or less and informative through the importance of orientation, shades and dynamic solar shading [11][12].

The new climate-based daylight calculation only requires a modest enhancement of existing daylight prediction tools founded on cumulative daylight availability data, because daylight factor is still the basis for evaluating the climate-based daylight calculation [13][14][15][16][5]. The climate-based daylight calculation is a prediction of hourly levels of daylight illuminance, using realistic sun and sky conditions derived from standardised climate data [17][13][18][19]. The climate-based daylight calculation is a statistically based prediction of daylight conditions in an interior space and Denmark means that it primarily rely on climate data based on multi-year performance with show the most representative month and not extreme conditions for the current location, and after that, on the influence of the space and its surroundings [5].

The 300-lux rule based on the Danish building regulation and described by the matrix called Spatial Daylight Autonomy ( $cDA_{300\text{-lux } 50\%}$ ) (illustrated in Figure 1.1-1). sDA is the 50% fraction of the relevant floor area in which daylighting achieves 300 lux in at least 50% of the daylight hours [5][20]. The relevant floor area can be calculation as grid points with quail mesh size defined in SBi 272[6], with edge of 0,5 meter from the wall and a height above the floor of 50 centimetre for residential building and 85 centimetre for non-residential buildings. 300 lux is representing minimum brightness of light for office task.

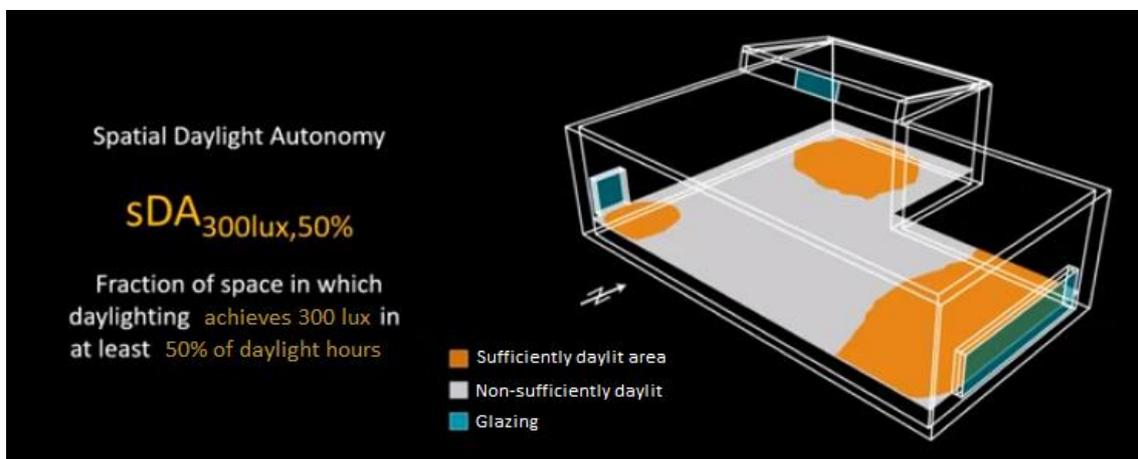


Figure 1.1-1 Illustration of the Spatial Daylight Autonomy [20]

The Danish building regulation 2018 (BR18), BR18 voluntary building class, DGNB-DK form DK-GBC and European standard indicate that the development is moving towards climate-based approach [7][21][22][5] according to an interview from Steffen Maagaard Appendix 9.1. The climate-based approach can be calculated, based on climate data for a whole year, by several simulation tools [23]. Table 1.1-2 below shows some of the most common indicative calculation metrics for CBDM evaluation.

Metrics	Sym- bol	Refer- ences	Recommendations
<b>Illuminance based:</b>			
Daylight Autonomy	DA	[24][25]	DA <sub>300lux</sub> 50% of the time.
Spatial Daylight Autonomy	sDA	[5] [26]	sDA <sub>300/50%</sub> DA + 50% of relevant floor area
Annual Sunlight Exposure	ASE	[26] [27]	ASE <sub>1000lux &gt;250h</sub> % of acceptable occupied area
Total Annual Illumination	TAI	[28]	Cumulative amount of exposure visible light
Useful Daylight Illuminance	UDI	[29][30]	UDI-a <sub>300-3000</sub> . -a for autonomous daylight
<b>Luminance based:</b>			
Daylight Glare Probability	DGP	[5][29][31]	DPG <sub>exceed</sub> for 95% fraction of time

Table 1.1-2 Most common annual daylight metrics for CBDM evolution

[32][33][25][34][35][24][36][37][17][10][38][31][39].

Based on the SBi 272 and the DK/EN 17037 the daylight provision can be determined using an adequate software for the daylight simulation[6][5]. The Danish construction industry's needs for annual daylight evaluation is changing during the different design states as shown in Table 1.1-3. In subchapter 2.1 the Danish construction industry's needs in different stages is investigated. In the early design there is a need rapidly in terms of working hour and fast execution time with several alternative designs to investigating large design space, design concepts and guide the designer towards better performing buildings [40] which a compromise of a fairly accurate calculation method. In detailed design here the time perspective is not that important if the program can provide accurate result. Rapidly and accurately software can be used both in the whole design process.

Design stages and their focus	Criteria and requirements	Investigation areas and values
<b>Early Design</b> Decisions through fast simulation and modelling time where fairly accurate results are acceptable.	Few details on geometry and material properties. Comparison between design concepts and solutions suggesting.	Proactive, intelligent, and experience based CBDM simulation. Goal based design, parametric analysis tool (PAT) and uses of sensitivity analysis.
<b>Conceptual design</b> Daylight, artificial lighting, functional properties and element behaviour.	Simple model to shown compliance check for annual daylight evaluation.	CBDM simulation to studie the sunlight, properties of shades and blinds and operation modes.
<b>Detailed design</b> Accurate results where longer calculation time is acceptable.	Advanced and detailed design model. Types of code: prescriptive or performance based.	Detailed prediction of interior lighting including elements as dynamic representation of blinds, sensors, shades switches and complex fenestration system (CFS).

Table 1.1-3 The needs in a Danish context in the different design stages [41].

## 1.2 Research questions

### Problem statement

How can the daylight provision through a climate-based daylight model (CBDM) simulation be rapidly and accurately determined in the Danish building industry in the early design?

### Further questions

- What is the Danish construction building industry needs for CBDM evaluation in early design?
- What is the useful information regard climate-based daylight modelling?
- Which Building Performance Simulation (BPS) software for CBDM evaluation are most promising for the Danish construction industry?
- How to preform CBDM evaluation in Danish construction building industry?
- How to make uniformity in the way of calculating annual daylight in the Danish construction industry?

## 1.3 Research limitation

The focus of this study is on indoor daylighting, particularly for single room which also consider the building and the surrounding for better prediction on the availability of the daylight inside the room. The research will only focus on how to calculate the daylight level. The study of software tools usage was limited to a Danish context and the requirement from the Danish building regulation and DS EN 17037 [5][7]. The daylight factor method will not be the focus in this report, but the focus will be on climate-based daylight modelling for making annual daylight evaluation. The literature review was the main data collection method used in gathering information of available software and only literature in English and Danish is reviewed. The interoperability between BPS software and architectural geometrical tools is not the focus of this research so the report does not focus on fast data transfer between the architect model and between BPS software for CBDM evaluation. The verification and testing of the software program bases on a countries and regions using the European standard 17037 and typical simple rooms where used as a testcase. The research is focus on the Danish building industry and an investigation of the needs in early design. The simulation time and accuracy are based on the literature and are limited tested through the simulation software. The Danish guideline is made based on the literature and work done in the report. In the test case and guide the dynamic shading and parametric modelling will not include but an investigation of the software possibility to handle these areas includes in the research.

## 1.4 Structure of the report

### 2 Literature review

- Danish context
- BPS software for CBDM evaluation
- Light sources and sky model
- Inter-model comparison
- Deliberation and features in daylight simulation tools.

### 3 Methodology

- Choice of research method
- Methodology for program selection
- Methodology for CBDM evaluation verification and guideline

### 4&5 Results

- Results: Investigation of the most promising methods
- Flow chart
- Results: Testing of the most promising methods
- Guideline to Danish daylight performance simulation

### 6 Discussion

- Discussion of the promising method
- Discussion of program testing
- Discussion of guideline
- Tendency and development in the light simulations industry
- Limitations

### 7 Conclusion

- Summary
- Key findings

Figure 1.4-1 General structure of the report

## 2 State-of-the-art literature review

This chapter firstly, investigate Danish construction building industry needs for CBDM evaluation in early design and secondly, a literature review of useful information regard climate-based daylight modelling (CBDM). “*CBDM is a prediction of the daylight level inside all spaces with daylight opening(s)*” [5].

### 2.1 Danish context

This subchapter tray to investigate the Danish construction industry needs for BPS software to predict the daylight availability. This subchapter base on an interview with Steffen Maagaard from MOE (full interview available in appendix 9.1) and information from supervisor Rasmus Lund & Torben Østergaard. As mentioning in the introduction, the regulation and certification indicates that the development is moving towards climate-based approach base on an hourly calculation of the predicted daylight level inside the room to see if the  $cDA_{300\text{-lux } 50\%}$  is fulfilling. In the future 10pct.-rule will be used for residential buildings and adapted to 300lux-rule and non-residential buildings must fulfil the  $cDA_{300\text{-lux } 50\%}$  rule. Sweco, Rambøll, Cowi and MOE expressed that they would like to base their consultancy on a CBDM approach.

#### 2.1.1 Simulation frame

The Danish construction industry need a calculation method for compliance check with a fast execution time with several alternative designs to guide the designer towards better performing buildings [40]. Parametric simulation will avoid trial-and-error approach and provide better design suggestion. Parametric simulation can help explore large design spaces and handle uncertainties, with possibility to runs a large number of simulations in a structured manner. It is preferable that the software is intelligent so that the simulation can be executed in a structural way to guide, rather than evaluate in design comparing and suggesting different design options based on experience. To decrease the working hour on modelling time interoperability between CAD-software and building performance software is preferable. In the Danish construction industry, the interoperability process between software is not that straight forward process and after the conversion the model cannot always be use afterwards. CBDM-approach is difficult to calculate without costing a lot of time and computational forces and Radiance CBDM techniques simulation time for annual daylight simulation variate from hours and up to many days depending on which CBDM techniques used [18][42]. Danish construction industry needs an easier way to calculate  $cDA_{300\text{-lux } 50\%}$ , but at the same time delivering the needed quality to provide reliable results.

## 2.1.2 Accuracy of CBDM evaluation

When looking at accuracy of CBDM evaluation here an accurate simulation is preferable. There are not always precise limits of when the simulations are accurate enough. Comparison between real measured and simulated daylight conditions different deviation can be acceptable for different design stages as shown in Figure 2.1-1. A deviations of about 10% of the actual value for detailed design is expected [43][44][45][46]. For conceptual design state a simulation values of 20% of actual values can be accepted [20][47]. Torben Østergaard in article early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis show that for early design with thousands of simulation with a metamodel investigating overheating inside the room through Be18 lower accuracy of about 40% could help guiding and pointing an metamodel in the right direction [48]. For daylight simulation with lux level inside the room a smaller accuracy in early design can be investigated to see if the model is still guiding and pointing in the right direction.

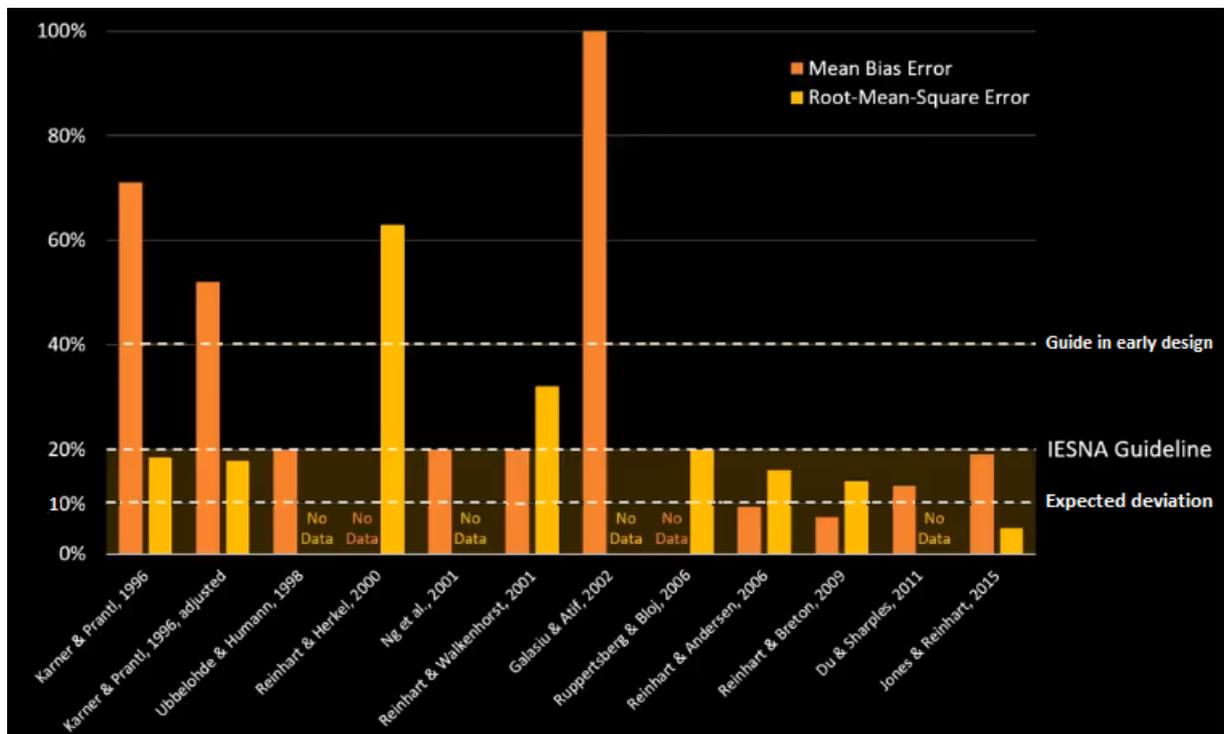


Figure 2.1-1 modified and show different accuracy for different design states [20]. IESNA stand for Illuminating Engineering Society of North America, mean bias error is a measure of overall bias error compared to measurement, root mean square error is a measure of average deviation. Detail design a deviations of about 10% can be expected [43][44][45][46]. For conceptual design a simulation values within 20% of actual values can be accepted [14][26] and for guiding in early design accuracy down to 40% could maybe help guiding and pointing the model in the right direction [49].

## 2.1.3 Rapidly

Table 2.1-1 show that a rapidly the simulation time should be less than 0,5 seconds for interactive simulations and less than 24 seconds by using parametric design.

	Early design	Conceptual design	Detail design
Modelling time	½ to 2 day		
Simulation time	Interactive Simulation < 0,5 sec. [47] Parametric design < 24 sec.	< 3,7 min.	< 8 hours equal to a night simulation.

Table 2.1-1 Simulation time in different design stages - experience values (Rasmus lund & Torben Østergaard) [47]. Interactive Simulation is a representation of a dynamic display of a system model where the user can change the outcome of the simulation [50]. Parametric design is changing in design aspects and dimension of architectural design by coordinating and integrating design components in BPS software simultaneously and here software like Grasshopper3D and DynamoBIM can be used [51][52][53]. Parametric design is especially useful with the possibility to apply statistical analysis such as sensitivity, uncertainty and multi-variate analyses [49].

To figure out which parameter influence the CBDM simulation accuracy and execution time it is important to understand the general architecture and elements included in a BPS software and investigated in chapter 2.2.

## 2.2 BPS software for CBDM simulation

BPS software have a general architecture as shown in Figure 2.2-1 and the BPS software have precomputed or define input, simulation, output and graphical user interface (GUI) help to control these elements. Daylight simulation software aims to predict different aspects of daylight such as quantitative, qualitative and general distribution of daylight in a room or space. The accuracy of the software depends on the definition of the boundary condition such as physical properties; sky and scene. The physical model used to predict the behaviour and operation, and the result depends on which aspect of daylight is studying and how to visualise the results from the human being by ether photorealism or by physical-based rendering. Physical-based rendering is the area of interest in this report.

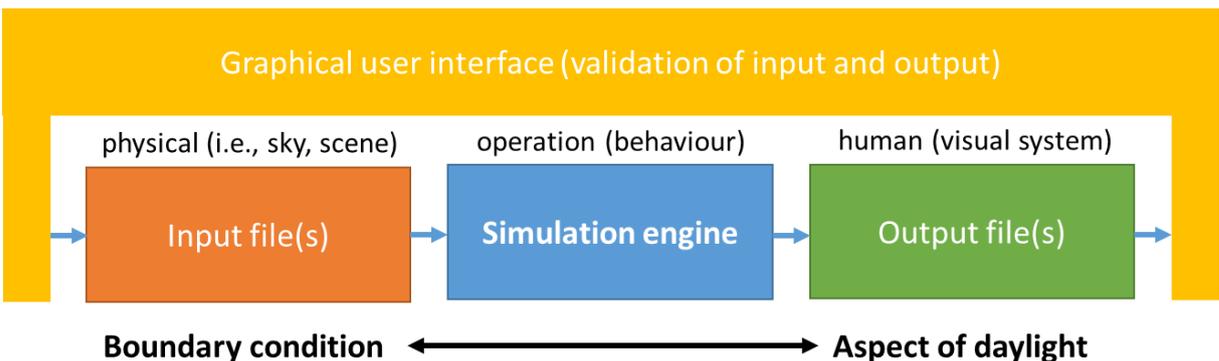


Figure 2.2-1 General architecture of daylight simulation program. Input parameter and the mathematical model employed for the calculations influencing the quality of the results obtained and graphical user interface which forms the framework of the program. Boundary condition depending on what aspect of lighting is studied. [41] [32]

The CBDM is a simplification of reality and therefore a validation of the software and verification of the simulation process is needed to see how good the model represents reality of the model. By looking at the model input, a distinguish of two type of input can be made, direct

input from reality or input with abstraction of reality. Figure 2.2-2 show different elements in a daylight performance simulation. The simulation engine uses different methodology to generate the behaviour of light. Glass-box light simulation algorithms commonly used explained in detailed in subchapter 2.5.1 Table 2.5-2 and are radiosity, raytracing and an extended version of ray-tracing technique is photon-mapping.

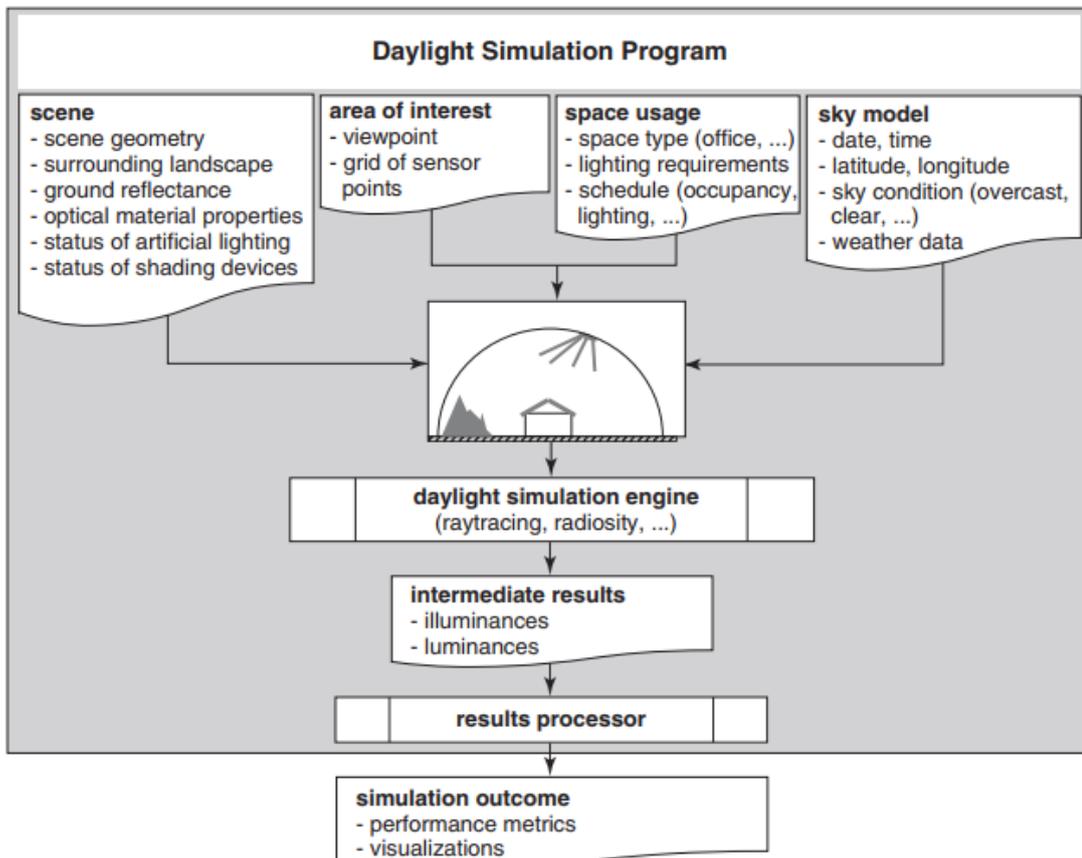


Figure 2.2-2 Daylight performance simulations needed elements [32].

### 2.3 Light sources and sky model

Information regards measuring light and how to build up a Climate based model will be investigated in the next subchapter because it makes the foundation of the CBDM evaluation. The measurements of the weather data have some simplifications of reality and here it is not profitable to go deeper than these simplifications. The upper detailed lined of the model description of the sun and sky is related to chosen equipment made to measure the given climate data, which simplification is made and chosen time steps for provided climate file data. The minimum frame of detail is to meet the setup requirement or criteria, which is set by the DK/EN 17037 and the criteria set from a Danish context [5]. The accuracy depends on the boundary conditions and the better they are the better accuracy and here several types of data can be measured, collected, and inserted in the simulation. As the DK/EN 17037 describes, “The daylight in an interior space depends, primarily, on the availability of natural light and after that, the properties of the space and its surroundings” [5].

### 2.3.1 Climate file

The climate files are a set of long-term measured weather data collection from the ground weather station. Climate file include the dynamic aspects in the CBDM, such as changes in cloud cover, variations over time, and the seasons. The standard meteorological years are a classification type most commonly used for daylighting evaluations and building performance simulation. The standard meteorological data sets represent typical conditions for a specific locale from a lengthy measurement period and structured to have the same properties as the actual data with typical site variation and averages [8][28].

Countries used different methods to create the Climate files, based on different years of measured data. The data are usually represented on an hourly bases by 8760 records and if the interpolation creates sub-hourly time steps through a linear model [28]. Climate data used in Denmark is developed base on Design Reference Year (DRY) shown in Table 2.3-1.

. The design reference year analysed for a multi-year period where the most representative month from the collected data chosen. After that each month most important parameters are weighted, and adjustments are made based on true mean values and variance from the multi-year period. The DRY file is a single year climate data based on multi-year performance with show the most representative month and not extreme conditions. The developed method behind design Reference Year (DRY) agreed by the IEA Solar Heating and Cooling Programme, Subtask 9 E, Solar Radiation and Pyranometry Studies Procedure [54].

Weather data set	Number of years	Weather station	Method
DRY (Design Reference Year)	9 (2001-2010)	Landbohøjskolen, Taastrup	Measured hourly horizontal diffuse and direct irradiance

Table 2.3-1 Climate data characteristics

The specific Danish DRY file is available on SBI Climate data website [55].

### 2.3.2 Sky model

Climate data file cannot be used directly for daylight simulation purposes. Daylight simulation programs need a sky model to calculate the angular illuminance distribution patterns across all sky types from overcast to clear, through partly cloudy, skies [56][6]. Perez all-weather sky model stands for the conversion of weather data. The weather data file contains data for total global radiation on a horizontal surface because the pyranometer measure the total global radiation is setup on a horizontal plane. Perez used to reconstructing the directionality from horizontal or tilted surfaces of arbitrary orientation sky zenith luminance and to sky luminance angular distribution [28][57]. Which means that Perez all-weather sky model is a mathematical model that converted the global total radiation data from horizontal to vertical plane and split the data into diffuse Irradiance form the sky alone and direct Irradiance from the sun alone to know how the light is distributed depending on orientation. The irradiance data units are watts

per square meter. The luminous efficacy models of Perez convert the Danish DRY weather data from irradiance into illuminance for the direct and the diffuse components and this is important because sky luminance distribution data are available only in research locations [58][56]. In the conversion of solar radiation into daylight the luminous efficiency of the radiation need to be known [15] and the luminous efficiency of direct sun, overcast sky and clear sky radiations are differentiated [59]. In the daylight simulation programs, the daylight is divided into direct and diffuse respectively from sky and sun because of that.

Alternatively, HDR photographs can obtain actual accurate luminance values and record the distributions instead of using sky models for predictions of sky luminance distribution [60][61][62]. HDR photographs can provide a reasonably good interior illuminance and luminance values [63][64]. Use directly in the model. Satellite data and satellite-derived values are the most accurate available estimates of hourly global horizontal irradiance.

In an article with evaluation of 12 models to estimate hourly diffuse solar irradiation on inclined surfaces from those measured on horizontal surfaces shows that Perez is a suitable model for daylight simulations programs [65].

### 2.3.3 Daylight Coefficient approach

Accurately and efficiently predicted of annual daylight evaluation based on the daylight coefficient approach [66][19][67][68][33][69][70][71]. Model realistic weather conditions are not practical, in partly cloudy weather the sky luminance may vary on a time scale of minutes. Modelling diffuse daylight therefore requires a simplifying mathematical model, which in turn requires measured weather data [10]. Here the Daylight Coefficient approach can be used to accurate and efficient computation of time-varying daylight illuminances based on hourly meteorological data for an annual period. The method used radiance raytracing (forward or backward). Daylight Coefficient method make a finite element subdivision of the indoor place and the outdoor sky. The daylight coefficient method set up a relation between internal and external illumination that is directly proportional. There is some debate about how many subdivisions are necessary for the sun and sky but often 145 is used for the sky equal to classic Tregenza sky subdivision as shown in Figure 2.3-1 [57][56][68][18] and one patch is used to represent the ground. The Equation 2-1 shows formula behind daylight coefficient approach.

$$E = DC \cdot S$$

$$8760 \cdot n \quad n \cdot 146 \quad 146 \cdot 8760$$

*Equation 2-1 Daylight coefficient approach using standard Radiance.*

Where:

- DC Daylight Coefficient matrix
- E the internal illuminances for a full year
- S Sky matrix
- n the number of interior ‘virtual’ sensors

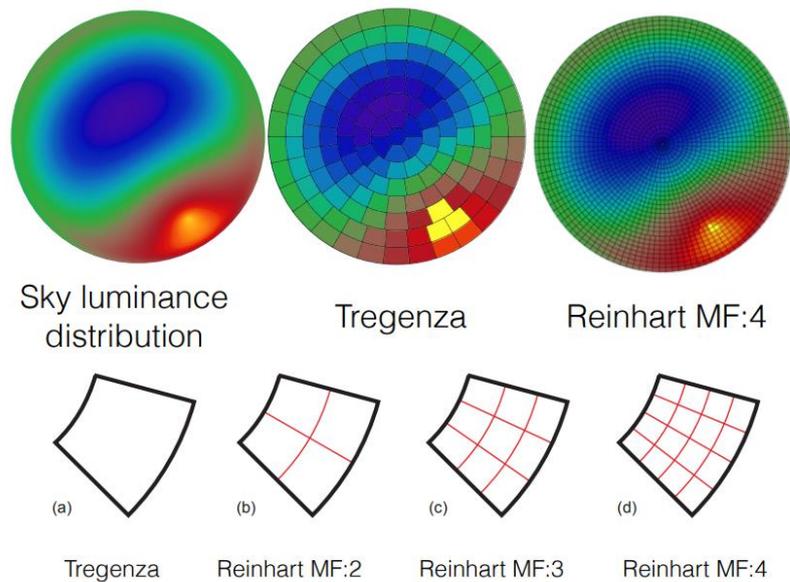


Figure 2.3-1 Tregenza sky subdivision scheme into 145 patches and Reinhart further subdivisions of Tregenza [72][73]

To understand how the daylight coefficient work, it is important to follow the light from source to receiver. The Figure 2.3-2 illustrate the sky elements as a source which could be represent by 145 lamps and the room camera is the receiver. Light traveling depending on forward or backward raytracing algorithm. Forward ray tracing calculates the radiation path of the individual lamp into the room (direct, diffused and reflected light) and then into the camera and measured how much light hits the camera. Backward raytracing calculates the light out from the camera onto the walls until it hits a light source. Every time the light bouncing off a surface its losses some energy because of the materials reflecting value. When calculated the daylight coefficient from the source to the receiver, radiance can afterwards adjust the brightness of each lamp by multiplying a value from a table to match the sky at any given time. Daylight coefficient calculate the relationship between the sky and the camera one and adjust the brightness instead of during full ray tracing calculated for every hour of the year and that the advantage of the daylight coefficient approach.

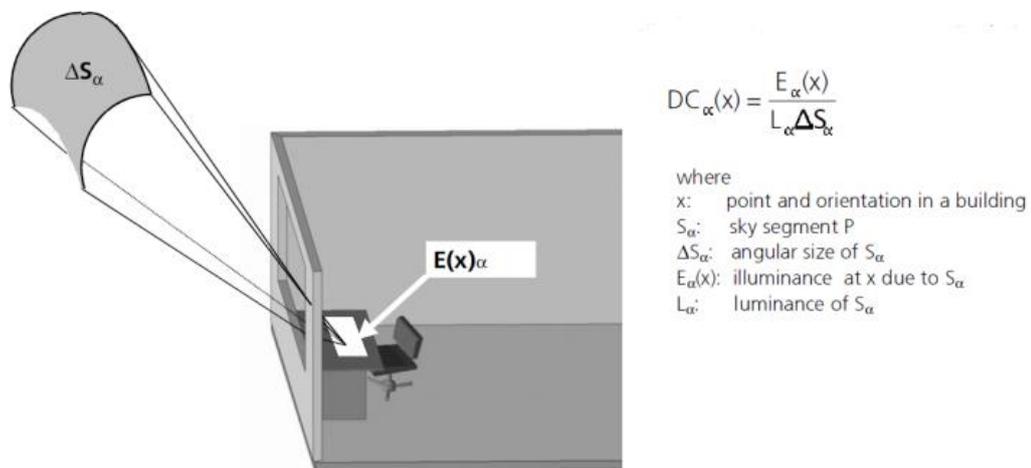


Figure 2.3-2 Graphical definition of a daylight coefficient method [44][66].

### 2.3.4 Direct sunlight calculation

Direct sunlight can reasonably model as distant sun positioning that produces a beam of light which is calculated by parallel rays of light. The direct sunlight on an arbitrarily orientated surface can be calculated based on information from the weather data for accurate determine the sun positioning, sky model, solar disk size and cloud cover size [15]. The solar disk is only 0,5° solid angular sun source in apparent width [74][75] and to calculate the position of the sun [76] Certain simplification of reality is often used for calculation the direct sunlight contribution. Compromise of accurate spatial resolution of the direct solar contribution affect the amount of light entering the room especially in the winter in Danish location, with low altitude sun which means that the sun angle is closer above the ground [74] and this will influence the sun-light penetrate deep into the room. Azimuth is the other parameter that define the position of the sun and sky. Azimuth is the angle in horizontal plane where 0 degrees is south, and west is 90 degrees and east are +90 degrees.

	daylight source type	solid angle	typical radiances $\left[\frac{W}{m^2 \cdot sr}\right]$
	ground reflection	$\Omega = 2\pi \approx 6.28$	$\approx 2 - 20$
	one sky patch	$\Omega \approx 2\pi/145 \approx 0.40$	$\approx 5 - 300$
	sun	$\Omega \approx 6 \cdot 10^{-5}$	$\approx 3 - 5 \cdot 10^6$

Table 2.3-2” Solid angles as initial indicator for potential coefficient size of the daylight sources in decreasing order” [75]

DS/EN 17037 defined that the detailed CBDM calculation method could calculate the internal daylight illuminance values on hourly or sub-hourly basis using hourly or sub-hourly sky and sun conditions derived from climate data appropriate to the site [5]. If an accurate representation of the direct sunlight is needed the direct sunlight needs to be calculated separate on an hourly basis independently from the diffuse sky.

Renihart subdivision scheme in Figure 2.3-3 show the different refinement of the sun positioning during the year [5][6]. Figure 2.3-3 show different compromise of accurate spatial resolution of the direct solar contribution and smaller subdivision scheme will result in a more accurate spatial resolution of the sun. For having an accurate hourly sun positions Renihart subdivision scheme of minimum MF:4 2305 should used and MF:6 5035 will correspond to accurate half-hour sun positions. These fixed positions calculate the position of the sun in the sky depend on the latitude and time of day and year.

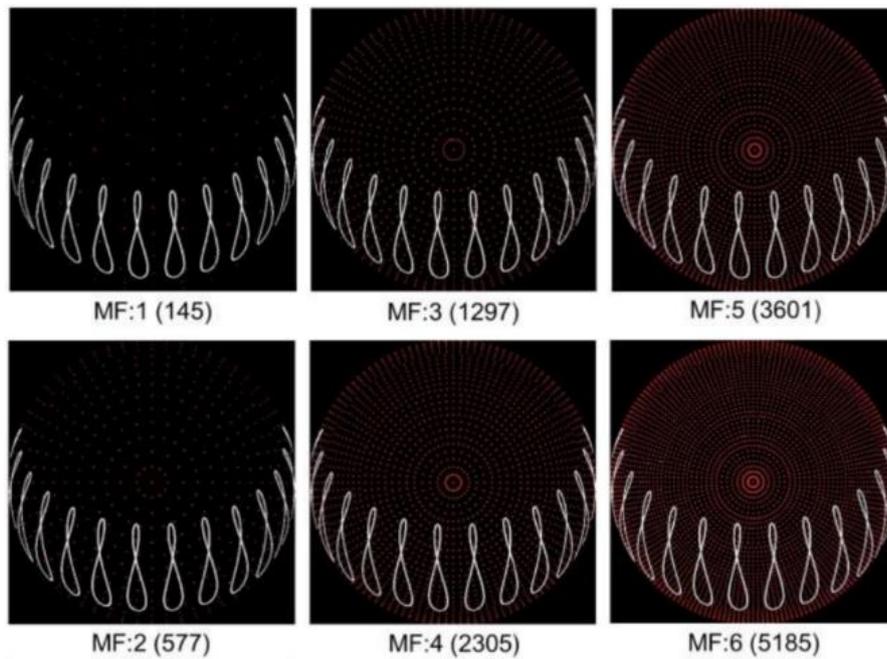


Figure 2.3-3 Amount of sun position compared to Renihart subdivision scheme used to calculated the contribution of the direct sunlight. Multiplication Factor (MF)-option generate the different number of suns which can calculated as  $(MF \times MF \times 144 + 1)$  [66].

The Figure 2.3-4 show an improved method to handle the direct sunlight contribution which is calculating the contribution from the sky and sun separately and the sun positioning is evaluation true hourly positioning or though analemma. Analemma show the sun position in the sky as a diagram from a fixed location same time every day for a whole year period and can do that for a chosen hour in a day.

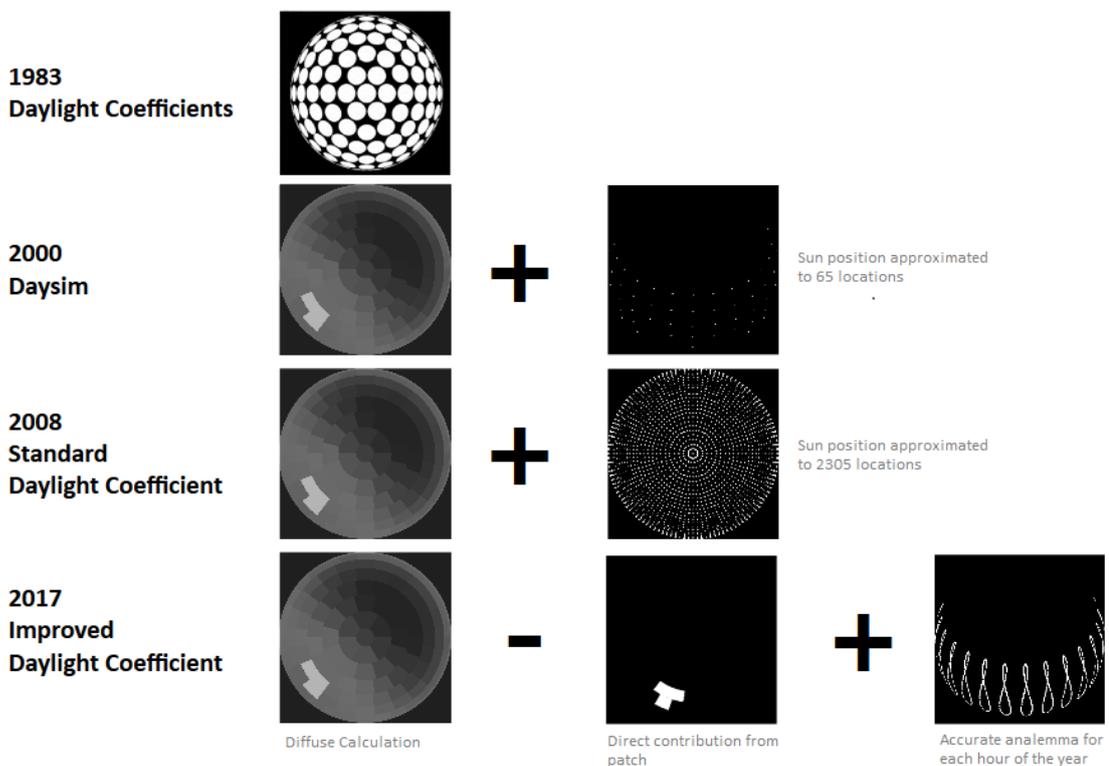


Figure 2.3-4 A More Accurate Approach for Calculating Illuminance with Daylight Coefficients [51] [77]

## 2.4 Conversion between software and scene geometry

The export from a geometric model to a daylight simulation tools is not a 1 to 1 conversion so a manipulated by lighting designers is often needed. Here different programs like Rhino can help the lighting designers to handle the conversion. In the conversion process various elemental need to be taking into consideration, such as reduction in the model size, the window geometry, needed simplifications, material reflectance etc. Illustrated of the different modelling technique shown in Figure 2.4-1 and Figure 2.4-2. Revit Spaces or Revit rooms can be used to pull out specific room geometry from at geometrically design tools and into a daylight simulation software. Geometry conversion is not a part of this project.

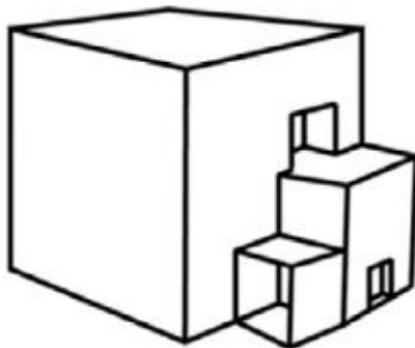


Figure 2.4-1 Geometric model in a design program [78]

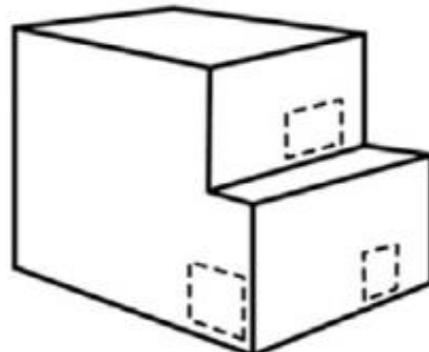


Figure 2.4-2 simplified equivalent model in a daylight simulation program [78]

Surrounding landscape and ground reflectance influence the amount of daylight entering the room and should therefore also be include in the geometry. In daylight simulation program the daylight calculation grid is defined as the distance above from the polygon mesh [6][5]. The window modelling is a complex discipline which require knowledge about the flexibility of used software and the different optical material properties of the window. When modelling the window in a daylight simulation “*programs tend to assign the optical properties of multiple glazing’s to a single surface*” [32] and often only one glass layer should be include as shown in Figure 2.4-3 to the right.

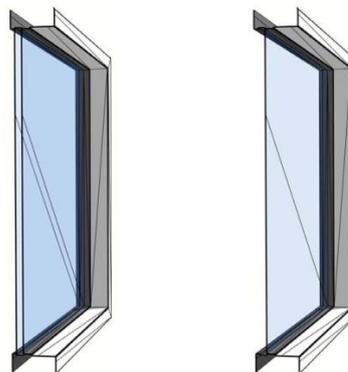


Figure 2.4-3 “Daylight simulation programs tend to assign the optical properties of multiple glazing’s to a single surface” [32] [79]. Architectural design tools model windows with double/triple glazing as two/three closely spaced parallel surfaces and therefore it is an important check point before modelling [32].

## 2.5 Simulation engines

### 2.5.1 Algorithms for light simulation

#### Glass-box light simulation algorithms

Different glass-box light simulation algorithms and their calculation method shown in Table 2.5-1. In glass box the tester knows the internal structure, design and implementation of the simulation software. Direct calculation often used for lighting fixture, sun and daylight opening and calculate lighting directly from light sources using physical formulas and simplifications [41]. Direct calculation is often implemented in national standard and cover most usual situations [41]. Calculation aids used for implementation of different algorithms show in Table 2.5-2 in computing system to obtain values in an acceptable period using statistical sampling [41]. Light transport of rays and light bounce of split rays follow the energy conservation principles [23]. Rays can split into components for reflection, transmission (refraction), absorption in participating media and emission in cases with incident radiosity is equal to sum of radiosity values [23]. A split ray controlled by either deterministic or stochastic- Monte Carlo methods. Deterministic method is a classical numerical approaches often used for calculating the sun because here it is known where to trace the next ray [23]. Monte Carlo or stochastic method used a random rays numerous times to give an accurate approximation of the solution and therefore the accuracy is depending on the level of model description and number of samples and bounces. Monte Carlo approach can be useful for calculating the diffuse light in the scene.

Algorithm	View-dependent	Scene-dependent	Direct calculation	Calculation aids
Value	Forward ray tracing Backward ray tracing Bi-directional ray tracing	Radiosity Photomap Integrative approaches Multi-pass approaches	For artificial lighting, follows national standards	Deterministic methods (classical approaches) Statistical sampling methods (Monte Carlo)
What it is (mainly) used for	Limited for daylight and small surfaces. Generate renderings	Radiosity: complex or daylit scenes.	Simplified calculation of lighting fixtures	Implementation of algorithms in computing systems

Table 2.5-1 Algorithm and calculation methods for lighting simulation programs [80]

Prevailing glass box algorithms for light simulation are radiosity, raytracing and photon-mapping which is a ray-tracing extended version. The three most common method shown in Table 2.5-2.

Finite element methods - Radiosity	The method divided the scene geometry into patches that are called finite element and calculate as show in Figure 2.5-1. The light exchange by using the view factor for every patch in the scene and simplification of the exchange by perfect reflecting of the diffuse light to all directions. The method is very time-efficient because the view factor calculation is made once and stored in front of the program and the brightness can be adjusted by table multiplying to match the sky at any given time similar to the daylight coefficient approach in chapter 2.3.3. Radiosity is lacking in the ability to recreate accurate specular reflections same reflection as for a mirror [81] but is time-efficient.
Stochastic (Monte Carlo)	Ray tracing is a rendering technique illustrated in Figure 2.5-2 which tracing the light transport particles called photons from a chosen view by calculating the

based methods - Ray tracing	geometric (ray). Stochastic (Monte Carlo) random calculation of Rays. Forward raytracing is tracing the light from source to receiver or backward is tracing rays from receiver to source and both methods have the same accuracy. Backwards is more efficient by calculating less rays only from the chosen receivers and forward is more inefficient by calculating all rays form sky and sun. Ray tracing can provide high resolution rendered picture with physically accurate results [82][78].
Photon mapping	Photon Mapping is a three steps ray tracing method that firstly, built the photon map (photon tracing) and secondly, photon map sorting (density), and thirdly, rendering the image using the photon map [83] [84]. Monte Carlo simulation and Russian roulette [85]. Photo mapping used two-pass raytracing algorithm illustrated in Figure 2.5-3. Forward algorithm is tracing the light rays into the scene and store them in a data structure called ‘photon map’ to be accessible when the backwards rays from the camera is tracing them and reads the stored information for calculating diffuse part of indirect illumination [86]. Photon mapping can handle different light effects, complex scenes, relatively fast and simple to parallelise [83][87][88]. Photon mapping is more efficient by precomputation of Irradiances for the rendering process. When enough photon map is in the room a rendering is started based on interpolation between points and rendering nearest Nighbor’s around the points based on precomputed data to give the results.

Table 2.5-2 Prevailing glass box algorithms for light simulation [78][23][79][80]

Ray Tracing and Radiosity are not able to model all possible lighting effects in a scene. Ray tracing only simulates indirect illumination by adding constant ambient term in the lighting calculation, whereas Radiosity only simulates diffuse reflections, completely ignoring mirrored surfaces [83]. Photon mapping can handle various light effects (all combinations of specular, glossy and diffuse reflection and transmission and including caustic), suitable for computing complex scenes because the method is independent of surface representation, simple to parallelise and relatively quick due to precomputation of Irradiances as explained in Table 2.5-2 [83].

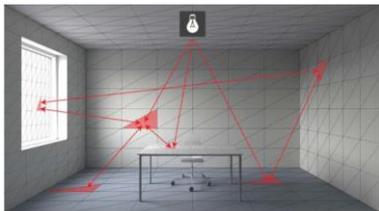


Figure 2.5-1 Radiosity [79]

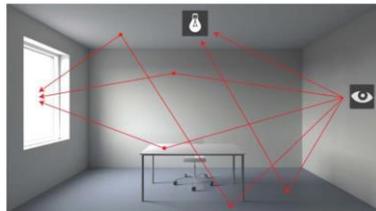


Figure 2.5-2 Ray tracing [79]

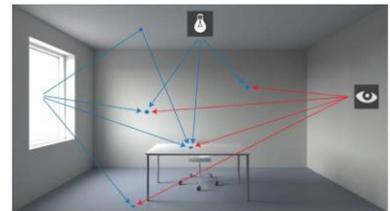


Figure 2.5-3 Photon mapping [79]

## 2.5.2 Radiance CBDM Technik

Radiance is a powerful and accurate lighting simulation engine [89], which offer high flexibility in terms of scene geometry and materials. Radiance is highly validated software for daylight simulation[43][68][19][44][90][45][91][92][93][94]. Radiance is often preferred for research and highly specialised applications and use radiance command line that you must be familiar with, otherwise radiance can be used in different Graphic user interface (GUI) shown in Figure 2.5-4. Many annual daylight simulation tools use RADIANCE because its robust, validated, flexible, accurate, free and open source.



Figure 2.5-4 List of applications that use Radiance as a simulation engine [95].

Radiance use different CBDM techniques shown in Table 2.5-3 to make daylight simulation and these techniques are also the most commonly used methods to perform CBDM evaluations [28]. The different listed application in Figure 2.5-4 only adapted some of the CBDM techniques and radiance options. Blended CIE have defined the relative sky luminance distribution and sky parametrisation of the fifteen standardised patterns [96]. Perez All-Weather explained in subchapter 2.3.2.

Method	Sky Discretisation	Sun Positioning	Luminance Distribution
4-component	MF:1	2056 points	Blended CIE
2-phase	MF: [1, 2, 4, ...]	In the sky patch	Perez All-Weather
2-phase* (Daysim)	MF:1	up to 65 points	Perez All-Weather
2-phase DDS	MF: [1, 2, 4, ...]	up to 2305 points	Perez All-Weather
3-phase	MF: [1, 2, 4, ...]	In the sky patch	Perez All-Weather
5-phase	MF: [1, 2, 4, ...]	5185 points	Perez All-Weather

Table 2.5-3 Main differences in the sky description of the investigated methods. MF indicates the Multiplication Factor, i.e. the number of subdivisions on each side of a Tregenza patch as shown Figure 2.3-1 [28]

All these different techniques take advantage in the daylight Coefficient approach to increase the calculation efficiency by subdivide the sky values into finite number of patches [28]. Table 2.5-4, Table 2.5-5 and Table 2.5-6 show an overview of the different software's and there CBDM techniques and can also see in Appendix 9.3.2.

		Daylighting simulation software											
		Radiance - classic	Radiance - DAYSIM	Radiance - Photon map	DIVA (Rhino)	DAYSIM pm	Revit Lighting analysis	Daylight Visualizer	LightUpAnalysis	DIALux (4, evo)	DIAL+ Suite	Su2ds	Light Stanza
<i>(✓) edited the .hea files</i>													
<i>Method</i>													
<i>CBDM Technik</i>	® 2-phase	✓											
	® 2-phase* (Daysim)	✓	✓		✓	✓						✓	
	® 2-phase (DDS)	✓	(✓)		(✓)	(✓)						(✓)	
	® 3-phase	✓											✓
	® 5-phase	✓											✓
	Other ® Technik			✓						✓	✓		
	Other non-® Technik						✓	✓	✓	✓			

Table 2.5-4 Overview of the different software's CBDM techniques

		Daylighting simulation software											
		SPOT	Relux	Accelerad	Geronimo	Light studio	Rayfront	AGi32	ElumTools	Lightsolve	ecoBIM	Ocean	BIM IQ
<i>(✓) edited the .hea files</i>													
<i>Method</i>													
<i>CBDM Technik</i>	® 2-phase												
	® 2-phase* (Daysim)			✓						✓			
	® 2-phase (DDS)			(✓)						(✓)			
	® 3-phase			✓									
	® 5-phase			✓									
	Other ® Technik	✓	✓		✓		✓						
	Other non-® Technik					✓		✓	✓		✓	✓	✓

Table 2.5-5 Overview of the different software's CBDM techniques

		Daylighting and whole building energy software								
		TAS Engineer-	OpenStudio	Sefaira	DesignBuilder	IES-VE ® * »	BSim SimLight	HoneyBee	IDA ICE ®	ODS Studio
<i>(✓) edited the .hea files</i>										
<i>Method</i>										
<i>CBDM Technik</i>	® 2-phase					✓				
	® 2-phase* (Daysim)			✓	✓			✓		
	® 2-phase (DDS)			(✓)	(✓)			(✓)		
	® 3-phase Method	✓	✓					✓	✓	
	® 5-phase Method							✓		
	Other ® Technik									✓
	Other non-® Technik						✓			

Table 2.5-6 Overview of the different software's CBDM techniques

Table 2.5-7 show an overview and explanation of the different CBDM techniques and a detailed explanation can found in Appendix chapter 9.2.1.

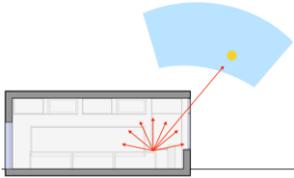
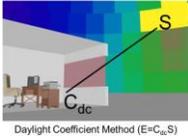
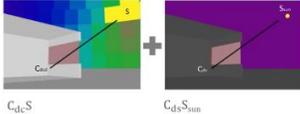
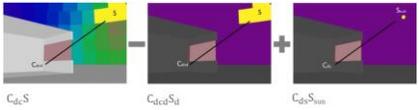
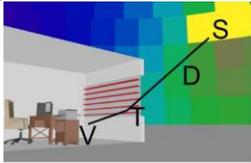
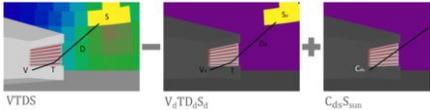
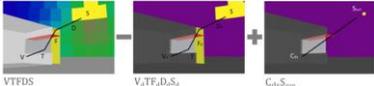
Radiance - Raytracing technique	What	Why	How	Illustrations
<div style="background-color: #800000; color: white; padding: 2px; display: inline-block;">4CM</div> <b>4-component method</b>  <b>Radiance rtrace command. Provide a framework for all the radiance techniques.</b>	Method that collect the contribution from the four daylight components: <ul style="list-style-type: none"> <li>• Direct sunlight</li> <li>• Indirect sunlight</li> <li>• Direct skylight</li> <li>• Indirect skylight</li> </ul>	High accuracy went through a thorough validation process. Method that tray to maintains a connection with reality	Long computation time because it calculated light contribution by tracing ray at each time-step independently. 2056 or 5035 sun positionings and 145 patches sky subdivision	
<div style="background-color: #008080; color: white; padding: 2px; display: inline-block;">2PM</div> <b>2-phase Method</b>  <b>Radiance command rtrcontrib/rcontrib</b>	Also called 1-phase method because the sun and the sky contributions putting together in one daylight coefficient.	Quicker method but also least documented and accurate method of all the CBDM techniques	145 sun and sky division which give high luminance variance in the sky.	 <p style="font-size: small;">Daylight Coefficient Method (E=C<sub>dc</sub>S)</p>
<div style="background-color: #FFA500; color: white; padding: 2px; display: inline-block;">DAY</div> <b>2-phase* (Daysim)</b>  <b>Radiance command rtrace_dc.</b>	2-phase* have default up to 65 direct solar positions, 145 sky subdivision and three ground segments.	High efficiency compared to 4CM because it calculates the rays once by storing all the ray hits data in daylight coefficient itself	Calculation several daylight coefficients separately for sun and sky in a single run. Separate direct and diffuse component.	
<div style="background-color: #000080; color: white; padding: 2px; display: inline-block;">2PM<sub>DDS</sub></div> <b>2-phase dds Method</b>  <b>Radiance command rtrace_dc_2305.</b>	Like 2-phase* increase accuracy with hourly sun positioning and only one ground segments	Increased simulation time compared to 2-phase* but achieved higher accuracy.	Diffuse calculation [-] Direct contribution from patch [+] hourly analemma of the direct sun contribution.	
<div style="background-color: #483D8B; color: white; padding: 2px; display: inline-block;">3PM</div> <b>3-phase Method</b>  <b>Radiance command called rcontrib</b>	Like 2-Phase method by adding an extra function of modelling CFS based on BSDF - Klem's basis.	Possible to model CFS system (Dynamic blinds, multiple glazing, change in interior or context).	Calculated the light travel inside the room to the window and afterward from window to source using the density of light	 <p style="font-size: small;">Three-Phase Method (E=VTDS)</p>
<div style="background-color: #FF8C00; color: white; padding: 2px; display: inline-block;">5PM</div> <b>5-Phase Method</b>  <b>Radiance command called rcontrib</b>	Like 3-phase adding greater accuracy by calculating the sky and sun contribution separately. CFS based on BSDF - Tensor Tree basis.	High accuracy by separate the sky and direct contribution from the sun	Using the 2305 or 5185 sun-like hourly or half hourly positioning using the deterministic algorithm	
<div style="background-color: #90EE90; color: white; padding: 2px; display: inline-block;">4/6PM</div> <b>4- or 6-Phase Method</b>	Extension to the 3-Phase and the 5-Phase method	Model change in external non-coplanar shading	Remarkably different in procedure and applications.	

Table 2.5-7 CBDM techniques [97][51]

The researchers have proposed advanced methods that “split” the ray-tracing aspect of the Daylight Coefficient Method into multiple “phases” also called techniques [51]. Figure 2.5-5 show different techniques that contain simplifications and various parameters that help to speed up the calculation time and possibility to calculate specific dynamic elements without losing the mount accuracy but 2-,3- and 4-phase method used a compromise of accurate spatial resolution of the direct solar contribution. It is possible with radiance to make parametric simulation that investigate scenario clear glazing, dynamic blinds, multiple glazing, change in interior, change in context and change in external non-coplanar shading in parametric way show in Figure 2.5-5. The different phases can be used to make parametrically simulate depending on scenario, efficiency and available accuracy.

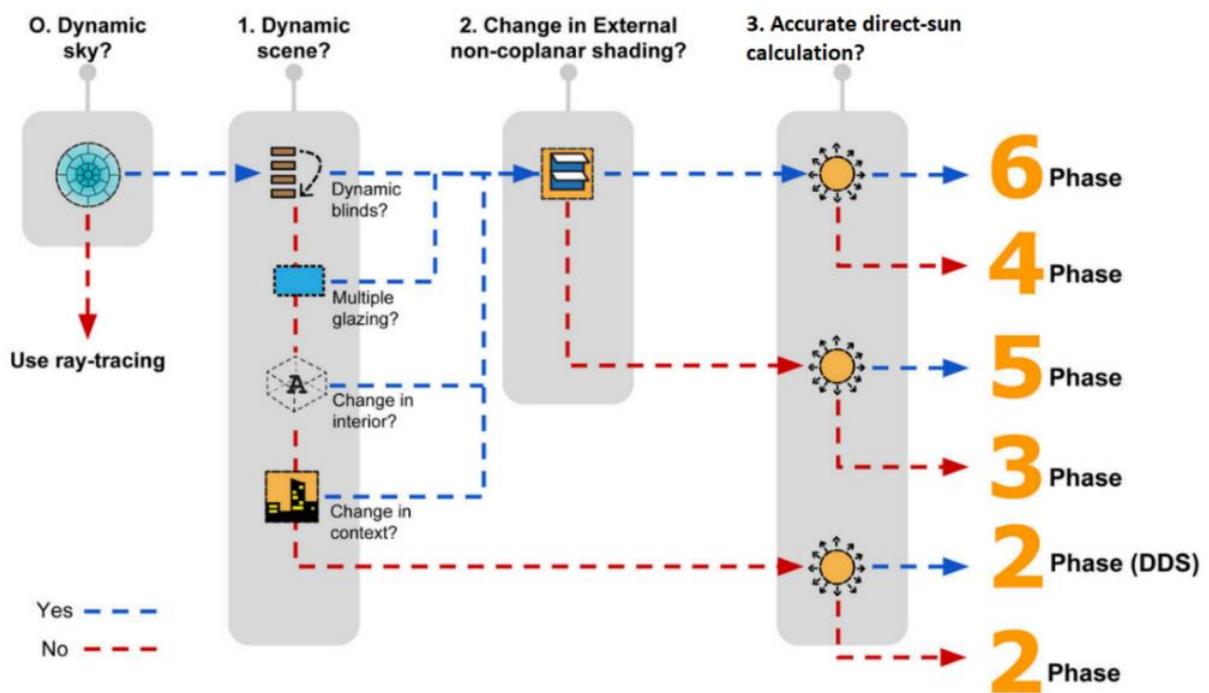


Figure 2.5-5 Modified illustration [73]. A simple decision tree for simulation of different CBDM techniques. The questions represent decisions and phase method is influencing simplification, accuracy and parameter included in the simulation.

### 2.5.2.1 CBDM techniques suitable for the Danish building industry

Eleonora Brembilla analyses of 5 CBDM technique for four different test room show in Figure 2.5-6 [28].

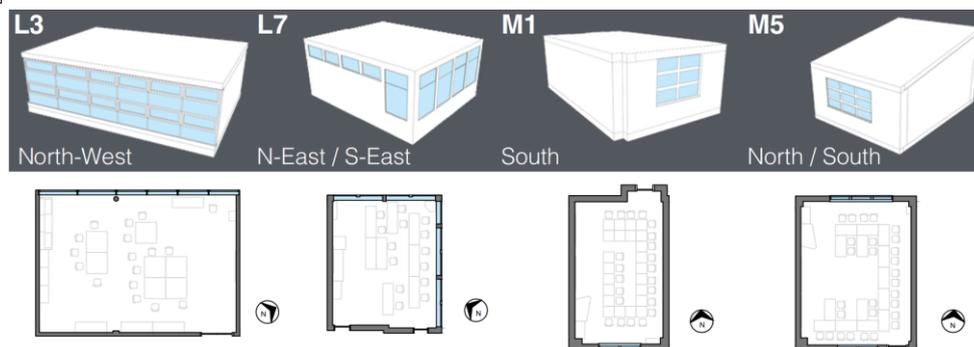


Figure 2.5-6 4 case rooms [28]

Eleonora Brembilla analyses used the 4-component method as a benchmark technique, here the reliability of the CBDM techniques are comparing for the different daylight matrix sDA, UDI, TAI and ASE. Figure 2.5-7 show similar or low different DA, where the Figure 2.5-8 show big variation of the ASE results obtain from the 5 CBDM techniques especially 3-phase, 2-phase and 2-phase\* (Daysim) results where fair way from the benchmark case. The reason is the calculation of the direct solar contribution, which the accurate spatial resolution of the direct solar contribution has a big influence on light penetration length inside the room.

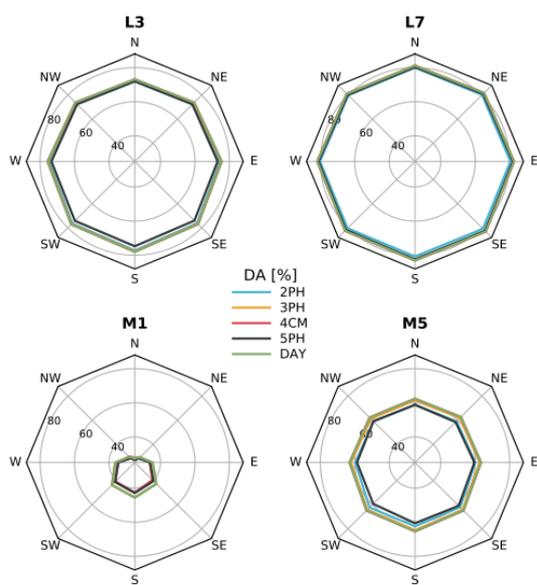


Figure 2.5-7 Daylight Autonomy (DA) results for 4 case rooms and the y-axis show the DA result in percent for the 5 CBDM techniques in a scale from 20% to 90%. [28]

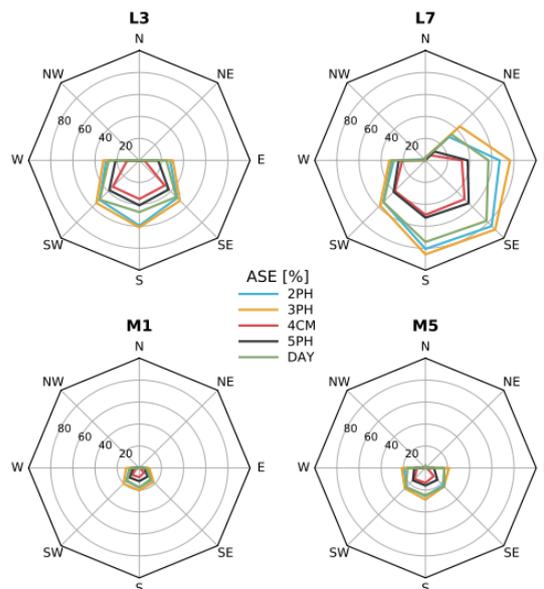


Figure 2.5-8 Annual sunlight expositor (ASE) results for 4 case rooms and the y-axis show the ASE result in percent for the 5 CBDM techniques in a scale from 20% to 90%. [28]

A more accurate direct solar contribution and a better spatial resolution can be results by the 2-phase (DDS), the 5-phase and 6-phase method for CBDM evaluation with at least hourly sun positions. When looking at smaller time steps such as a day the accurate direct solar contribution can have a strong influence on the simulation results as shown in Figure 2.5-9.

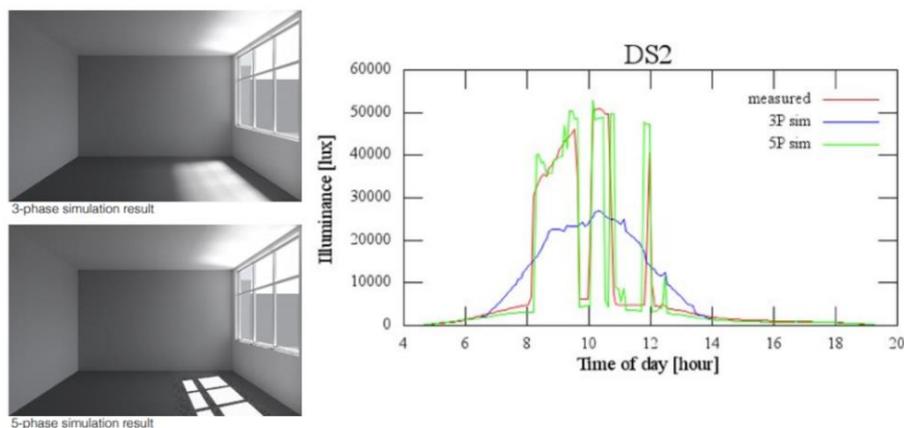


Figure 2.5-9 Modified picture [72][99] show the influence of 5-phases accurate direct solar contribution and implementation of high resolution Bidirectional Scattering Distribution Function (BSDF) compared to 3 phases and measured results.

## 2.6 Annual daylight metrics and visualisation

Annual daylight metrics is a way to show an extraction of the huge amount of data and visualise different aspects of the daylight. This subchapter explains some of the most common daylight metrics used for CBDM which is DA, ASE, TAI, UDI and DGP.

Daylight Autonomy (DA) is the percentage of hour per year when a minimum illuminance threshold met by daylight alone and Spatial Daylight Autonomy (sDA) also included the amount of relevant floor area that complies with the DA requirement. No upper limit and therefore a change of daylight design with poorly performing because of too much illuminance.

Annual Sunlight Exposure (ASE) is a threshold of 1000 lx for a maximum of 250 hours. ASE show where the direct sun is incident on the surface and indicate problem areas with chance of terminal discomfort. ASE predict area of high amount of direct sunlight but do not address issues of glare from specular reflections or high luminance ratios.

Total Annual Illumination (TAI) is the sum of hourly recorded illuminance by virtual sensor point for the averaged over the working plane. Daylight Glare Probability (DGP) is a luminance matrix that intended to measure if persons get disturbed by glare. Time consuming calculation with peak glare from specular reflection and DGP do not calculate reflection from surface. The DGP recognise a problem but do not specified a solution for the specific qualitative problem.

Useful Daylight Illuminance (UDI) is specific ranges of relevant area where the indoor horizontal daylight illuminance reach a faction of time in a year and the usefulness of illuminance have four different ranges shown in Table 2.6-1. More complicated way to communicate space performance because of 4 data points for every area of interest.

• 0-100 lx: UDI-n for non-sufficient,	• 300-3000 lx: UDI-a for autonomous,
• 100-300 lx: UDI-s for supplementary,	• over 3000 lx: UDI-x for exceeded

Table 2.6-1 Useful daylight Illuminance are area of interest [28].

Daylight Glare Probability (DGP) is a calculation method that predicts potential glare issues and is especially useful where occupants have fixed seats with reading, writing and computer devices [5]. The daylight glare probability is calculating the faction of dissatisfied of the luminance within the eye level and individual glare sources and calculated for a vertical or inclined daylight opening [5]. Problem with the method is time consuming calculation, only results for specific area, glare peak is not calculated and do not detect specific qualitative problem.

### 2.6.1 MRSE Mean Room Surface Exitance

Mean room surface exitance is the total amount of light that's bouncing in the space MRSE which go from light on the horizontal plane illustrated in Figure 2.6-1 to mean room surface exitance suggested by Christopher Cuttle illustrated in Figure 2.6-2. It's a change from the

amount of light that lands on the horizontal plane or the floor to the total quantity of light that's bouncing around in a space.

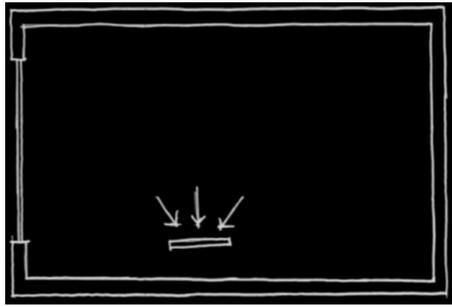


Figure 2.6-1 light on the horizontal plane

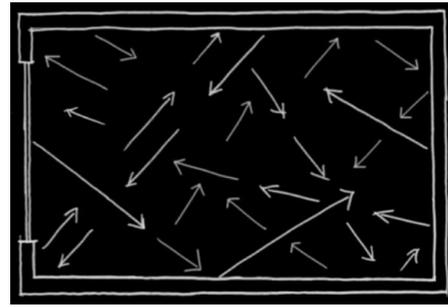


Figure 2.6-2 Mean Room Surface Exitance

### Virtual reality and game engine - AccereladRH

Visualisation of different daylight solutions for the customers today is challenges especially with the different metrics. Different number do not give a visualisation of how good amount of daylight is present inside the room. Virtual reality can be a way to solve the problem of how to illustrate different daylight solutions for the customers. The client must rely on that consultancy when he, says that 300-lux is good enough daylight. If the client could enter the model and visualise daylight more smartly and intelligently. Then it doesn't have to be 100% right (Appendix 1).

## 2.7 Development in daylight simulation tools.

Multi-disciplinary parametric studies of different building design with available parametric interfaces such as Grasshopper3D and DynamoBIM are adoption in the Architecture Engineering and Construction (AEC) industry [51][100]. Energy modelling, daylighting, acoustics and computational fluid dynamics (CFD) are typically featured in whole building simulations [101]. Still certain reservations of these whole building simulation options need to be considering. Each of the disciplinary investigate different area of the building so different model with different interest must be made and then afterwards the different disciplinary most considering as a whole. Daylight simulation plugins such as Honeybee built on top of the parametric interface and Rhino is used to link modelling platforms like Revit to BPS tools for CBDM evaluation [40][102][103].

One of the challenges making parametric studies is to make many simulations in short time and here the computer forces and computation time is important factors. A commercially available desktop computer with maximum efficiency is incapable of performing the amount of simulation in a short time [51] because the parametric simulations with rapidly generation of design alternatives utilising computer capacity in full [104]. Here parallel computing by simulating in a combination of the flexibility of general-purpose conventional Central Processing Units (CPUs) with the efficiency of current Graphics Processor Units (GPUs) for data parallel computations can help speeding up the computation time and give new possibilities to make more simulation on a less amount of time [105][106][107]. AccereladRT adds bi-directional path

tracing capabilities which give the possibilities evaluate real-time daylighting, glare and visual comfort analysis. Using most virtual reality headsets and includes AcceleradVR, an immersive visualisation interface is compatible. New possibility for early design daylight visualisation of various scenarios for a given client or customers.

Simulation engine based on photon Mapping algorithm is under development. Radiance EvalDRC tool for predicting annual daylight with assessing the performance of daylight redirecting components (DRS) [108][109][75]. Development of simulation program like Velux Daylight Visualiser to be able to make CBDM evaluation with photon mapping algorithm and handle annual daylight simulation and with the possibility to speed up the execution time with help from GPU.

## 3 Methodology

### 3.1 Choice of research method

The quantitative research methodology was used thus the hole report to collect information, structuring the data collection and give the basis knowledge about the theoretical research which included science & daylight, daylight tools and how to implement it in the field. The research quantifying the data and statistically aided analysis, resulting in specific recommendations. The research divides the literature into literature review, Peer reviewed journal and conference articles and websites with reports and documents.

The literature review was used to get a deeper understanding of the already known research area by a systematic literature review of all the studies obtained from secondary sources and documents. Peer reviewed journal and conference articles collecting from the main bibliographic databases from the University for collecting reliable articles and books. From different websites software manuals and relevant documents where collected and information used from different sources like online forums, tools, reports, websites, and media.

### 3.2 Methodology for program selection

Figure 3.2-1 is an attempt to get an overview of the various criteria and there influencing on different programs to figure out which program is best suited to the Danish construction industry and the methodology is the base of the work done in chapter 4.

The bottom part of Figure 3.2-1 shows an overview of the main aspect which is input needed, simulation engine and the output - visualising the results. The top of Figure 3.2-1 shows the overall practicality of the program, possibility, workflow, user experience and what results are needed compared to scale and design phase. The different criteria in the Figure 3.2-1 are weighted (highlighted, normal or dimmed) based on the BR18 requirement, standard and software requirement for verification of daylight provision. When looking at the most promising daylight simulation tools many aspects are considering. The different programs need to be investigating into deep to see if they fulfil the requirement and to see which one have most of the important criteria — the suggestion based on a qualitative approach.

The different simulation programs put into five different categories found in Table 3.2-1 to make the selection process manageable and usable. The available building performance simulation (BPS) software for daylight will be found based on literature and a analyse of which program is best in each category.

Simulation engine: Light algorithm & CBDM techniques	Computation	Graphic user interface (GUI)	Plug-in	Graphical algorithm editor
---	-------------	---------------------------------	---------	-------------------------------

Table 3.2-1 show five different categories that is necessary or useful function in a daylight simulation software.

Deliberation, possibility & Features

Technology currently available. Perfect program is utopia. One off simulation and comparison of the results				
scale	Design phase	Systems & pricing	Design workflow	Practicality
<ul style="list-style-type: none"> <li>• <b>Single room</b></li> <li>• <b>Building</b></li> <li>• Urban</li> <li>• Module (façade component)</li> <li>• Cell</li> </ul>	<ul style="list-style-type: none"> <li>• <b>conceptual/early phase</b></li> <li>• schematic</li> <li>• design development</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Graphical user-interface</b></li> <li>• Operation system (windows)</li> <li>• Open-source (Freeware) or Proprietary software (Payware)</li> </ul>	<ul style="list-style-type: none"> <li>• real-time simulation/progressive</li> <li>• multiple solutions comparison</li> <li>• integrated optimisation</li> <li>• parametric design (node based)</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Interoperability &amp; Integration (BIM, CAD/CAM, general 3D, stand alone)</b></li> <li>• <b>Reliable (i.e. debugged and tested)</b></li> <li>• <b>Availability and flexibility</b></li> <li>• <b>Application-friendly</b></li> </ul>

Inter-model comparison

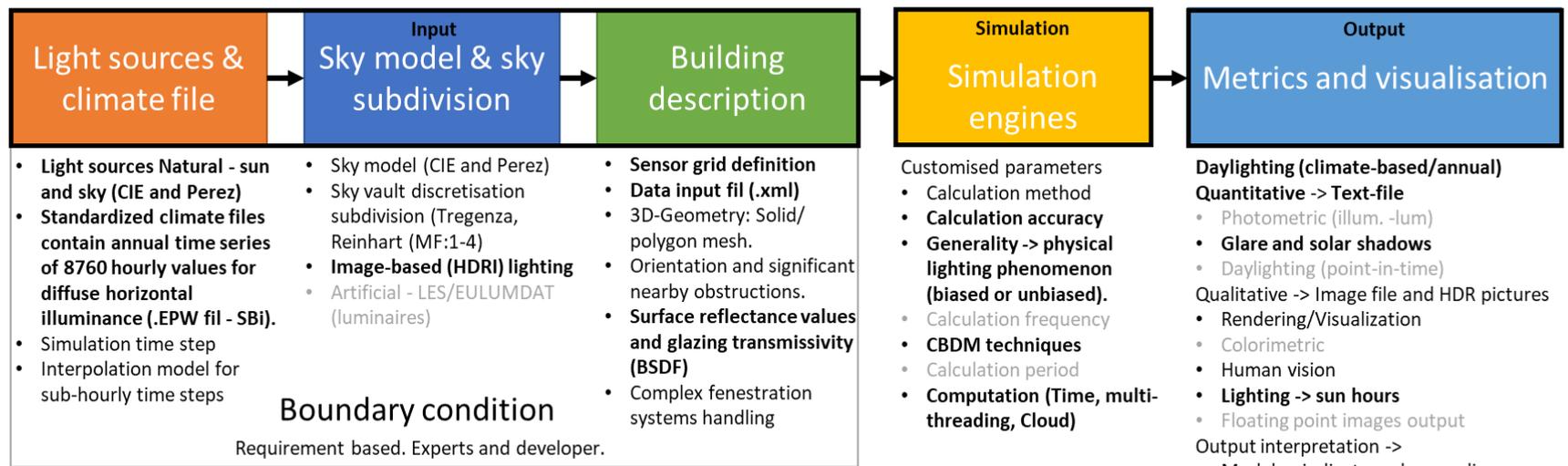


Figure 3.2-1 Methodology for program selection [17][28][27]. Deep weighted overview of various aspects in a daylight design tool which is developed based on a general architecture of a lighting simulation program. Methodology for selection of daylight simulation programs which can determine daylight provision calculation rapidly and accurately in the Danish building industry in the early design.

Before a daylight simulation program can be suggested. There is a need for a deep understanding of which of the different criteria influence the results. Comparison of how the different programs deal with the input, simulate the results and compare the output obtained using different methods.

### 3.3 Methodology for CBDM evaluation verification and guideline

This methodology is the baseline for the work done in chapter 5 and chapter 6. Chapter 5 included a verification of the results and how to make the daylight calculations in practice [110] and the guideline in chapter 6 will be based on work done in the verification process.

Verification of the chosen program based on three of the five typical rooms from daylight calculations in practices [110]. The three rooms use as testcases for further study and go through a verification process to test the programs accuracy against other tools in the ability to calculate daylight factor. The verification test will be limited to diffuse light with simple sky distribution and geometry, windows and reflection from materials, but the approach does not study the use of weather data and the treatment of direct sunlight. This verification process is a simple and fast way for verification of the calculation accuracy but does not include all aspects of CBDM evaluation, but the daylight factor is still the basis for CBDM evaluation. The three different test cases will look at the program's ability to simulate a simple room, a simple room with obstructions and a simple room with borrowed light. All spaces are set up with clear glazing and no dynamic shading device, to maximise the daylight access during the evaluation. These setups will also be used for CBDM evaluation when testing the room's ability to fulfil the building regulation spatial daylight autonomy (sDA<sub>300lux 50%</sub>).

#### 3.3.1 Choice of study case

The three typical room inputs are shown in detail in appendix 9.5.1, 9.5.2 and 9.5.3. Table 3.3-1 shows the three typical rooms' main characteristics.

	Simple room	Simple room with obstruction	Simple room with borrowed light
Floor area [m <sup>2</sup> ]	14	14	14
Glazed area [m <sup>2</sup> ]	2,6	2,6	8,044
WWR	7%	7%	26%
WFR	19%	19%	57%
Orientation	South	South	South

Table 3.3-1 Main characteristics of the three typical rooms

The Figure 3.3-1, Figure 3.3-2 and Figure 3.3-3 show a 3D view of the three chosen test cases.

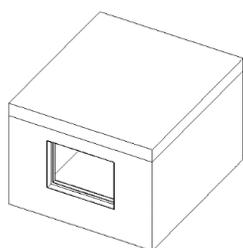


Figure 3.3-1 Simple room 3D view

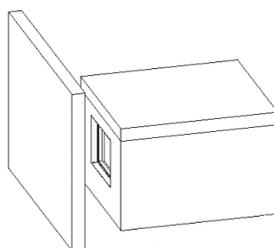


Figure 3.3-2 Simple room with obstruction 3D view

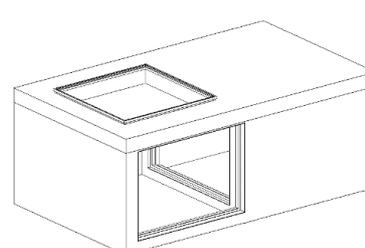


Figure 3.3-3 Simple room with borrowed light 3D view

The optical material properties of the three typical rooms shown in Table 3.3-2. These parameters used for all simulations carried out for the verification purpose.

<b>Surface</b>	<b>Surface reflectance value [111]</b>
Ceiling	0,70
Interior walls	0,40
Floor	0,10
Window lighting, inside	0,70
Window lighting, outside	0,30
Window frames	0,80
Significant neighbouring obstructions	0,30
Urban neighbourhood	0,10
<b>Window</b>	<b>Glazing properties [111]</b>
Check window glazing's consisting surfaces	Model as one layer
LT-value: Light transmittance: Outside glass layer	0,76
LT-value: Light transmittance: inside glass layer	0,85
<b>Climate data</b>	Data, time, latitude and longitude
Sky model	CIE/Perez sky model [6]
Sky subdivision <sup>1</sup> . Tregenza and Reinhart	≥MF:1
Sun positions	up to 65 points
<b>Grid settings [6]</b>	Value [111]
Spacing -> resolution defined in SBI 272	0,25
Edge (Excepted from the calculation area)	0,5
Height above the floor (Office)	0,85 m
Min/Max ratio	1
<b>Weather file</b>	DRY 2001-2010 epw-fil

Table 3.3-2 Optical material properties

All spaces had clear glazing and no shading device, to maximise the daylight access during the evaluation. The output of a CBDM evaluation is generating a time-series of illuminance values at every grid point over the year and the method for CBDM evaluation based on the Danish building regulation. Danish building regulation 2018 states that evaluating CBDM is true the spatial daylight autonomy (sDA) metric) which is the 50% faction of the relevant floor area in which daylighting achieves 300 lux in at least 50% of the daylight hours [5][7][6].

The three typical room is tested with the high-quality radiance parameters as shown in Table 3.3-3 for given accurate results for the simulation software. These parameters influencing the simulation time and the detailed explanation of these is in appendix 9.5.4.

	<b>Radiance - Parameters</b>				
<b>Simulation quality</b>	<i>-ab</i>	<i>-ad</i>	<i>-as</i>	<i>-ar</i>	<i>-aa</i>
<i>High quality (final simulation)</i>	6	4096	4096	128	0,10

Table 3.3-3 Radiance - parameters and rendering quality [112][113][114]

<sup>1</sup> For the 'phased' methods only

## 4 Results: Investigation of the most promising methods

This chapter is firstly, looking at previous reviews to get an overview of different software's available and secondly, sets up different criteria based a Danish context [6], DS/EN 17037 [5], Nebojsa Jakica article table overview with knockout criteria and nice to have criteria [23] and the methodology work in chapter 3.2 and Figure 3.2-1. The different criteria help to create a selection process of which software is most promising for CBDM in the Danish constructing industry. A table and illustration overview for the selection process shown in appendix 9.3.

### 4.1 Previous reviews of BPS software for CBDM

Nebojsa Jakica article presented in 2017 an overview of almost 200 solar design tools, with 70 features and their integration in around 50 3D, CAD/CAM and BIM software packages [23]. The international energy agency investigated in 2016 methods and tools for lighting retrofits [115] as well as advanced and future in simulation tools [116]. In 2016 a survey on CBDM show commonly used software and CBDM techniques in academia and industry, furthermore the survey also shows a missing framework for preform CBDM. In 2011 a literature review that investigate state of the art in lighting simulation for building science [80]. In 2016 Torben Oes-tergaard made a review that investigate different building simulations which supporting decision making in early design [40]. This review makes a comparison of the different software features and limitations from a desired framework. One of the key findings is that building simulation software in early design is faces several challenges; modelling is time-consuming, design changings, conflicting requirements, input uncertainties and large design variability [49]. The commercial software can address these challenges by proactive building simulations, statistical methods, holistic design, optimisation, CAD-BPS interoperability, and knowledge-based input generation [49]. The desired BPS software for CBDM evaluation in the Danish consultancy industry must also be able to handle these challenges.

The previous reviews in the field make a foundation for the available software and this analysis cover a scope of 30 different daylight and lighting product shown in the Table 4.1-1 and 15 daylighting and whole building energy products shown in the Table 4.1-2 in total 45 tools.

Radiance - Classic	Su2ds	DIALux (4, evo)
Radiance - DAYSIM	LightStanza	LightCalc
Radiance - photon map	Light studio	CSTB D1 PHANIE-2010
DIVA	Rayfront	ecoBIM (TAS Engineering)
DAYSIM pm	Lighting analysis for Revit	LD Assistant
SPOT	Solar Analysis tool	Shadow Analysis
ReluxSuite / Pro	VELUX Daylight Visualizer	Chronolux
Accelerad	AGi32	Ocean
Geronimo	ElumTools	BIM IQ
DIAL+ Suite	Lightsolve	LightUpAnalysis

Table 4.1-1 Overview of the 31 daylight and lighting BPS software

TAS Engineering	Green Building Studio	ODS Studio
OpenStudio	BSim - SimLight, Xsun	Vabi building performance
SEFAIRA	Honeybee and HoneyBee +	AECOsims Building Designer
DesignBuilder	Mr. Comfy	ArchiWIZARD
IES-VE	COMFEN	IDA ICE

Table 4.1-2 Overview of the 14 daylighting and whole building energy BPS software

12 of the 45 software are excluded from the analysis because they are not well documented software or used for other purpose that point in time and climate-based daylight analysis. The 12 different excluded software and their specific purpose shown in Table 4.1-3, Table 4.1-4 and Table 4.1-5.

<b>Software:</b>	Light-Calc LD Assistant	Chronolux Solar Analysis tool Shadow Analysis	CSTB D1 PHANIE	Mr. Comfy
<b>Purpose:</b>	Artificial light	Shadow Analysis BIPV purposes	Not a well-documented software	Visualisation tool for Grasshopper3d

Table 4.1-3 Seven excluded software, because of their other specific purpose.

<b>Software:</b>	Green Building Studio, COMFEN, Vabi building performance, AECOsims Building Designer and ArchiWIZARD
<b>Purpose:</b>	Whole building energy analysis

Table 4.1-4 Five excluded software, because of their other specific purpose.

<b>Software:</b>	Grasshopper Dynamo
<b>Purpose:</b>	<b>Graphical algorithm editor</b> for software interoperability and parameter simulation

Table 4.1-5 Useful software's to perform annual daylight evaluation.

## 4.2 Selection of BPS software for CBDM in a Danish context

The 33 software goes through a sorting process to figure out which are the most suitable for the Danish building industry, with knock out criteria from DS/EN 17037, Danish context and missing requirement to calculation of the direct contribution. Furthermore, Nice to have criteria are made to narrow down to a specific software for the Danish construction industry. The different criteria from the different headings listed in the subchapter below with a table illustration of the amount of software left. The basis requirement from DS/EN 17037 and BR18 illustrated in appendix 9.3 Table 9.3-1 and Table 9.3-2. Table 4.2-1 illustrate 17 of the software that fulfil the basis software requirement listed below:

- Import type of climate data DRY (.EPW file format) developed by SBI
- Delimit the hours assessed for "the 50% daylight hours"
- Adjustable size of calculation grid to meet the requirements of BR
- Adjustable reflections of the surfaces

The different available software put into four categories which describe their different function in a daylight simulation software.

BPS (own engine)	GUI (external engine)	Plug-in:
Radiance - Classic	DAYSIM pm	Honeybee and HoneyBee +
Radiance - DAYSIM	DesignBuilder	DIVA
Radiance - photon map	SEFAIRA	
BSim - SimLight, Xsun	IES-VE	<b>Computation:</b>
IDA ICE	OpenStudio	Accelerad
SPOT	Su2ds	
ODS Studio	LightStanza	

Table 4.2-1 17 BPS-software there fulfil the basis requirement from DS/EN 17037 and BR18

The next sorting process based on Nebojsa Jakica table overview show in appendix 9.3 Table 9.3-5, Table 9.3-6, Table 9.3-7 and Table 9.3-8. The table overview shows 70 different criteria which are prioritise as Knock-out, Nice to have and Not needed for the 33 BPS software. Table 4.2-2 illustrated 11 of the 17 BPS software left that can be used for CBDM in a Danish context based on the following knockout criteria below:

- Daylighting (Hourly -> climate-based)
- Conceptual/early design phase
- Calculation accuracy or validation (CIE 171:2006)
- Approved Luminance Distribution model (Perez)
- Scale: Single room with building

BPS (own engine)	GUI (external engine)	Plug-in:
(Radiance - DAYSIM)	DAYSIM pm	Honeybee and HoneyBee +
IDA ICE	DesignBuilder	DIVA
ODS Studio	SEFAIRA	
	IES-VE	<b>Computation:</b>
	Su2ds	Accelerad
	Light Stanza	

Table 4.2-2 11 BPS software after knockout criteria from Danish Context

Here two new tables in appendix 9.3 Table 9.3-3 and Table 9.3-4 is used to see which of the 11 software fulfil the knockout requirement listed below and Table 4.2-3 show the nine software that can handle hourly sun positioning - most of them only by changing the 2-phase\* daysim heater file.

- Minimum hourly Sun Positioning Tregenza, Reinhart (MF:4)
- Sky Discretisation - minimum Tregenza, Reinhart (MF:1)

BPS (own engine)	GUI (external engine)	Plug-in:	Computation:
Radiance - DAYSIM	DAYSIM pm	DIVA	Accelerad
	DesignBuilder	Honeybee and HoneyBee +	
	Su2ds		
	SEFAIRA		
	Light Stanza		

Table 4.2-3 9 BPS software can handle minimum of hourly sun positioning and sky subdivision (MF:1).

A last sorting process is to see with of the nine software fulfil the nice to have criteria from Nebojsa Jakica table overview show in appendix 9.3 Table 9.3-5, Table 9.3-6, Table 9.3-7 and Table 9.3-8. The nice to have criteria mentioning below:

- Computation: GPU based
- Interoperability and BIM integrated
- Availability
- Price – Freeware or cheap calculation tool
- Update and maintenance.
- Same calculation engine in the entire design process

### 4.3 Discussion of the most promising methods

The nice to have criteria cannot be fulfilling by only one software but several software's in combination can together and separated meet the needs of the industry and the availability for the software depend on the analyse needed which influencing the amount of knowledge required within the field. Type of analyses and required knowledge is especially depends on the interface and Graphical algorithm Editor chosen and therefore the functionalities of these will be further discussed.

#### 4.3.1 GUI and graphical algorithm editor for CBDM evaluation

The Velux daylight visualizer is executed from the previous analysis because it can only handle point in time simulation that provide data to the daylight factor metrics. Velux daylight visualizer has some advantages as graphic user interface (GUI) because it is simple and easy to use GUI, easy to build up geometry and have the important input for at daylight simulation software but have certain limitation in form of specific windows components and not suitable for annual daylight evaluation.

Diva is a plugin for Rhino can make daylight simulations directly in Rhino, but also using grasshopper. Diva use Daysim as GUI built on top of Radiance backward raytracing and because of that some of the Radiance flexibilities is limited to the Daysim interface. Diva screen visualisation using CIE overcast/or clear skies and collar mapping or WXfalsecolor for rendering image results and output can be exported to spreadsheets or as a text file. DIVE is suitable for make daylight simulation and the required inputs include a weather file, sensor nodes, materials that are defined by RADIANCE parameters all other parameter is predefined in Diva. Diva4Rhino can visualise into three categories “daylight images”, “daylight grid-based” and “thermal single-zone”.

HoneyBee+ is built directly to radiance simulation engine and give the radiance flexibility and therefor Honeybee+ is preferable for more complex geometry and parametric simulation. Honeybee+ have BIM interoperability functions as illustrated in Figure 4.3-1. Both Diva and

HoneyBee+ can use dynamo BIM as graphical algorithm editor links Radiance to Revit and Grasshopper3D links Radiance via Rhino respectively. Diva have also the possibility to link direct to rhino without using grasshopper. Grasshopper Rhino geometry can be modified in Rhino and having inbuilt functionality for easy user interaction and data visualisation. Grasshopper limitation is no implantation of 4-, and 6-phase method. Dynamo is a direct Revit plugin which is preferable but is a new implementation and therefore not have the same possibility as grasshopper. Dynamo has no implantation of 4-, 5- and 6-phase method and is only handling the phase methods by scripting. Dynamo is very interesting but now personal recommendation is for Grasshopper or Diva direct plugin for Rhino. Diva is payware and HoneyBee is freeware, but both Rhino and Dynamo is also payware. The logical structure of honeybee shown in Figure 4.3-1.

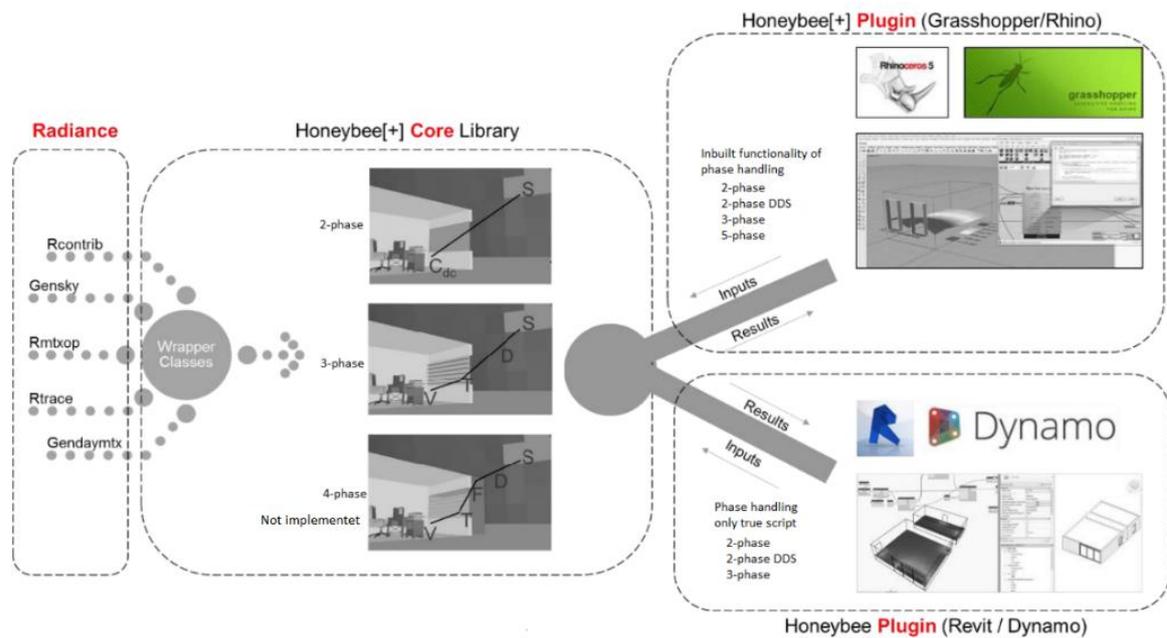


Figure 4.3-1 Modified picture of Honeybee [+ ] logical structure [51]

When a program says that they use DAYSIM as a calculation engine, the program often only uses up to the 65 sunlight positions (simulation errors to direct sunlight). DAYSIM (DDS) with 2305 sunlight positions is more precise with a longer calculation time and is only available by edited the .hea files if using another interface than DAYSIM or run DAYSIM Subprogram: gen\_dc [117][118]. HoneyBee+ have the possibility calculate direct on Radiance simulation engine with using Daysim as a GUI and therefore it is possible to do annual daylight evaluation with hourly sun positioning in HoneyBee +. Based on the analysis and conclusions drawn from this study, a daylight coefficient simulation with 145 sky patches and precise sun positions recommended as the optimal solution for illuminance based on speed and accuracy [51].

### 4.3.2 Computation for speeding up the CBDM simulation time

Computation of the CBDM simulation throughout Accelerad is the only available tool for performing GPU-based simulations for ray-tracing and has only been subjected to few empirical

validations and tethered to a GPU manufactured by a single commercial manufacturer but Accelerad is built up on top of the Radiance technique which is well validated. Implementing different interface on top of radiance like honeybee+ and Diva will slow down the calculation time more than using radiance command-line [51]. Table 4.3-1 show a combination of different software that will together be described as the most promising methods for CBDM evaluation in the Danish construction industry.

Accelerad is using a method for speeding up the calculation time by using a GPU instead of a CPU and how to speed up the computation time referred to Accelerad webpage [119].

Computation	Calculation engine	Light algorithm	CBDM techniques	GUI	Plug-in	Graphical algorithm editor
CPU	Radiance	Ray tracing	2-phase dds	Daysim	Diva4Rhino	Grasshopper
GPU	Accelerad					
CPU	Radiance		2-phase dds & 5-phase	Daysim	Honeybee+	
GPU	Accelerad					

Table 4.3-1 The available program that fulfil the nice to have criteria

This different software fulfils the given setup, but it does not necessarily mean that they are the most appropriate for each category. Simulation complexity depending on the different chosen BPS software's, their Graphic user interface and the program flexibility. In the bullet point below the program are put into three different categories of complexity:

- The most detailed calculation only a few in Denmark knows how to calculate these by using Radiance command line 4- and 6-phase CBDM techniques.
- HoneyBee and Diva4Rhino is the less advanced software where several people can lean and calculate these using Daysim Graphic user interface or just on top on Radiance calculation engine.
- Simple program like Velux daylight visualiser is a standalone program where many in the field can do a daylight factor metrics calculation.

One number and program cannot account for the complexity of the world.

### 4.3.3 Sub-conclusion bifurcated

No tools are best for everything and when looking at the available program on the market, different program combinations will be suiting the various complexities, different design phases and objects involved, availability in connection to user expertise, speed and accuracy.

#### Theoretical approach (idealistic, perhaps impractical):

The requirement and recommendations are here on a purely theoretical level. Accelerad, Radiance and HoneyBee+. 2-phase dds and 5-phase method there can handle the direct sun independent. Accelerad speed up the computation time with a high precision and quality calculation. Can handle complicated window set up and dynamic sun protection along the window. Practically, handling and learning is difficult and therefore recommend is not there. The

complexity increases by using the radiance command line and include all the radiance CBDM techniques with all the phase methods and Accelerad by not computed the 4- and 6-phase method.

**Pragmatic approach (realistic, practical and solution-oriented):**

Program that calculates on an hourly basis, GPU with give an easy and quick GUI that can give the solution needed. It must also be operational. Diva for Rhino is relaxing on the requirement without changing the heater file for having hourly sun positioning, but this program is more suitable and user friendly for CBDM evaluation, but without implementing 2-phase DDS the quality of the calculation is not as accurate. Table 4.3-2 show the most promising methods which the different software functions and importance for including for the final recommendation.

Software and related topic	Functions and importance
<b>Computation:</b> Accelerad only GPU based software for Radiance.	<b>Accurate:</b> implementation of 2 phase DDS and 5-phases method for CBDM evaluation. <b>Free:</b> development is based and implemented on radiance functions. <b>Fast:</b> GPU instead of CPU, which can make parallel processing with interactive speeds using 2880 cores instead of 8 cores [20].
<b>Calculation engine:</b> Radiance CPU based	Robust, powerful, validated, flexible, free (open source code), Accurate (highly validated software) and often preferred in industry.
<b>CBDM techniques:</b> 2-Phase to 2-phase DDS	2-phase for early design and 2-phase DDS for more accurate spatial resolution of the direct solar contribution.
<b>GUI:</b> Daysim is a simple GUI used for daylight modelling.	Daysim is designed for incorporation into other modelling software by its open-source modules and build up by expanded header file formatting.
<b>Plug-ins:</b> Diva has a daylight plug-in for Rhino.	DIVA-for-Rhino allows users to carry out annual daylight evaluations of individual rooms and buildings and use Climate-Based Daylighting Metrics for visualise the results and can export the yearly results as a test file.
<b>Plug-ins:</b> Honeybee <b>GUI:</b> Honeybee [+] has an open source library and working under the umbrella called Ladybug Tools [120] with the Ladybug multiply functionalities.	Are focused on daylight simulation and have inbuilt functionality for easy user interaction and data visualisation [51]. Possibility to do sub-annual, image-based and parametrical daylight simulations. Tregenza sky model subdivision and Renihart subdivision scheme. Advantages daylight multi-phase simulation with CFS with BSDF materials to simulate window groups, shading groups and dynamic blinds (e.g. 3-phase and 5-phase) but not supported external shading device with 4 to 6-phases method. Templates (scripts) -> Control of the speed of the analysis.
<b>Graphical algorithm Editor:</b> Grasshopper3D or Dynamo BIM	Graphical algorithm editor with visual programming interfaces for building design and simulation that facilitate parametric workflows, and create software interoperability by link radiance to Revit and Rhino [51]. Rhino payware used in the industry for Energy, indoor climate and daylight.

Table 4.3-2 Most promising methods which different functions and importance

#### 4.4 Flow chart – Investigation of the most promising methods for CBDM evaluation

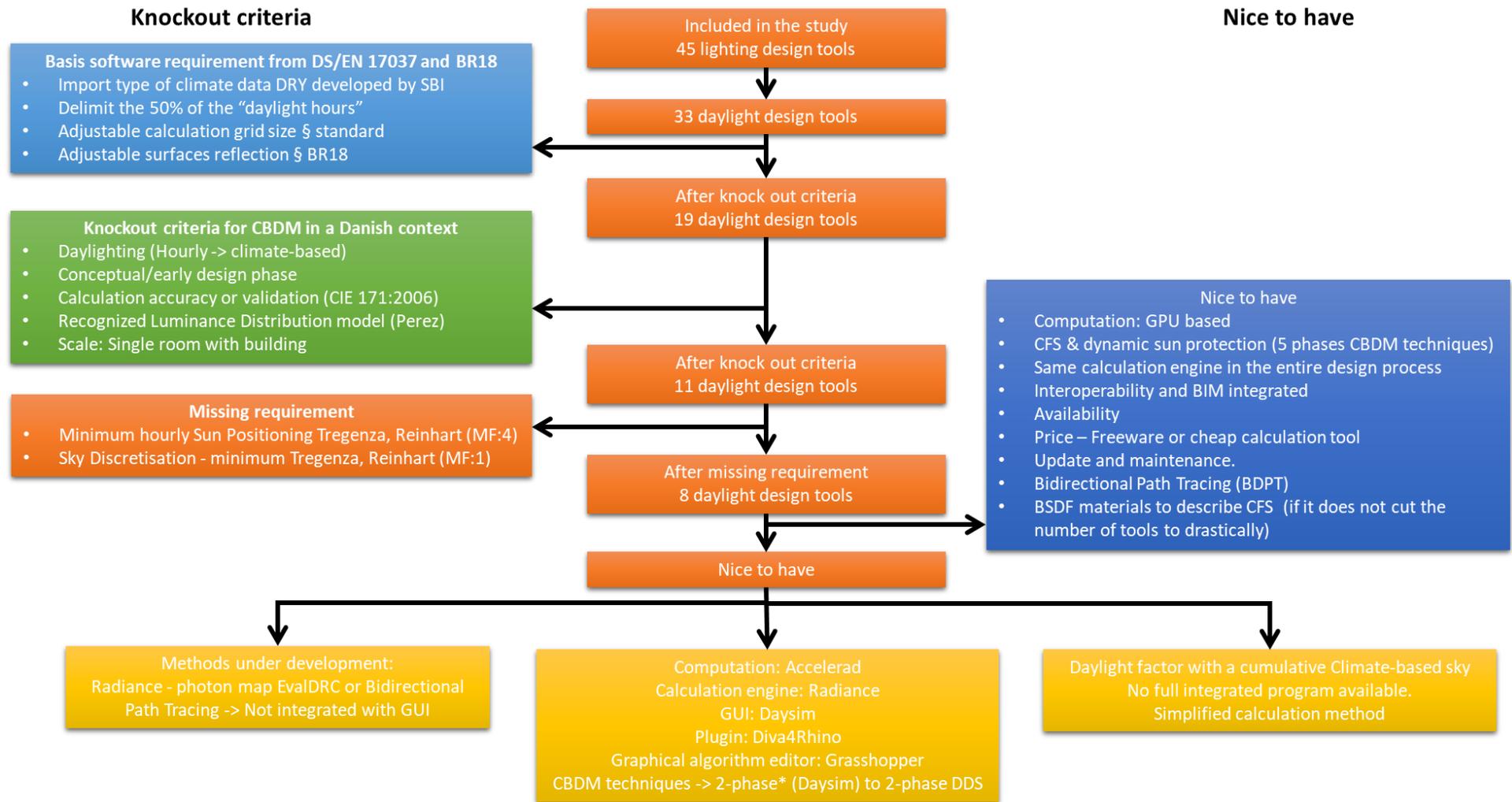


Figure 4.4-1 Flow chart – Investigation of the most promising methods on the market for CBDM evaluation

## 5 Results: Testing of the software methods

CBDM evaluation in a Danish context here different setup used depends of which type of output and simulation phase the CBDM evaluation is needed.

### 5.1.1 Diva4Rhino for daylight analysis

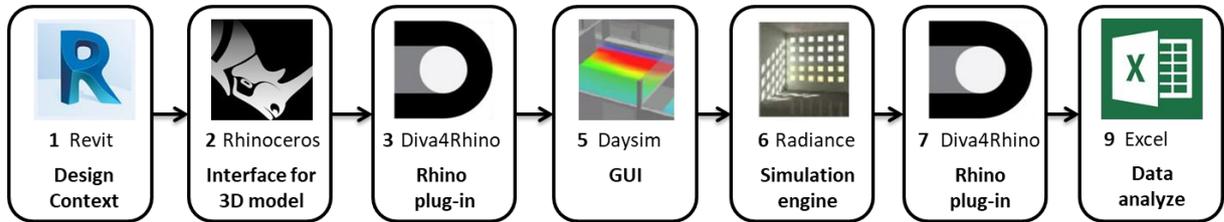


Figure 4.4-1 Steps in a Diva4Rhino for daylight analysis true Radiance CPU based processor.

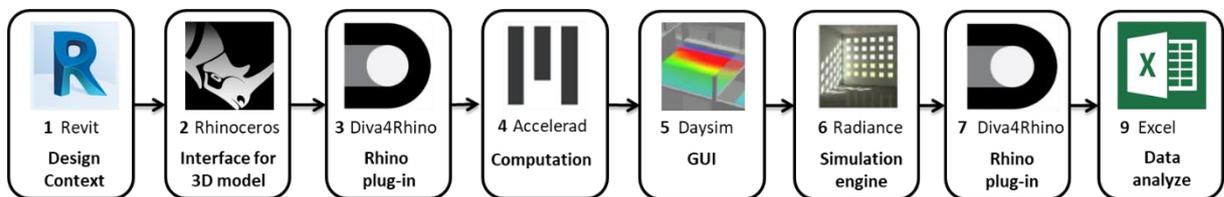


Figure 4.4-2 Steps in a Diva4Rhino for daylight analysis true Radiance and GPU computation with Accelerad

#### General step in a daylight analyse by using Diva4Rhino

The difference between Figure 4.4-1 and Figure 4.4-2 are Accelerad which make the simulation run on a GPU instead of a CPU and both figure illustrate the different steps in a daylight analyses which elaborated below:

1. Design context with geometrically model from Revit
2. Rhinoceros is an interface for conversion of the geometrically model.
3. Diva is a Rhino plug-in that provides the data to Daysim with is the GUI to Radiance.
4. Accelerad used if the computer has an external GPU processor that is better than the CPU. Accelerad speed up the computation time by parallelism the large numbers of ambient bounces or ray tracing over the different sensor points shown in Figure 4.4-2.
5. Daysim is validated graphic user interface based on Radiance simulation engine.
6. Radiance is a powerful and accurate lighting simulation engine, highly validated and flexible.
7. Diva used the information from Daysim and has multiple visualisation possibilities of the results.
8. Excel used for different data analysis

It is preferred to use the current and maintained version through Diva4Rhino. Honeybee+ is preferable for using the grasshopper script because it gives more possibility to set flexible and parametric simulations.

## 5.1.2 Honeybee+ and Grasshopper for parametric daylight analysis

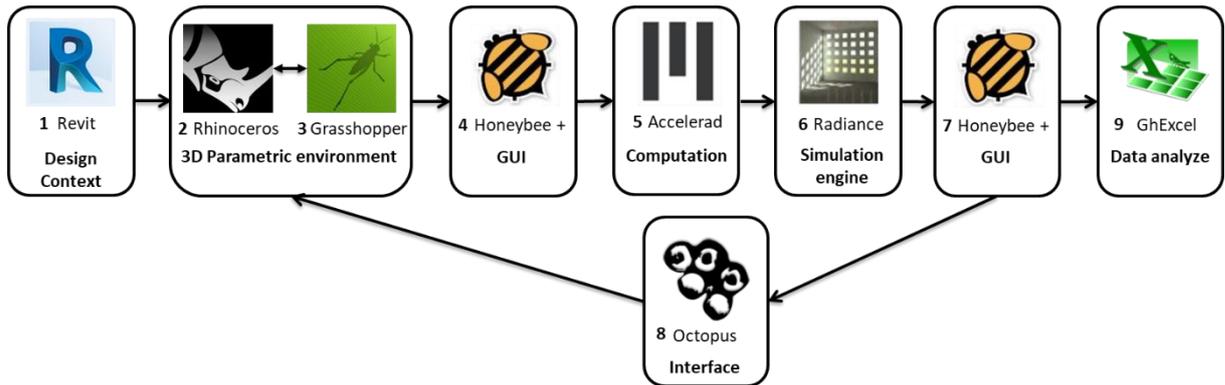


Figure 4.4-3 Diva Grasshopper geometrical daylight analysis with parametric simulations

1. Design context with geometrically model from Revit
2. Rhinoceros is the parametric environment used for conversion of the geometrically model.
3. Grasshopper is the interface for all model programming.
4. HoneyBee+ provides the data to Radiance where Accelerad can speeded up computation time.
5. Accelerad used if the computer has an external GPU processor that is better than the CPU. Accelerad speed up the computation time by parallelism the large numbers of ambient bounces or ray tracing over the different sensor points.
6. Daysim is validated daylight simulation software based on Radiance simulation engine.
7. Radiance is a powerful and accurate lighting simulation engine, highly validated and flexible.
8. Diva used the information from Radiance and has multiple visualisation possibilities of the results.
9. Octopus is used for parametric simulation by reading the data from Diva and optimises the geometrically model through grasshoppers.
10. Excel used for different data analysis

## 5.2 Verification of CBDM-evaluation software Diva for Rhino

Software validation-based either on data from analytical calculations of validated programs or data from experimental measurement for both scale models and real-world scenarios. The test cases in CIE 171 to assess the accuracy of lighting computer programs used a combination of both validation methods [121]. Typically, different specific area of the program rather than the entire calculation part in one. Radiance and other programs is validated against all the CIE 171 test cases [122]. The CIE 171 limited the number of independent parameters and the light propagation and simulation and divided the considerations into three main groups and high-light calculation different of each of them:

- Light source description true CIE sky models
- Light transmission through openings and window components or around obstacles.
- Internal reflections between different types of optical material properties.

In Denmark SBI 2013:20 made a book called daylight calculation in practices which setup five typical rooms and investigate different aspects of daylight calculation programs, to see how the different programs calculate in relation to each other and how technically to build up a daylight model [111]. SBI daylight calculation in practices compared nine different simulation programs in relation to the daylight factor calculation where Velux Daylight Visualizer show average results close to Radiance, Daysim and therefore these programs is selected for the validation for simulation accuracy for Diva for rhino. SBI 2013:20 is a simple and fast way for verification of the calculation accuracy and daylight factor is still the basis for evaluating the climate-based daylight calculation. Using the daylight factor approach only check the software possibility to calculate diffuse light with simple sky distribution and geometry, windows and reflection from materials, but the approach do not study the use of weather data and the treatment of direct sunlight.

For comparison on the median and % floor area observed a deviation of +/- 10% is acceptable. Verification of the two other typical room and investigated radiance parameters influencing on the simulation results is in appendix 9.4.

Room and area of interest	Simple room - Daylight factor			
Program	DIVA4Rhino	Radiance	Daysim	Velux Daylight visualizer
Average	3,2	3,3	3,4	3,0
% different in Average DF	0,0%	6,1%	8,8%	-3,3%
Median	2,1	2,3	2,2	1,9
Minimum	0,9	0,9	0,8	0,7
Max	12,1	12,9	13,6	12,6
Uniformity (minimum / average)	0,3	0,3	0,2	0,2
Uniformity (Max / average)	0,1	0,1	0,1	0,1
Calculation accuracy	High	High	High	High

Table 5.2-1 Show verification of Diva4rhino of a simple room against testing results from daylight calculation in practices [110]. All the simulation tools set up high calculation accuracy.

### 5.3 Spatial Daylight autonomy for typical room Diva4Rhino

The simple room results shown in Table 5.3-1 and Figure 5.3-1 and a room with borrowed light in Table 5.3-2 and Figure 5.3-2 both fulfil the Danish building regulation requirement 300lux-rule with is shown through the sDA metrics. Simple room with obstruction shown in Table 5.3-3 and Figure 5.3-3 do not fulfil the requirement.

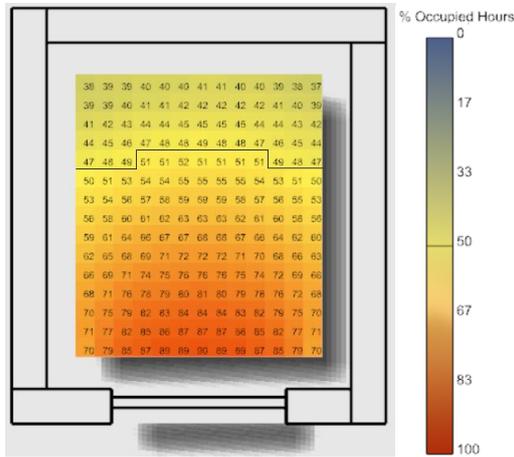


Figure 5.3-1 sDA for a Simple room

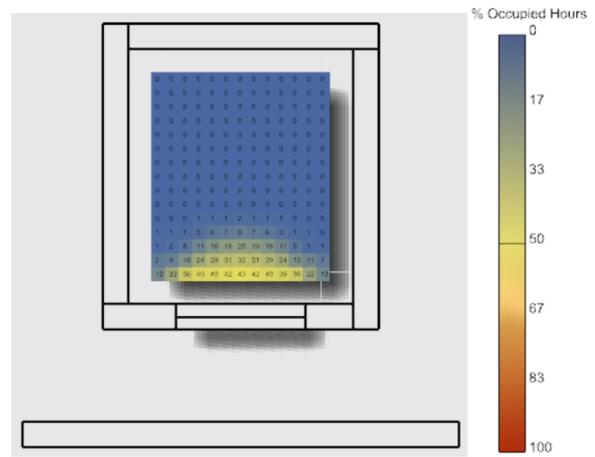


Figure 5.3-2 sDA for a Simple room with obstruction

Result	Occupied hour	Grid points
Investigated area	4380	195
Number above 50 %	2625	135
Percent above 50 %	60 %	69 %
<b>Requirement</b>	<b>✓</b>	<b>✓</b>

Table 5.3-1 sDA for a Simple room

Result	Occupied hour	Grid points
Investigated area	4380	195
Number above 50 %	0	0
Percent above 50 %	0 %	0 %
<b>Requirement</b>	<b>✗</b>	<b>✗</b>

Table 5.3-2 sDA for a Simple room with obstruction

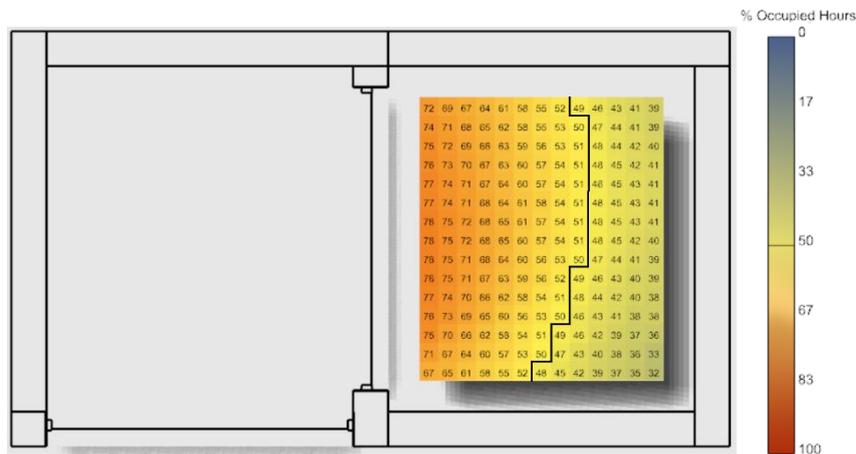


Figure 5.3-3 sDA for a room with borrowed light

Result	Occupied hour	Grid points
Investigated area	4380	195
Number above 50 %	2401	121
Percent above 50 %	55 %	62 %
<b>Requirement</b>	<b>✓</b>	<b>✓</b>

Table 5.3-3 sDA for a room with borrowed light

### 5.3.1 Different between 2-phase\* (Daysim) and 2-phase DDS

The chapter 2.5.2 explained the different between 2-phase\* (daysim) and 2 phase DDS. Chapter 2.5.2 also investigated the reliability of the simulation results compared measurement from 2-phase DDS in relation to 2-phase and 2-phase\*. As mentioning in chapter 2.5.2 for including an accurate direct-sun calculation in the Radiance simulation engine there is a need of hourly sun position. Many programs need to change from point in time and hourly prediction to annual daylight simulation with a timestep of hour or less and for speeding up the computation time simplification made of the spatial resolution in the direct-sun contribution the Radiance CBDM techniques and the simplified spatial resolution implemented in different graphic user interfaces (GUI). The different available software and there CBDM techniques shown in Appendix 9.3.2.

An article from 2019 made by Eleonora Brembilla show that CBDM techniques have a deviation up to 39% from the benchmark in predicting Annual Sunlight Exposure and metrics that consider both direct and diffuse illuminance where more robust and show results of  $\pm 15\%$  within the benchmark results [98].

#### Program default setup

Table 9.3-3 in appendix 9.3.2 show that Diva4rhino use a default 2-phase\* (daysim) method. For the program to calculate in the right way there is a need for changing the heater file. There is no GUI-based way of doing DDS simulations. To run an annual daylight simulation there is a need for setup DDS simulation through a text-based editor irrespective of which GUI-front the program is using. Two lines added to heading file [118] which is:

#### Compile `rtrace_dc` and `rtrace_dc_2305` [123]

- In `src/rt/CMakeLists.txt`, uncomment the line `add_definitions(-DDAYSIM)` and build `rtrace`. Rename the resulting `rtrace` program to `rtrace_dc`.
- In `src/rt/CMakeLists.txt`, uncomment the lines `add_definitions(-DDAYSIM)` and `add_definitions(-DDDS)` and build `rtrace`. Rename the resulting `rtrace` program to `rtrace_dc_2305`.

Comment both lines from `src/rt/CMakeLists.txt` before building the other programs.

## 6 Guideline to Danish daylight performance simulation

This guide is developed based on the research and analysis performed in the thesis of how to make annual daylight simulation. The guide highlights which BPS simulation software are available for making CBDM evaluation and created a framework to make uniformity in the industry which is a benchmark of what to include in a CBDM evaluation for early design and to figure out which level of detail and inputs is needed for making acceptable CBDM evaluations.

### 6.1 CBDM evaluation

CBDM evaluations require an understanding of software input, simulation and outputs interpretation. High number of diverse parameter input is needed and established of an advanced framework of input conditions for a CBDM approach in the beginning. During the design process the input goes from experience values to a more refined, fixed and exact input value with narrow uncertainties, variance and fluctuation and the different input importance for simulation accuracy can be investigated based on a sensitive analysis. Sensitivity analyses aimed at understanding how variations in input factors affect CBDM results.

In early design the inputs detail is not that crucial, but the overview of input is more important. Having the same calculation engine from the early to detailed design is more advantageous. The simulation interpretation output in terms of post-processed metrics control the needed inputs. The ability to understand what is happening under the hood allows trading the software to give the wanted output.

### 6.2 BPS-software for CBDM-simulation in Danish context

BPS software for CBDM evaluation play a significant role in the decision-making process for the building design and how the different daylight concepts have a strong impact on the general experience and wellbeing in the building [124]. Table 6.2-1 shows the BPS software that can handle minimum hourly sun positioning by either editing the Daysim header file or calculation directly through radiance command line or through HoneyBee + plugin for grasshopper.

BPS (own engine)	GUI (external engine)	Plug-in:	Computation:
Radiance - DAYSIM	DAYSIM pm	DIVA	Accelerad
	DesignBuilder	Honeybee and HoneyBee +	
	Su2ds		
	SEFAIRA		
	Light Stanza		

Table 6.2-1 9 BPS software can handle minimum of hourly sun positioning and sky subdivision (MF:1).

## 6.3 Different steps in a CBDM evaluation

Guide of different step including in an CBDM evaluation based on the work done by Christoph Reinhart in the book Building Performance Simulation for Design and Operation in chapter 9 Daylight performance predictions [32].

### Before starting:

- Define space type (office, residential building...)
- Define matrix based on the daylight requirements: Spectral Daylight Autonomy.
- General idea of results: Range from 50% to 90% throughout the space
- Schedule of “daylight hour” sunrise to sunset (4380 h) in the year [6] [125]
- Make sure that the simulation program is validated.
- Secured local climate data: Design reference year (DRY) 2001-2010 epw file.

### Export and important aspect of preparing architectural model for daylight simulation:

- Architectural design tools model windows with double/triple glazing as two/three closely spaced parallel surfaces and therefore it is an important to check the converted model before simulating [32].
- Select scale: Single room, building, urban, model (façade component), cell.
- Clean up the model in Revit
  - 1. "Clean up views"; And purge unused; Reduce the model and file size
  - 2. "Clean up elements" that do not relate to the daylight analysis (casework, railings etc.)
  - 3. "Solibri Model CHECK". The model should be as simple as possible in Revit because it will significantly reduce simulation time.
- “room” and “spaces” can be used to take out selected room.
  - “All volume” minus spaces and overlap
  - "Room Bounding Element"; Check or Uncheck.
  - Define all Upper and Lower Boundaries
- Only include the outline of the surrounding "Building geometry"
- Export selected file format (DWG and ACIS Solid).

### 3D model preparing inside daylight simulation software:

- Space dimensions 5cm tolerance. Façade details with a 2cm tolerance.
- Define neighbouring obstruction: Building, trees and ground plane.
- Check wall thicknesses, interior partitions, hanging ceilings, fixed fixtures and furniture
- Make sure building orientation is right
- Make sure all scene components assigned with optical material properties.
- Window modelling: Check if the window is model correct, model one layer of glass without thickness “*daylight simulation programs tend to assign the optical properties of multiple glazing’s to a single surface*” [32][111].

### Simulation setup:

- Setup or check file names (no blank spaces)
- Check if the grid setting of the sensor is correct
- Define sensors orientation: work plane sensor facing up.
- Define simulation parameter about scene complexity (technical user manual)
- Define sky model (CIE, Perez etc.)

### Climate based dynamic lighting simulation

- Input: 1) weather data, 2) Optical material properties 3) Schedule of “daylight hour” 4) 3D model, 5) define sensor points
- Pre-process: Defend which CBDM technique is need 2-phase to 6-phase. If dynamic daylighting systems are using movable blinds, sun tracking systems, electrochromic glazing, etc., use 3- and 5-phase method and Change in external non-coplanar shading 4- and 6-phase method is needed. Accurate direct-sun calculation 2-phase DDS, 5-phase and 6-phase should be used.
- Simulation: predict the model behaviour by coupling the daylight coefficients and climate data and used the chosen time basis and occupancy profile.
- Results: spaces illuminance and luminance with different time series it could be annual, seasonal, daily, etc...
- Post-process: Analysing and plotting the results. The different program can have inbuilt functions or otherwise a text file should be provided to visualise the results in excel or implement the results in the company’s general workflow. Visualise different time series and different matrix can be used to visualise the results such as daylight autonomy, continuous daylight autonomy, useful daylight illuminance, annual light exposure.

Reduce the input uncertainty by collecting more real-world data, when feasible — Independent parametric input distributions.

### 6.3.1 Detailed input (boundary conditions)

Table 6.3-1 show a detailed overview of required input in climate-based daylight model for annual daylight evaluation.

Scene	Element included
Scene geometry	Measurement and thickness
Surrounding landscape significant neighbouring obstructions	Buildings, landscape and vegetation [111]
Ground reflectance	Area in front of windows
Indoor space configurations and furniture, if known	Fixed objects and gurniture
Window	Frames and mullions
Shading devises	Static or dynamic (blinds) [126]
Sensors orientation workplan	Facing up
Building orientation	Rotation of the model (true north)
All assumptions made shall be stated.	

<b>Surface</b>	<b>Surface reflectance value</b>
Deviations permitted with justification	Default values § SBI 272 [6][11]
Ceiling	0,70
Interior walls	0,50
Floor	0,20
Window lighting, inside	0,70 [111]
Window lighting, outside	0,30 [111]
Window frames	0,70
Significant neighbouring obstructions	0,10
Urban neighbourhood	0,20
<b>Roughness and secularity</b>	
<b>Window</b>	<b>Glazing properties</b>
Check window glazing's consisting surfaces	
T <sub>uv</sub> : UV transmission. Ultraviolet radiation	Manufactory data
LT-value: Light transmittance: inside and outside layer	Glasfakta [127]
VT-value: Visual transmittance	Window 6.3 Research Version to model
P <sub>v</sub> -value: Light reflection, outward (LR <sub>ud</sub> )	CFS[128]
R <sub>a</sub> -index: Colour representation index	
G-value: solar heat gain coefficient.	
<b>Grid settings [6]</b>	<b>Value</b>
Spacing -> resolution defined in SBI 272	≤1m [6][5][111][110]
Edge (Excepted from the calculation area)	0,50 m [6][5]
Height above the floor (Dwellings)	0,50 m [6]
Height above the floor (Office)	0,85 m [6][11]
Min/Max ratio	1
<b>Climate data</b>	<b>Data, time, latitude and longitude</b>
Sky model	Approved like CIE/Perez [6]
Sky subdivision <sup>2</sup> . Tregenza and Reinhart	≥MF:1
Sun positions. Reinhart and Walkenhorst	≥MF:4
<b>Space usage</b>	<b>Elements</b>
Space type	Office, school, residential building
Lighting requirements	sDA 300 lux [7][6][5]
The 50% daylight hours (sunrise to sunset)	sunrise to sunset [6] [125]
Time step	≤1 hour
Status of artificial lighting	
Occupancy schedule in times	8 - 17 [129] and 7 - 18 [130]
<b>Weather file</b>	<b>Design reference year, DRY (2001-2010)</b>

Table 6.3-1 Required input (boundary conditions)

<sup>2</sup> For the 'phased' methods only

## 7 Discussion

### 7.1 Verification of results

The Diva4rhino goes through a verification process with three typical room from the SBI Daylight calculation in practices [111] and Diva4Rhino provide similar results compared to Radiance, Daysim and Velux daylight visualiser. Afterwards Diva4Rhino provide a simulation of spatial daylight autonomy where two of the three rooms fulfil the Danish building regulation 2018 requirement for  $sDA_{300\text{lux } 50\%}$ . The verification based on SBI Daylight calculation in practices investigating the deviation between the different programs where the results does not compare towards real measured data [111]. Verification based on comparison with other programs may mislead the calculations accuracy and the direct sun and the climate data are not going through a verification process. Here the report investigated these two areas through the literature and look at the influence of implementing hourly or sub hourly sun positioning which will provide more accurate light penetration into the deep part of the room especially in Danish country in the winter with low altitude sun above the ground. Climate data is a part of the boundary conditions used in simulation tools. In Denmark the climate data is developed base on Design Reference Year (DRY) with is a single year climate data based on multi-year performance with show the most representative month and not extreme conditions. The annual daylight evaluation obtains using these data will not consider extreme conditions. Modelling of solar and illuminance data are significant drivers of building performance simulation and should therefore handling with great care [32].

### 7.2 Most promising method

The Table 4.3-1 below show the different setup categories and different available software and techniques that give the possibility to perform a CBDM evaluation in the Danish building industry. The research illustrate most of the available daylighting tools used ray-tracing engine in the field especially for CBDM evaluation and considered as a state-of-the-art method for annual daylighting evaluation [23][80].

Computation	Calculation engine	Light algorithm	CBDM techniques	GUI	Plug-in	Graphical algorithm editor
CPU	Radiance	Ray tracing	2-phase dds	Daysim	Diva4Rhino	Grasshopper
GPU	Accelerad					
CPU	Radiance		4- & 6phase	Radiance command line		
GPU	Accelerad					
CPU	Radiance					

Table 7.2-1 The most promising available program that fulfil the nice to have criteria

New possibility to Accelerad the radiance engine by using the flexibility of the CPU and the GPU for Parallelism can make an increase speedup in the simulation time for accurate

simulation in detailed design shown in appendix 9.4 Figure 9.4-2. The simulation time is not below the set requirements setup in for early design with is  $< 0,5$  sec [49] for interactive Simulation and  $< 24$  sec for Parametric design. Accelerad have speeding up the computation time by using a GPU with only around 1 % error compared to a CPU calculation [20]. The execution time is influencing by the obtain accuracy of the simulation. Lower accepting model accuracy can obtain a faster execution time in relation to radiance parameter as shown in appendix subchapter 9.5.4 and by different sky and sun simplification and subdivision shown in appendix subchapter 9.4 and an overview of the different CBDM techniques as shown in Table 7.2-2 and appendix 9.4 Figure 9.4-2.

Accelerad computation of the different methods:

Model	Processor	DAYSIM		3-/5-phase			5-phase		
		$D_{dir}$	$D_{dif}$	$D$	$T$	$V$	$D_d$	$V_d$	$C_{ds}$
Small	CPU	39.2	22.9	1.6	0.1	10.3	0.0	2.1	600.3
	1x GPU	8.8	3.9	0.2	0.1	2.3	0.1	0.5	21.1
	2x GPU	5.6	2.8	0.7	0.2	3.3	0.6	0.7	45.2
Medium	CPU	78.0	45.5	1.6	0.1	20.9	0.0	4.1	1219.7
	1x GPU	12.0	6.3	0.2	0.1	6.2	0.1	1.2	85.6
	2x GPU	7.8	4.2	0.7	0.2	6.2	0.6	1.3	73.2
Large	CPU	331.5	177.8	1.7	0.1	111.2	0.0	22.6	6031.0
	1x GPU	142.4	117.0	0.2	0.1	32.5	0.2	5.8	374.9
	2x GPU	84.6	68.2	0.7	0.2	21.3	0.6	4.4	323.9
Blinds	CPU	96.1	42.9	1.6	21.8	10.1	0.0	2.1	623.5
	1x GPU	9.1	4.1	0.2	0.8	2.3	0.1	0.5	21.6
	2x GPU	5.8	2.9	0.7	0.7	3.2	0.6	0.7	47.8

Table 7.2-2 “Matrix calculation times by *rtrace\_dc* and *rcontrib* in minutes” [42].

The aspects including in the simulated is explained in appendix 9.2.1 and subchapter 2.5.2.

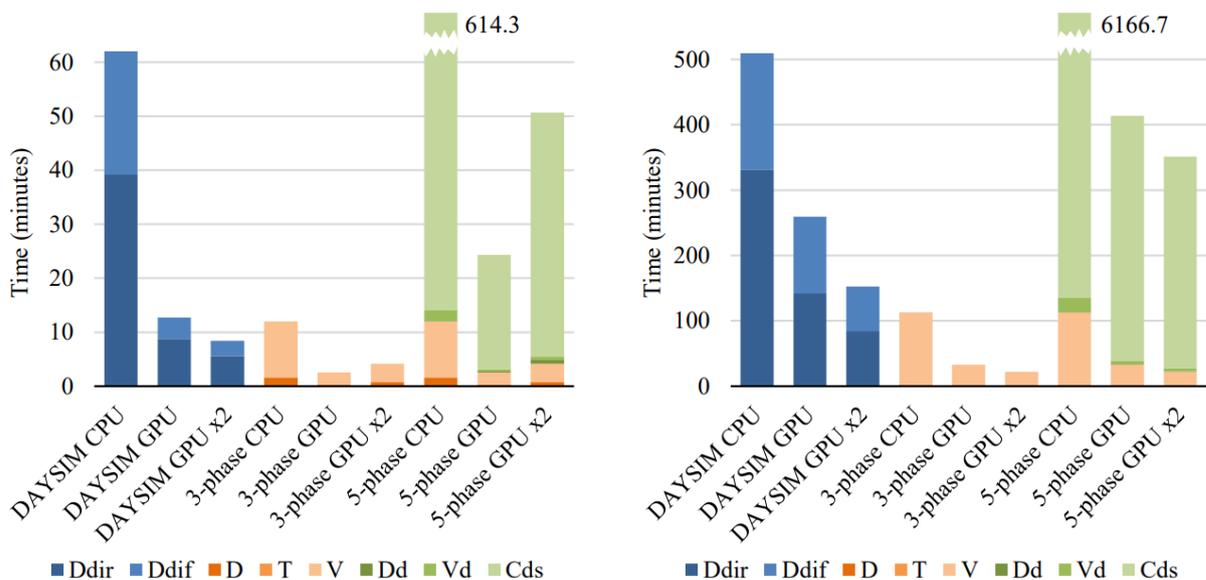


Figure 7.2-1 “Cumulative matrix such as  $sDA_{300,50\%}$  and  $ASE_{1000,250}$  calculation times by *rtrace\_dc* and *rcontrib* for the small model to the left and large model to the right” [42].

Parameter	DAYSIM	3-/5-PM
Ambient accuracy (-aa)	0.05	0
Ambient bounces (-ab)	8	8
Ambient divisions (-ad)	4096	50000
Ambient resolution (-ar)	300	256
Ambient super-samples (-as)	20	0
Direct jitter (-dj)	0	0.9
Direct relays (-dr)	2	3
Direct sampling (-ds)	0.2	0.2
Max. ray reflections (-lr)	6	-10
Minimum ray weight (-lw)	0.001	0.00002
Specular sampling (-ss)	1	1
Specular threshold (-st)	0.15	0.15
Irradiance cache size (-ac)	4096/16384	N/A
<i>GPU only</i>		

Table 7.2-3 "defaults Radiance simulation parameters" used for the simulation in Table 7.2-2 and Figure 9.4-2 [42].

The fastest execution time down to few minutes can be obtain by using the 3-phase method with the default radiance simulation quality parameters show in Table 7.2-3 and by adding low radiance simulation quality parameter even faster execution time can be obtain. By adding multiple GPU, a faster execution time will be obtained. By implementing lower simulation quality and multiple GPU requirement a more rapidly and fairly accuracy simulation can be obtained but as the results are here simulation run with 1 GPU and high simulation quality will not fulfil the Danish construction industry needs for rapidly and accurate annual daylight evaluation in early design.

### 7.3 Most promising method based on the tendency

When looking at the development in the field integration of Radiance concepts with other advanced rendering tools and engines into hybrid approach will give the daylight simulation industry a step forward in the future. Computation of a hybrid photon-mapping approach using GPU Parallelism for global illumination will give a significant improvement in speed and accuracy compared to Radiance ray tracing [131]. EvalDRCTool possibility to evaluate Daylight Redirecting Components (DRC) in architectural spaces with help of radiance lighting software environment [75]. An integration of Accelerad [47][20] with all the CBDM techniques with an available GUI, easy to use plug-in, and a Graphical algorithm editor in Dynamo with all the grasshopper and ladybug facilities will be suitable for the Danish construction building industry. The most promising method based on the tendency in the lighting simulation industry is visualise in the Table 7.3-1 below. A program like Velux daylight visualizer with the ability to make CBDM evaluation would be suitable for the Danish construction industry.

Computation	Calculation engine	Light algorithm	CBDM techniques	GUI	Plug-in	Graphical algorithm editor
CPU flexibility and GPU Parallelism	Accelerad the photo mapping	Photon mapping bi-directional capabilities	2-phase to 6-phases	Like Velux daylight visualize	Honeybee+ capability and Diva4rhino interface	Dynamo direct plugin to Revit

Table 7.3-1 Most promising method based on the tendency in the lighting simulation industry

Development in method for result visualisation here Precomputed Light Transport (PLT) for rendering complex scenes and the afterward present it in real time with dynamically control local light and viewing directions with full indirect illumination [132][23]. There is a high precomputed time for making high accuracy global illumination representation for the real-time rendering which can be reduced significantly in the future. Precomputed light transport in combination with AcceleradRH is a new way to implement virtual reality in daylight simulation to visualise the annual daylight modelling [23][119][133]. Approach for cross industry packages of visualisation tools for qualitative aspects and rendering tools for quantitative aspects could become common in architecture engineering and construction (AEC) building industry [134][23].

## 7.4 Different inclusion descriptions from DS/EN 17037 and BR18

The Danish/European standard 17037 set up requirement of how to preform annual daylight evaluation but problem arise when figuring out that no GUI are suitable for the requirement from the new standard. Before DS/EN 17037 no common framework in the field of how to preform annual daylight evaluation and it can also be seen on the available programs on the marked. Table 7.4-1 show some variation between DS/EN 17037 and BR18.

<b>Simulation inclusion</b>	<b>DS/EN 17037</b>	<b>BR18</b>
<b>Shading</b>	Moveable shading device [5] DS/EN 17037, section B.3.3.	Static shading [6] - SBi 272 § 379, STK.2. Building significant neighbouring obstructions.
<b>Sun and sky</b>	Hourly (or sub-hourly) sky and sun conditions [5] [5], section B.3.3.	
<b>Calculation method</b>	Equalize daylight factor and 300 lux - rule [5], section B.3	Equalize 10pct. - rule & 300 lux - rule and alternative daylight factor [5][6].
<b>Lux recommendation</b>	Minimum, medium and high [5] section A.1	Only minimum target [6][7]. SBi 272 § 379, STK.2
<b>Fraction of space</b>	50% and 95% [5], section A.2	50% [6][7] SBi 272 § 379, STK.2

Table 7.4-1 Different simulation inclusion descriptions from DS/EN 17037 and BR18

In the Danish building regulations, there are no direct requirements for dynamic solar shading, EN 17037 describes that the dynamic solar shading must be included in the calculation. In a Danish context the 5-phase and 6-phase method is not required [6]. However, it will still be an advantage that the program can handle dynamic sun protection. Model of simple geometry with clear glass 2-phase (DDS) is the most preferable method in a Danish context because of its accuracy by handling the direct sun separately and have a high calculation speed by including the calculation of several Daylight Coefficients in a single run by storing all the ray hits in the daylight coefficient itself. This method is still a slow than the 3-phase method but provide higher accuracy.

### 7.4.1 Dynamic solar shading

As previously mention the building regulation do not directly describe that dynamic sun protection must considered for annual daylight simulation. Dynamic solar shading and movable blinds has a great impact on the daylight result. The automatic sun protection will be switched on in many of the hours where the best daylight level can achieve. A climate-based daylight simulation without dynamic sun shading will therefore provide a better result than including the dynamic sun shading. Excluding the dynamic sun shading will not reflect the real daylight conditions in the room and should therefore include if dynamic shading obtained as described in EN 17037.

The dynamic shading control is depending on lux level on the faced. The normal lower limit for radiance values on the façade cloud approximately be set to 150 W/m<sup>2</sup> or approx. 18,000 lux [6] SBi 272 § 378. The dynamic shading should not depend on the inside temperature because of dynamic shading achieve in cloudy weather during the occupied hour.

Indoor climate classes	Minimum	Medium	Maximum
Dynamic solar shading in percentage of occupancy.			
Percentage of occupancy with achieve dynamic shading	30%	20%	12%

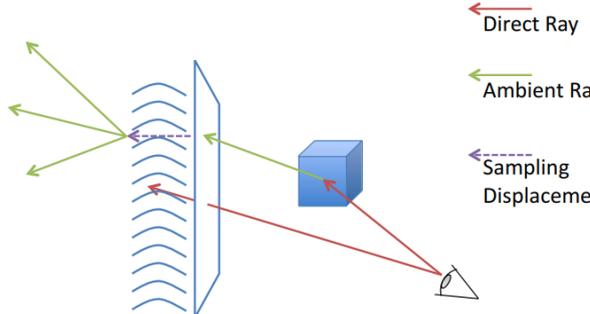
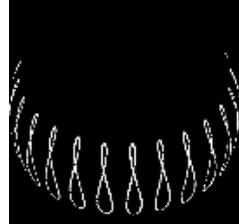
Table 7.4-2 show requirements specifications for indoor climate classes for residential buildings and non-residential building for dimensioning conditions [130][126].

Table 7.4-3 show an overview of the different CBDM techniques and the different dynamic possibilities including in the different phase methods.

CBDM techniques	Dynamic scene CFS: Blinds, multiple glazing, change in interior and change in context	Change in external non-coplanar shading	Accurate direct-sun calculation
4-components	Partially tested		
2-phase			
2-phase DDS			✓
3-phase	CFS description with a BSDF Klem's basis (.xml)		
4-phase		✓	
5-phase	CFS description with a BSDF Tensor Tree (.xml)		✓
6-phase		✓	✓

Table 7.4-3 CBDM Techniques and possibility for different parameter simulation

Figure 7.4-1 Figure 7.4-2 and Figure 7.4-3 illustrate the different element in Table 7.4-3.

<p>Dynamic scene CFS: Blinds, multiple glazing, change in interior and change in context</p>	<p>Change in external non-coplanar shading</p>	<p>Accurate direct-sun calculation</p>
 <p>With geometry</p> <p>Figure 7.4-1 Dynamic scene CFS: Blinds [72]</p>	 <p>Figure 7.4-2 photograph of a dynamic external non-coplanar shading [135]</p>	 <p>Accurate analemma for each hour of the year</p> <p>Figure 7.4-3 A More Accurate Approach for Calculating Illuminance with Daylight Coefficients [51] [77]</p>

## 7.5 Parametric design

Parametric design used for decision support and guide in the different design phase and include parameters studies, sensitivity analyses and many calculations. Different kind of parameters variation with an easy way to change the input file and call the program to automate the process. Used sensitivity analysis to see the input variation and design span. Here HoneyBee+ is suitable as a GUI for linking the parametric interface in Grasshopper with the modelling interface in Rhino to a simulation engine like Radiance. The simulation runtime for parametric studies typically spans a few hours to several weeks [51]. Figure 7.5-1 show design explorer used for data visualisation and incorporate filtering algorithms based on statistical analysis into a single graphical interface for large visualisation volume of results [51]. Table 7.5-1 show the different investigation areas for parameter variation.

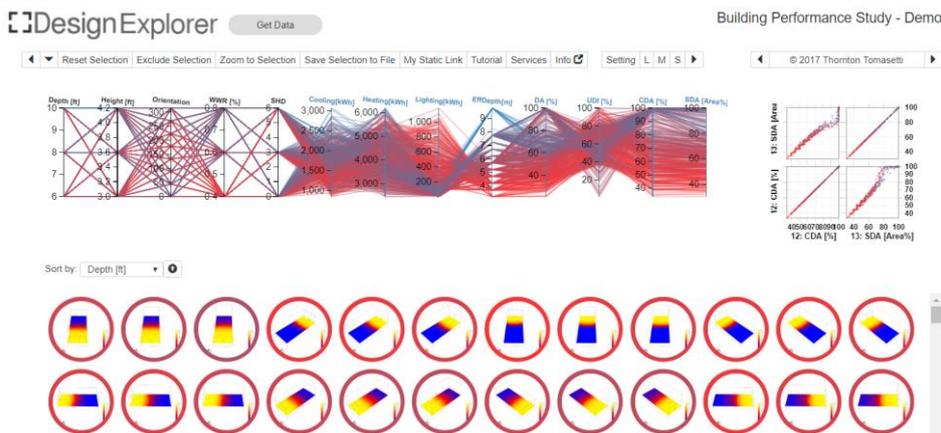


Figure 7.5-1 Design explorer [136]

Room size: Height & depth	Cooling [kWh]	Heat [kWh]	Eclectic Light [kWh]
Window to wall conditions	Orientation	Shadow Unit	UDI [%] overheating
Window still height	sDA [area%] Well-lit	ASE [%] area with high percent change of glare.	

Table 7.5-1 Different investigation areas for parameter variation

## 8 Conclusion

### 8.1 Conclusion

This paper investigated the Danish building industry needs in the early design and useful information and development regard climate-based daylight modelling (CBDM). This report showed a comprehensive review of daylight design tools for annual daylight evaluation found through state-of-the-art literature review. Forty-five tools compared to five different categories which includes simulation engine, computation, Graphic User Interface (GUI), plug-in and graphic algorithm editor which is developed based on various aspects involved in a daylight design tool. The five different categories are setup based on various weighted aspects in a daylight design tool.

This paper found that not only one program will be suitable for the Danish building industry but as the programs are out, different combinations from programs will suit the various complexities, objects involved and design phases. For compliance check in the Danish building regulation recommendation goes to following combination of programs Table 8.1-1, this combination of programs does not fulfil the Danish construction industry needs in early design.

Computation	Calculation engine	Light algorithm	CBDM techniques	GUI	Plug-in	Graphical algorithm editor
CPU	Radiance	Ray tracing	2-phase dds	Daysim	Diva4Rhino	Grasshopper
GPU	Accelerad		2-phase dds & 5-phase	Daysim	Honeybee+	Grasshopper
CPU	Radiance			4- & 6phase	Radiance command line	
GPU	Accelerad					
CPU	Radiance					

Table 8.1-1 Combination of program for compliance check in the Danish construction industry.

The state-of-the-art CBDM techniques used for annual daylight evaluation show a deviation up to 39% from the Benchmark CBDM techniques in calculation ASE and a metrics that include direct and diffuse illuminance provide more robust result of  $\pm 15\%$  within the benchmark.

A verification of combination of program based on SBi daylight calculation in practices and after that an annual daylight evaluation and three typical room where testing to see if they fulfil the Danish building regulation requirement and two out of three fulfil the 300lux-rule through Diva4Rhino. Based annual daylight evaluation and literature review a guide made of how to make CBDM evaluation.

In lake of available of program solution this paper found the best suitable, fictive combination as shown in Table 8.1-2. Velux daylight visualiser have a reasonable GUI but is not available for annual daylight simulations. The photon mapping as a light algorithm is better suitable for annual daylight evaluation than the ray tracing algorithm in term of speed and accuracy. Setup the simulation interface with a direct plugin into Revit via Dynamo could solve the

interoperability problem between BPS software and architectural geometrical tool with a plugin with Honeybee+ capability and Diva4Rhino easy interface. The program in combination should CPU flexibility and GPU Parallelism when simulation all the CBDM techniques.

Computation	Calculation engine	Light algorithm	CBDM techniques	GUI	Plug-in	Graphical algorithm editor
CPU flexibility and GPU Parallelism	Accelerad including photo mapping	Photon mapping bi-directional capabilities	2-phase to 6-phases	Like Velux day-light visualize	Honeybee+ capability and Diva4Rhino interface	Dynamo direct plugin to Revit

*Table 8.1-2 Most promising method based on the tendency in the lighting simulation industry*

To conclude no simple solution was found to solve the CBDM simulation in early design in the Danish building construction industry given none of the programs fulfil the need to rapidly and accurately determined. The most promising available program a combination of: Accelerad, Radiance, Daysim and Diva4Rhino and then wait for the future development of new better programs.

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## 9 Appendices

### 9.1 Appendix: Interview with Steffen from MOE

#### MOE and the Danish Building industry

Where are MOE and Danish consulting industry going and what is the development in lighting industry in Denmark? How do you think the industry sees it?

Everything indicates that the industry is moving towards climate-based approach. The next building regulations or perhaps the one after that, will be clarified that for non-residential buildings a 300-lux method must be used. It will be completely like calculating the thermal comfort. There is a simplified regulation for residential buildings 10% rule and non-residential buildings must use the climate-based 300-lux rule. Sweco, Rambøll and Cowi asked what method they would like to advise on, and they would like to use climate-based calculation.

#### Building regulations and certification

The 10% method goes in the same direction as the 300-lux method. 10% rule will be changed to be more comparable with the 300-lux rule in the next building regulations. Discussing at the overall level goes that residential buildings and multi-storey residential buildings will be under 10% rule -> presumably or hopefully corrected in the future. Non-residential buildings; Offices, institutions and schools must use the 300-lux rule. New Danish building regulation 2018 (BR18), BR18 voluntary building class, DGNB-DK form DK-GBC and European standard indicate that the development is moving towards climate-based approach [14][15][16][11], both from a European side, but also from the Danish side.

#### MOE and Automation of standard activities

MOE has tried to implement a solution for automate the 10% rule in the Danish industry. The same desire is about 300 lux rules, to be at the forefront and making it easier, but at the same time delivering that quality and reliably results. To see how to make it smarter than our competitors would be interesting to investigate.

#### VR game engine

Can be a way to solve one a problem of how to illustrate different daylight solutions for the customers. It is complex to illustrate and without illustration the client must rely on that advisor when he, for example, says that 300-lux is good enough daylight. If the client could enter the model and visualise daylight more smartly and intelligently. Then it doesn't have to be 100% right.

#### Calculation method and geometrically preparation

The method must be faster, more intelligent and more integrated with all our tools. The claim is that it is difficult to calculate without it costing a lot of time and computational forces. It can be resolved and considered today, but the problem is that it is heavy. The handling

method and the export from Revit is heavy. It is cumbersome and very often ends up that you cannot use the model anyway. Here modelling in Rhino or SketchUp are interesting. The daylight simulation tools MOE uses in Aarhus are Rhino, DaySim and grasshoppers. Copenhagen uses the DIVA for Rhino. Generally, it's not just something you do, get started and then give the client advises around.

### **Summary:**

Two main topics: one was to calculate daylight levels and the other one is to visualise daylight in VR. These are two very different projects. Unrealistic to visualise daylight in VR in 4 months. The calculation part can better work because of my background study.

Within the calculation section there are two options:

- A simple calculation in the design phase to guide how to make the best daylight design.
- A more advantage calculation in the end to document the daylight conditions.

The easiest, best and most interesting project will be to start simple with the simple calculation.

### **Integrated in the architect's modelling tool**

Revit integration instead of being exported. How does the information in Spaces enter a simulation model? How to construct the scene and then simulate on it? MOE has not investigated how to transform the models a lot. It will make it so much simpler when modelling and if updates is needed. Important with a thorough study of what is available now. You could start with Revit and Dynamo script. The boys behind Ladybug and Honeybee have made a Dynamo plugin calculation, but it is not certain that there is a connection to DaySim, which is Radiance based. Then you should do something that could transform it out and then connect it with a simple calculation core such as BSim or something else. BIM and data transfer project which could be carried out inside big companies.

## 9.2 Appendix: Theoretical background

### 9.2.1 Radiance CBDM techniques

#### 9.2.1.1 4-component method (rtrace)

Calculated light contribution at each time-step independently and are used for point in time simulation. 4-component method is the slowest of the CBDM techniques but also used as a benchmark because of its accuracy. 4-component method divided the light as a source into four components which are direct- and indirect sunlight, direct- and indirect skylight. Three daylight coefficients are calculated for the direct sunlight calculation, the direct skylight and the indirect sun and skylight together. Used the Radiance command `rtrace` for collect the contribution of each of the daylight components traded by simulation algorithm based on a mixed of random (stochastic or Monte-Carlo) in radiance using hemispherical sampling and deterministic backward raytracing approach [137]. A deterministic method calculation for the direct concentrated contribution such as the sun and hemispherical sampling calculation for the skylight or any reflected light coming from any direction[138]. Radiance's computing engine defined the light from the deterministic sampling as a light material assigned and hemispherical sampling as a glow material assigned.

**Direct sunlight** calculation sending a single sample ray towards the sun, and if it arrives unobstructed, the deterministic simulation algorithm of the direct sunlight is used, with calculate the total solar contribution based on the sun's known size, positioning and luminosity contribution [28]. Sun positionings are 2056 or 5035 equivalents to fixed hourly or half-hour time steps of the sun as earlier described. This simplification why to calculate the sun give only problem when the sun is partially occluded (solar shadow region).

**Indirect sunlight** is the circular patch nearest to the sun positioning and represent as the reflected or diffuse component of sunlight. A deterministic simulation algorithm used among the 145 patches which cover the entire sky [28].

**Direct skylight** is light from the sky that comes directly into the room treated by a deterministic simulation algorithm. Nine hundred rectangular patches of light source placed over each of the 145 patches that cover the whole hemisphere [28].

**Indirect skylight** is reflected light from sky and is at least reflected from one surface of the scene before sensor point is reach. Hemispherical simulation algorithm is used to calculate the contribution which comes from 145 circular patches [28].

### 9.2.1.2 DAYSIM (Rtrace\_dc)

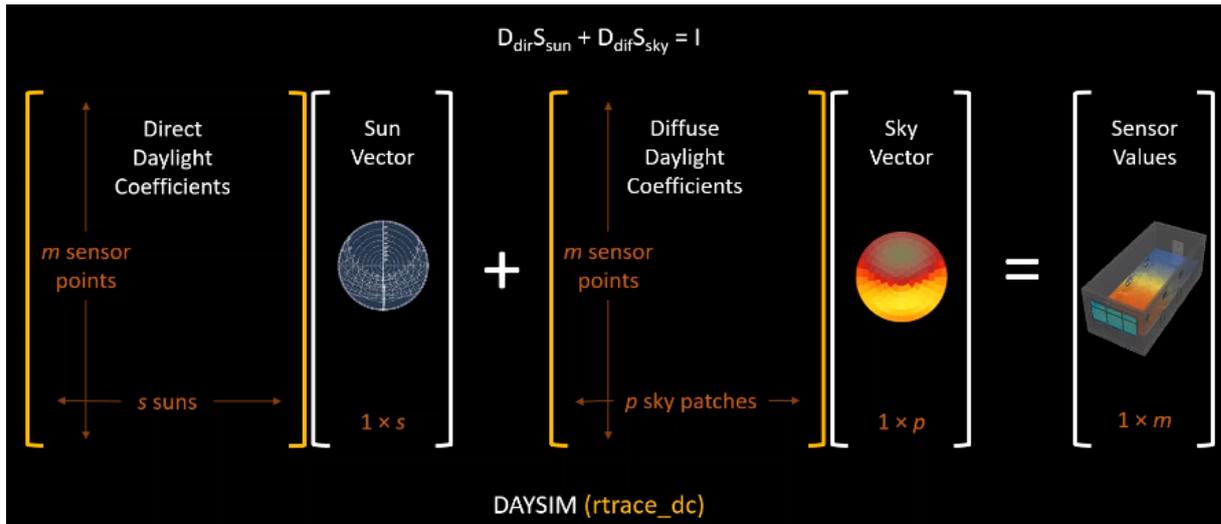


Figure 9.2-1 Daysim (rtrace\_dc) calculation illustration [20]

Daysim is a modified version of 4-component method to make climate based simulation that also used radiance backward ray-tracer and allows the calculation of several Daylight Coefficients approach with the Perez all weather sky model in a single run by storing all the ray hits in the daylight coefficient itself [18][139]. DAYSIM calculated separate for the direct and diffuse component. The first introduced Daysim version all the daylight coefficients include 145 sky subdivision, three diffuse ground and up to 65 direct daylight coefficients. The main different from the 4-component method is a simplifying assumption relates to the position of the sun and the number of solar discs. Only 65 sun location-specific over the solar path for the entire year as shown in Figure 9.2-2.

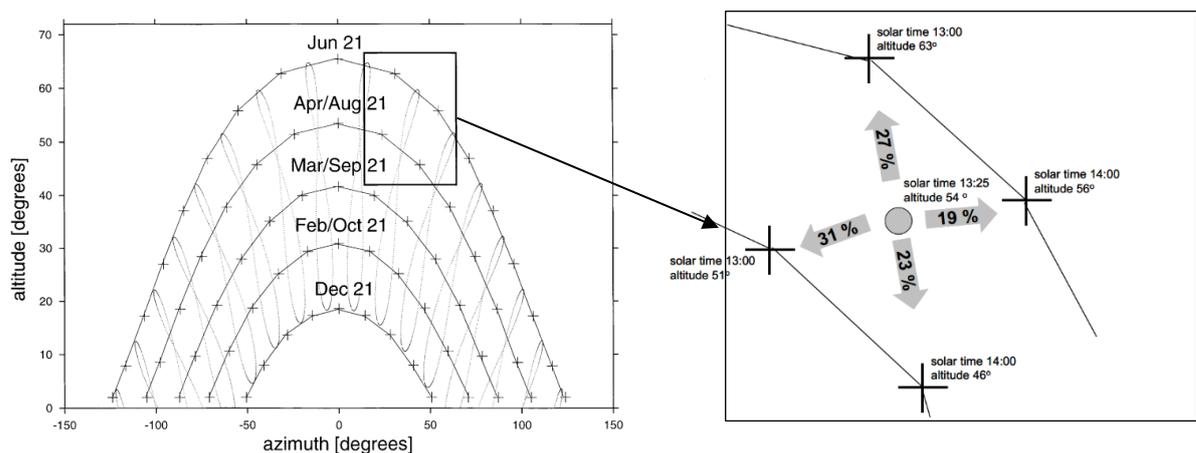


Figure 9.2-2 The actual hourly positioning of the sun is illustrated by dots mark in the background and Daysim 65 locations sun positioning is highlighted by crosses. The box illustrates the positioning of the sun and how the sun assigned to the four surrounding crosses near the sun [117].

Only in the Daysim research version there is a choice between 3 ways to assign the sun to the nearest crosses; Nearest Neighbour, Interpolation and Shadow test.

**Nearest Neighbour** the full sun luminance is assigned to the closest crosses. The sun area extension with same average which will cause errors in form of higher intern luminance from the direct sunlight contribution.

**Interpolation** algorithm redistributed the sun luminance on the closest crosses proportionally to their distance. The sun area extension and smaller average luminance will cause errors in form of lower intern luminance the direct sunlight contribution.

**Shadow test** for point in time simulation consider only the actual sun position that can ‘see’ the interior of the room and assigned the sun to those points only, proportional to their distance. Give more precise results but requires a longer calculation time and only recommended for glare study.

In 2008 a model on top of DAYSIM was proposed called DAYSIM\_DDS (Dynamic Daylight Simulation) [67]. This model calculation method calculation 145 diffuse sky segments, one diffuse ground segment, 145 indirect solar positions separately and have an increased direct solar positions to 2305 [28]. Inter model comparison of the two method the Daysim DDS sky division scheme achieved more accurate result. Figure 9.2-1 explain the Daysim calculate.

In 2017 Improved daylight coefficient where the

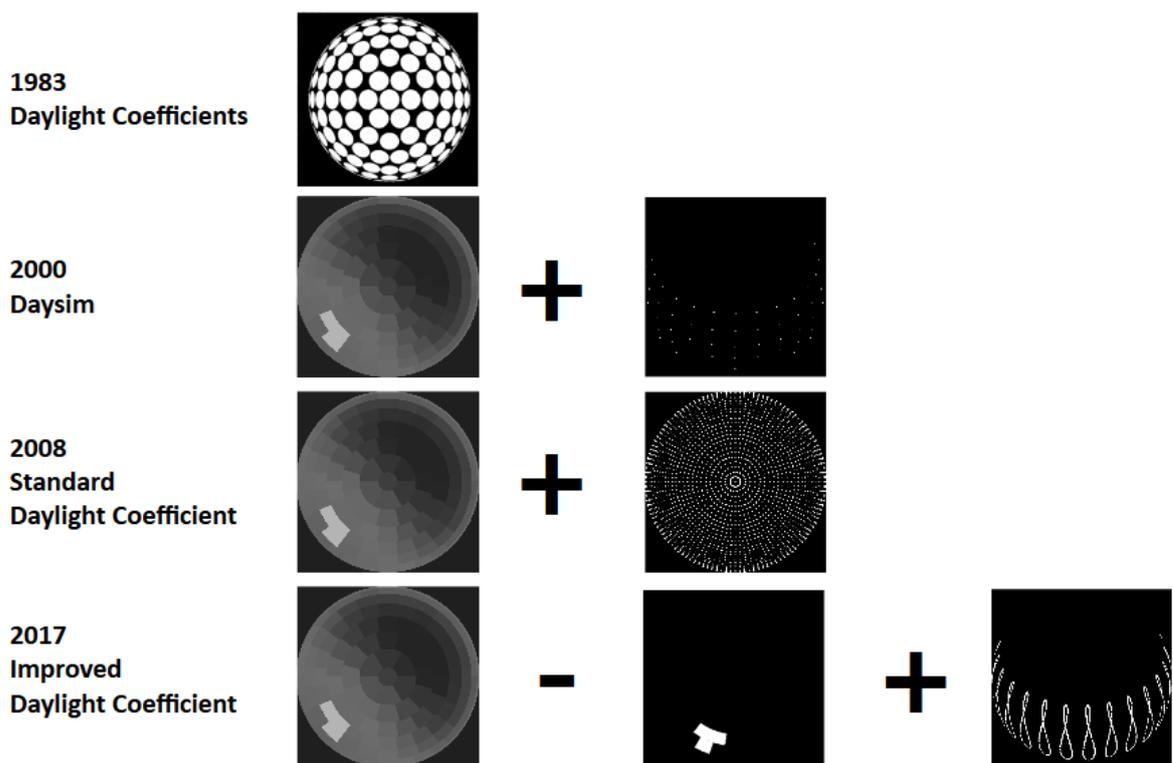


Figure 9.2-3 Daylight Coefficients development [66][77][140][141].

### 9.2.1.3 2-phase method (rtcontrib/rcontrib)

2-phase method also called 1-phase method is significantly quicker and least documented method of all the CBDM techniques [72]. The sun and the sky contributions putting together

rather and calculated by the stochastic sampling strategy. The sun assigned to the three nearest surrounding patches which causing a “smearing” effect because energy disperses at the window transmission and the luminous variance in the sky is so high which also lead to significant errors. The direct component sensitive calculations are not recommended. Tregenza’s and Reinhart sky subdivisions used MF:1 - 4 and typically Perez All-Weather model with gendaymtx command used or CIE skies (gensky) or Perez skies (gendaylit). When comparing the different CBDM techniques on different matrix. Spatial Daylight Autonomy (sDA), useful daylight illuminance (UDI) and Total Annual Illumination (TAI) the different CBDM techniques have good agreement but Annual sunlight Exposure (ASE) consistently higher [28].

### 9.2.1.4 3-Phase Method (rcontrib)

The Direct 3-Phase method is similar to 2-Phase method by adding an extra future of modeling Complex Fenestration Systems (CFS) with BSDF material option based on Klems basis BSDF description [93][142]. Subdivision of the BSDF in 145 patches. Considerable spread of the direct sunlight contribution. ASE consequently much higher than expected.

3-Phase Method use two separate raytracing processes, one for the indoor scene (view matrix to transmission matrix) and one for outdoor scene (transmission matrix to the daylight matrix), to not led the CFS slow Radiance to much down [28]. Figure 9.2-4 explain the 3-phase a calculate.

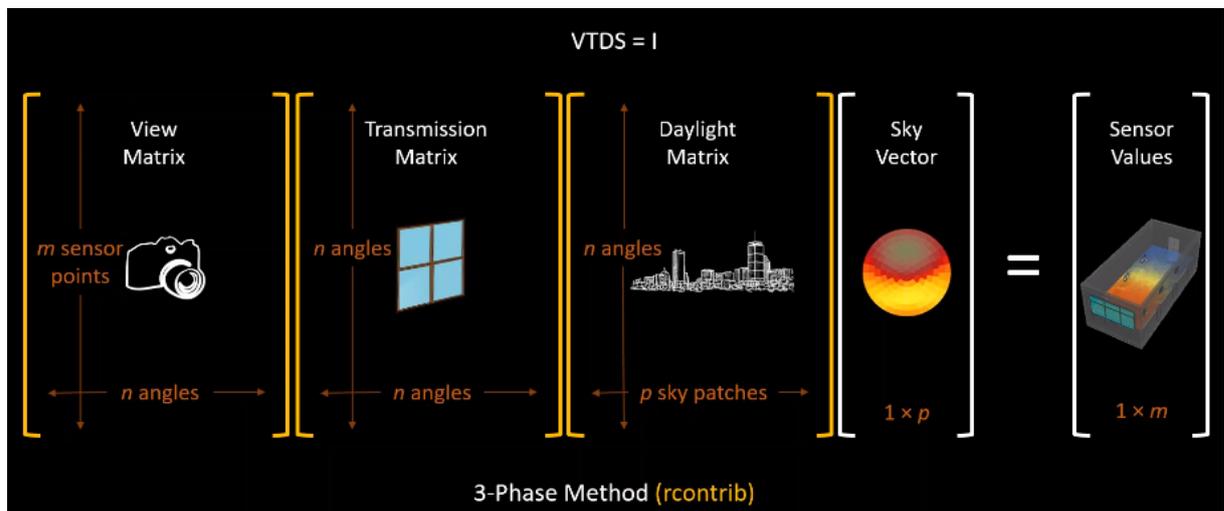


Figure 9.2-4 3-phase Method (rcontrib) calculation illustration [20]

### 9.2.1.5 5-Phase Method (rcontrib)

The Direct 5-Phase method is like 3-Phase method but stand out by adding greater accuracy by calculating the direct sunlight separately using the 2305 or 5185 sun-like hourly or half

hourly positioning using the deterministic algorithm [72][99]. Figure 9.2-5 explain the 5-phase a calculate.

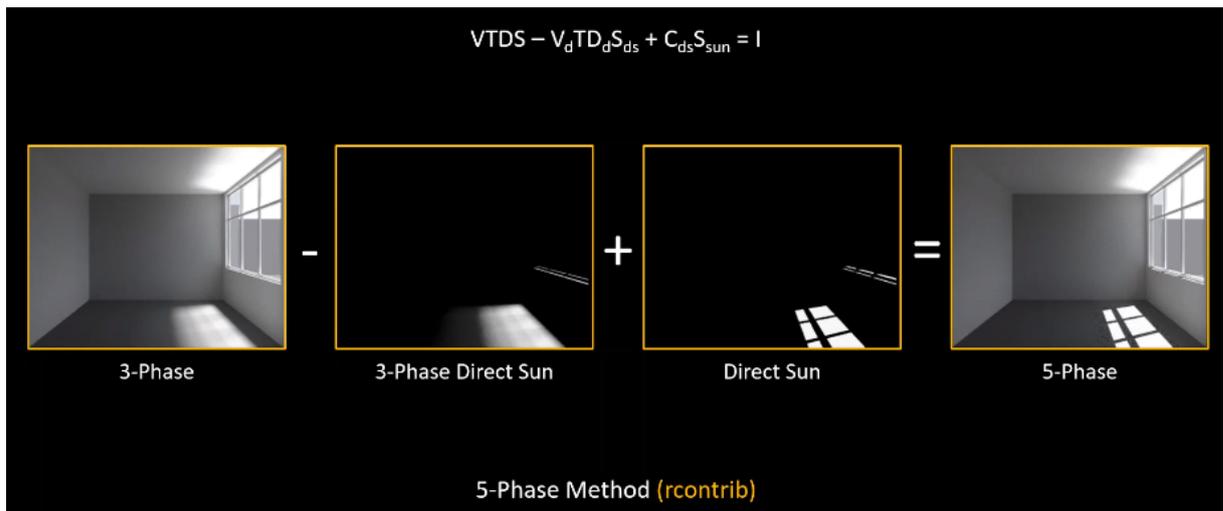


Figure 9.2-5 5-Phase Method calculation illustration [20]

The CBDM techniques have an significant influence on the simulation accuracy [28].

#### 9.2.1.6 4- and 6-Phase Method (rcontrib)

Addition to the existing Radiance techniques for model extra external shading systems and extension to the 3-Phase and the 5-Phase method but remarkably different in procedure and applications. It is possible to make a refinement of the sun and sky By add additional matrices as shown in Figure 2.3-3 and Figure 2.3-4.

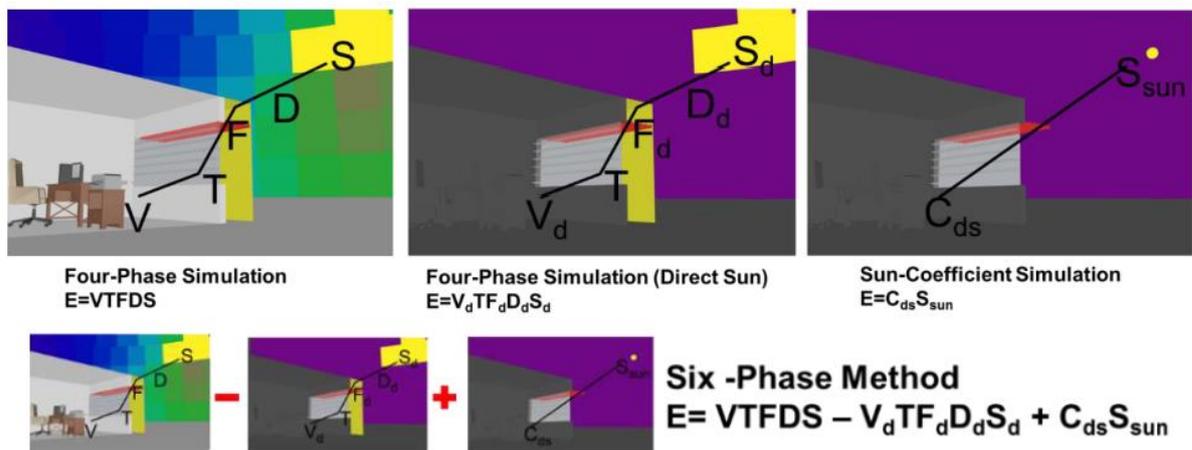


Figure 9.2-6 Illustration of the 6-Phase method which is a development of the 4-phase method with calculation of the direct-sun component separately like 5-phases [51].

### **9.3 Appendix: Investigation of the most promising methods**

This appendix illustrated the background information for investigation of the most promising method. The different table in this appendix are used to figure out with of the BPS software can be used in the Danish building construction industry.

### 9.3.1 Appendix: Basis software requirements from DS/EN 17037 and BR18

Software/index		Daylighting																			
		Radiance - classic	Radiance - DAYSIM	Radiance - Photon map	DIVA (Rhino)	DAYSIM pm*	SPOT	Relux	Accelerad	Geronimo	DIAL+ Suite	Su2ds	Light Stanza	Light studio	Rayfront	Lighting analysis for Revit	Daylight Visualizer	AGi32	ElumTools	Lightsolve	LightUpAnalysis
Regulation	Import of climate file (e.g. .EPW file)	√	√	√	√	√	√	√	√			√	√	√	()			√		√	
	Output text file: 50% “daylight hours”	√	√	√	√	√	√	√	√			√	√	√	√					√	
	Adjustable calculation grid size	√	√	√	√	√	√	√	√		√	√	√	√	√	(√)	√	√	(√)		√
	Adjustable surfaces reflection	√	√	√	√	√	√	√	√	(√)	√	√	√	√	√	√	√	√	√		√

Table 9.3-1 Basic software requirement for verification of daylight provision from DS/EN 17037 and BR18

Software/index		Daylight and whole building energy										Daylighting			
		TAS Engineering	OpenStudio	Sefaira	DesignBuilder	IES-VE	BSim SimLight	HoneyBee	IDA ICE	ODS Studio	DIALux (4, evo)	ecoBIM (TAS Engineering)	Ocean	BIM IQ	
Regulation	Import of climate file (e.g. .EPW file)	()	√	√	√	√	√	√	√	√					
	Output text file: 50% “daylight hours”	√	√	√	√	√	√	√	√	√					
	Adjustable calculation grid size	√	√	√	√	√	√	√	√	√	√	√	()	()	
	Adjustable surfaces reflection	√	√	√	√	√	√	√	√	√	√	√	√	√	

Table 9.3-2 Basic software requirement for verification of daylight provision from DS/EN 17037 and BR18

### 9.3.2 Appendix: Different software's CBDM techniques

		Daylighting simulation software																
		Radiance - classic	Radiance - DAYSIM	Radiance - Photon map	DIVA (Rhino)	DAYSIM pm	SPOT	Relux	Accelerad	Geromimo	DIAL+ Suite	Su2ds	Light Stanza	Light studio	Rayfront	Revit Lighting analysis	Daylight Visualizer	AGi32
<i>(✓) edited the .hea files</i>																		
<b>Method</b>																		
<b>CBDM Technik</b>	® 2-phase	✓																
	® 2-phase* (Daysim)	✓	✓		✓	✓					✓							
	® 2-phase (DDS)	✓	(✓)		(✓)	(✓)				(✓)		(✓)						
	® 3-phase	✓								✓			✓					
	® 5-phase	✓								✓			✓					
	Other ® Technik			✓			✓	✓		✓	✓				✓			
	Other non-® Technik													✓		✓	✓	✓

Table 9.3-3 Overview of the different software's CBDM techniques

		Daylighting and whole building energy software								Daylighting simulation software							
		TAS Engineer-	OpenStudio	Sefaira	DesignBuilder	IES-VE ® * »	BSim SimLight	HoneyBee	IDA ICE ®	ODS Studio	ElumTools	Lightsolve	LightUpAnalysis	DIALux (4, evo)	ecoBIM	Ocean	BIM IQ
<i>(✓) edited the .hea files</i>																	
<b>Method</b>																	
<b>CBDM Technik</b>	® 2-phase					✓											
	® 2-phase* (Daysim)			✓	✓			✓					✓				
	® 2-phase (DDS)			(✓)	(✓)			(✓)					(✓)				
	® 3-phase Method	✓	✓					✓	✓								
	® 5-phase Method							✓									
	Other ® Technik									✓				✓			
	Other non-® Technik						✓				✓		✓		✓	✓	✓

Table 9.3-4 Overview of the different software's CBDM techniques

### 9.3.3 Appendix: Nebojsa Jakica table overview

Daylight & whole building energy

		TAS Engineering	OpenStudio	Selara	besonbuilder	IES-VE	BSim-4	Honeybee	ODS Studio
light sources	natural - sun and sky (CIE/Perez)	✓	✓	✓	✓	✓	✓	✓	✓
	natural - sun and sky (Preenham)	○	○	○	○	○	○	○	○
	natural - sun and sky (Hosok-Wilkie)	○	○	○	○	○	○	○	○
image-based (HDR) lighting	artificial - IES/EULUMDAT (luminaires)	○	○	○	○	○	○	○	○
	solid (NURBS)	○	○	○	○	○	○	○	○
geometry	polygon mesh	○	○	○	○	○	○	○	○
	rendering/visualisation	○	○	○	○	○	○	○	○
simulations/ analyses	photometric (illum.-lum.)	○	○	○	○	○	○	○	○
	radiometric (irrad.-rad.)	○	○	○	○	○	○	○	○
	colorimetric	○	○	○	○	○	○	○	○
	human vision	○	○	○	○	○	○	○	○
	daylighting (climate-based/annual)	○	○	○	○	○	○	○	○
	daylighting (point-in-time)	○	○	○	○	○	○	○	○
	green certification report (LEED, etc.)	○	○	○	○	○	○	○	○
	BAPV/roof-mounted PV energy yield	○	○	○	○	○	○	○	○
	BIPV energy yield	○	○	○	○	○	○	○	○
	whole building energy	○	○	○	○	○	○	○	○
	glare	○	○	○	○	○	○	○	○
	lighting cost/LCC	○	○	○	○	○	○	○	○
	floating point images output	○	○	○	○	○	○	○	○
	accuracy of calculation	unbiased (physically-based)	○	○	○	○	○	○	○
biased		○	○	○	○	○	○	○	○
radiosity	radiosity	○	○	○	○	○	○	○	○
	forward (from light source)	○	○	○	○	○	○	○	○
	backward (from camera, sensor)	○	○	○	○	○	○	○	○
raytracing	bi-directional	○	○	○	○	○	○	○	○
	ray paths preview	○	○	○	○	○	○	○	○
	hybrid calculation	○	○	○	○	○	○	○	○
light spectrum	radiosity+raytracing	○	○	○	○	○	○	○	○
	rasterization+raytracing	○	○	○	○	○	○	○	○
BxDF	visible - RGB	○	○	○	○	○	○	○	○
	visible - spectral	○	○	○	○	○	○	○	○
	UV-VIS-IR - spectral	○	○	○	○	○	○	○	○
scale	polarisation	○	○	○	○	○	○	○	○
	BxDF (.xml)	○	○	○	○	○	○	○	○
	Material Definition Language	○	○	○	○	○	○	○	○
design phase	custom material BRDF	○	○	○	○	○	○	○	○
	basic materials BRDF	○	○	○	○	○	○	○	○
	urban	○	○	○	○	○	○	○	○
	building	○	○	○	○	○	○	○	○
design workflow	single room	○	○	○	○	○	○	○	○
	module (facade component)	○	○	○	○	○	○	○	○
	cell	○	○	○	○	○	○	○	○
	conceptual/early phase	○	○	○	○	○	○	○	○
computation	schematic	○	○	○	○	○	○	○	○
	design development	○	○	○	○	○	○	○	○
	real-time simulation/progressive	○	○	○	○	○	○	○	○
	multiple solutions comparison	○	○	○	○	○	○	○	○
system	integrated optimisation	○	○	○	○	○	○	○	○
	parametric design (node based)	○	○	○	○	○	○	○	○
	CPU based	○	○	○	○	○	○	○	○
	GPU based	○	○	○	○	○	○	○	○
system	multi-threading	○	○	○	○	○	○	○	○
	local network (multi-node)	○	○	○	○	○	○	○	○
	web/cloud	○	○	○	○	○	○	○	○
	graphical user-interface	○	○	○	○	○	○	○	○
system	open-source	○	○	○	○	○	○	○	○
	Windows	○	○	○	○	○	○	○	○
	Mac OSX	○	○	○	○	○	○	○	○
	UNIX (Linux)	○	○	○	○	○	○	○	○

Table 9.3-5 Priority criteria for the 13 daylighting and whole building energy products 1 part [23].

		TAS Engineering	OpenStudio	Sefira	DesignBuilder	IES-VE	Bism4d	Honeybee	COSS Studio
integration CAAD	AutoCAD								
	FreeCAD								
integration BIM	Revit			☑	☑				
	ARCHICAD								
	Vectorworks Architect					☑			
	ALLPLAN ARCHITECTURE								
	Microstation (Parasolid)								
	AECOsim Building Designer							☑	
	Digital Project								
	Trelligence Affinity					☑			
	Edificius								
	Caddie								
	DDS-CAD								
	BrisCAD								
	ZWCAD Architecture								
	TurboCAD								
	Architect3D								
Envisioneer									
ArchITeCH.PC									
integration CAD/CAM	Rhinoceros 3D							☑	
	Alias								
	Inventor								
	CATIA								
	Solidworks								
	Inspire								
	Evolve								
	Creo								
	Creo Parametric/Pro/ENGINEER								
	Siemens NX (Parasolid)								
	Solid Edge (Parasolid)								
	TopSolid (Parasolid)								
	SpaceClaim								
IronCAD									
Geomagic Design									
KOMPAS-3D									
integration general 3D	SketchUp	☑	☑	☑	☑				
	FormIt 360/Pro								
	3Ds max								
	Maya								
	Lightwave								
	Cinema 4D								
	Blender							☑	
	Poser								
	Camara								
	DAZ Studio								
	Houdini								
MODO									
formZ									
Bonzai3D									
integration general	stand alone	☑	☑	☑	☑	☑	☑	☑	☑
	3D plugin	☑	☑	☑	☑	☑	☑	☑	☑
	CAAD/BIM integrated plugin (online/cloud/app) web based	☑	☑	☑	☑	☑	☑	☑	☑
interoperability	live link - dynamic data exchange	☑	☑	☑	☑	☑	☑	☑	☑
	CAD Interop. (fbx, dwg, sat, obj, IGES)	☑	☑	☑	☑	☑	☑	☑	☑
	BIM interoperability (gbXML, IFC)	☑	☑	☑	☑	☑	☑	☑	☑
pricing	freeware	☑	☑	☑	☑	☑	☑	☑	☑
	free for educational/non-commercial	☑	☑	☑	☑	☑	☑	☑	☑
	educational/student discount	☑	☑	☑	☑	☑	☑	☑	☑
	payware	○	☑	☑	☑	☑	☑	☑	☑
	flexible payment (subscription)	☑	☑	☑	☑	☑	☑	☑	☑
validation	validated (DIE 171:2006)	☑	☑	☑	☑	☑	☑	☑	

Table 9.3-6 Priority criteria for the 13 daylighting and whole building energy products 2 part [23].

		▼ Radiance	▼ DAYSIM	■ A360	▼ Nvidia Optix	▼ Nvidia IRay/Optix	☆ PHANIE	▲ EnergyPlus	▲ OpenStudio	□ DOE	● standard feature	⊕ tweaking possible	○ data not provided	⊘ not supported												
		Dansk content		Knock out	Nice to have	Not needed																				
		Radiance - classic	Radiance - DAYSIM	Radiance - photon map	Dive	DAYSIMpm	IDA ICE	SPOT	ReluxSuite / Pro	Accelerated	Geronteo	DIAL + Suite	SUZUS	LightStanza	Light Studio	Rayfront	Lighting Analysis for Revit	VELUX Daylight Visualizer	AG32	ElumTools	Lightsolve	LightUpAnalytics	DIALux (4, eva)	ecobIM (TAS Engineering)	Ocean	BIM IQ
light sources	natural - sun and sky (CIE/Perez)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	natural - sun and sky (Preenham)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	natural - sun and sky (Hosek-Wilkie)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	image-based (HDR) lighting	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	artificial - IES/EULUMDAT (luminaires)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
geometry	solid (NURBS)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	polygon mesh	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
simulations/ analyses	rendering/visualisation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	photometric (illum.-lum.)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	radiometric (irrad.-rad.)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	colorimetric	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	human vision	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	daylighting (climate-based/annual)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	daylighting (point-in-time)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	green certification report (LEED, etc.)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	BAPV/roof-mounted PV energy yield	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	BIPV energy yield	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	whole building energy	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	glare	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	lighting	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	cost/LCC	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
floating point images output	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
accuracy of calculation	unbiased (physically-based)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	biased	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
radiosity	radiosity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
raytracing	forward (from light source)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	backward (from camera, sensor)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	bi-directional	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	ray paths preview	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
hybrid calculation	radiosity+raytracing	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	rasterization+raytracing	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
light spectrum	visible - RGB	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	visible - spectral	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	UV-VIS-IR - spectral	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	polarisation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
BSDF	BSDF (.xml)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	Material Definition Language	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	custom material BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
scale	basic materials BRDF	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	urban	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	building	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	single room	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	module (facade component)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
design phase	cell	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	conceptual/early phase	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	schematic	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
design workflow	design development	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	real-time simulation/progressive	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	multiple solutions comparison	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	integrated optimisation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
computation	parametric design (node based)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	CPU based	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	GPU based	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	multi-threading	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	local network (multi-node)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
system	web/cloud	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	graphical user-interface	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	open-source	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	Windows	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Mac OSX	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
UNIX (Linux)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		

Table 9.3-7 Priority criteria for the 26 daylight and lighting products 1 part [23].

		Daylight																											
		Radiance - classic	Radiance - DAYSIM	Radiance - photon map	Diva	DAYSIMpm	IDA ICE	SPOT	ReluxSuite / Pro	Accelerad	Greening	DIAL + Suite	su2d	LightStanza	LightStudio	Playfront	Lighting Analysis for Revit	VELUX Daylight Visualizer	AG32	BlumTools	LightSolve	LightUp/Analytics	DIALux (4, evy)	ecoBIM (TMS Engineering)	Ocean	BIM IQ			
		▼ Radiance	▼ DAYSIM	■ A360	▼ Nvidia Optix	▲ Nvidia Iray/Optix	☆ PHANIE	▲ EnergyPlus	▲ OpenStudio	□ DOE	● standard feature	⊕ tweaking possible	○ data not provided	○ not supported															
		Dansk content		Knock out	Nice to have	Not needed																							
integration CAAD	AutoCAD																												
	FreeCAD																												
integration BIM	Revit																												
	ARCHICAD																												
	Vectorworks Architect																												
	ALLPLAN ARCHITECTURE																												
	Microstation (Parasolid)																												
	AECOsim Building Designer																												
	Digital Project																												
	Trelligence Affinity																												
	Edificius																												
	Caddie																												
	DDS-CAD																												
	BrisCAD																												
	ZWCAD Architecture																												
	TurboCAD																												
Architect3D																													
Envisioneer																													
ArchITeCH.PC																													
integration CAD/GAM	Rhinoceros 3D																												
	Alias																												
	Inventor																												
	CATIA																												
	Solidworks																												
	Inspire																												
	Evolve																												
	Creo																												
	Creo Parametric/Pro/ENGINEER																												
	Siemens NX (Parasolid)																												
	Solid Edge (Parasolid)																												
	TopSolid (Parasolid)																												
	SpaceClaim																												
	IronCAD																												
Geomagic Design																													
KOMPAS-3D																													
integration general 3D	SketchUp																												
	FormIt 360/Pro																												
	3Ds max																												
	Maya																												
	Lightwave																												
	Cinema 4D																												
	Blender																												
	Poser																												
	Camara																												
	DAZ Studio																												
	Houdini																												
MODO																													
formZ																													
Bonzai3D																													
integration general	stand alone	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	3D plugin	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	CAAD/BIM integrated plugin	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
interoperability	(online/cloud/app) web based	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	live link - dynamic data exchange	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
pricing	CAD interoper. (fbx, dwg, sat, obj, IGES)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	BIM interoperability (gbXML, IFC)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	freeware	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	free for educational/non-commercial	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	educational/student discount	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
validation	payware	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	flexible payment (subscription)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
	bundled	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
validated (CIE 171:2006)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		

Table 9.3-8 Priority criteria for the 26 daylight and lighting products 2 part [23].

## 9.4 Appendix: simulation runtime and accuracy

### Simulation accuracy

The simulation engine radiance is highly validated software as investigated in subchapter 2.5.2. The Daysim as an interface validated against CIE 171:2006. Plugin as Diva4 Rhino and HoneyBee show similar results. The verification process in appendix 9.5 shows similar results. Accelerad have speeding up the computation time by using a GPU with only around 1 % error compared to a CPU calculation [20].

### Sky subdivision influence on the simulation runtime:

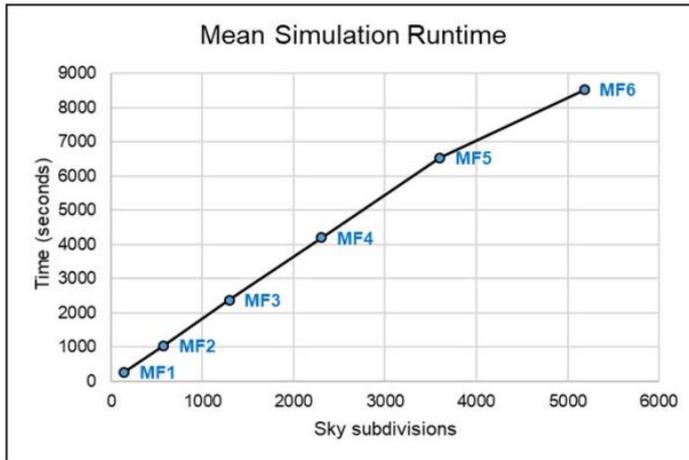


Figure 9.4-1 “Simulation runtime (for the set of 240 simulations) plotted as a function of sky patches used in the simulation. The runtimes plotted above were from simulations that performed with a Linux operating system on an Intel i7 3770 3.4GHz Desktop computer with eight virtual cores. The use of higher resolution skies accompanied by a corresponding increase in the value of ambient divisions (-ad) used for the simulation.” [51]

### Accelerad computation of the different methods:

Model	Processor	DAYSIM		3-/5-phase			5-phase		
		$D_{dir}$	$D_{diff}$	$D$	$T$	$V$	$D_d$	$V_d$	$C_{ds}$
Small	CPU	39.2	22.9	1.6	0.1	10.3	0.0	2.1	600.3
	1x GPU	8.8	3.9	0.2	0.1	2.3	0.1	0.5	21.1
	2x GPU	5.6	2.8	0.7	0.2	3.3	0.6	0.7	45.2
Medium	CPU	78.0	45.5	1.6	0.1	20.9	0.0	4.1	1219.7
	1x GPU	12.0	6.3	0.2	0.1	6.2	0.1	1.2	85.6
	2x GPU	7.8	4.2	0.7	0.2	6.2	0.6	1.3	73.2
Large	CPU	331.5	177.8	1.7	0.1	111.2	0.0	22.6	6031.0
	1x GPU	142.4	117.0	0.2	0.1	32.5	0.2	5.8	374.9
	2x GPU	84.6	68.2	0.7	0.2	21.3	0.6	4.4	323.9
Blinds	CPU	96.1	42.9	1.6	21.8	10.1	0.0	2.1	623.5
	1x GPU	9.1	4.1	0.2	0.8	2.3	0.1	0.5	21.6
	2x GPU	5.8	2.9	0.7	0.7	3.2	0.6	0.7	47.8

Table 9.4-1 “Matrix calculation times by rtrace\_dc and rcontrib in minutes” [42].

The aspects including in the simulated explained in appendix 9.2.1 and subchapter 2.5.2.

Accelerad computation of the different methods:

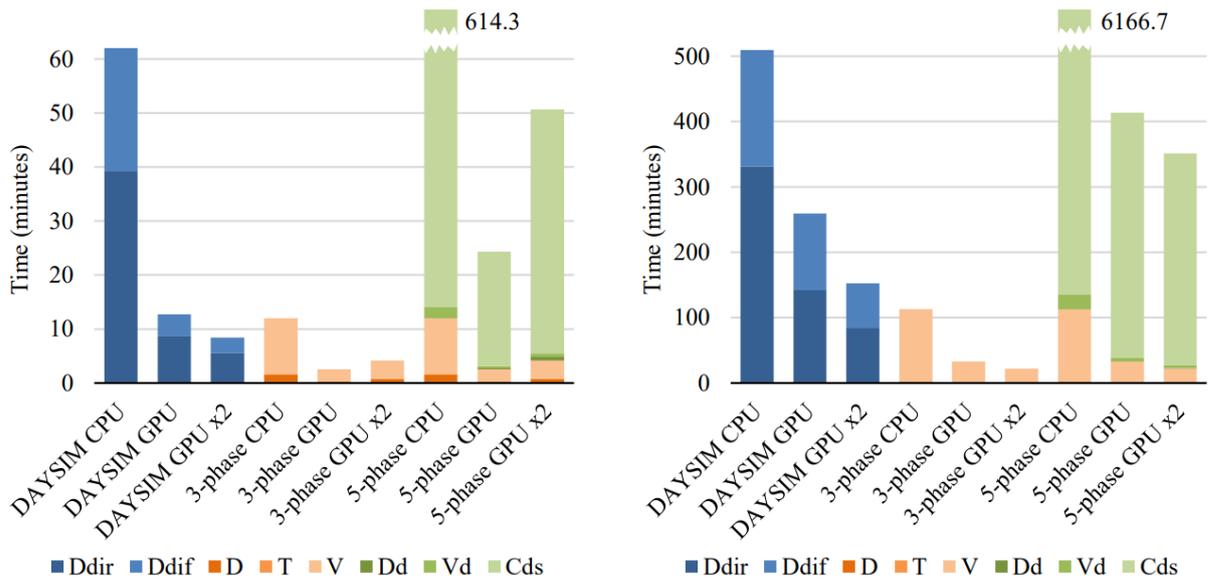


Figure 9.4-2 “Cumulative matrix calculation times by *rtrace\_dc* and *rcontrib* for the small model to the left and large model to the right” [42].

Accelerad speed up the simulation execution time

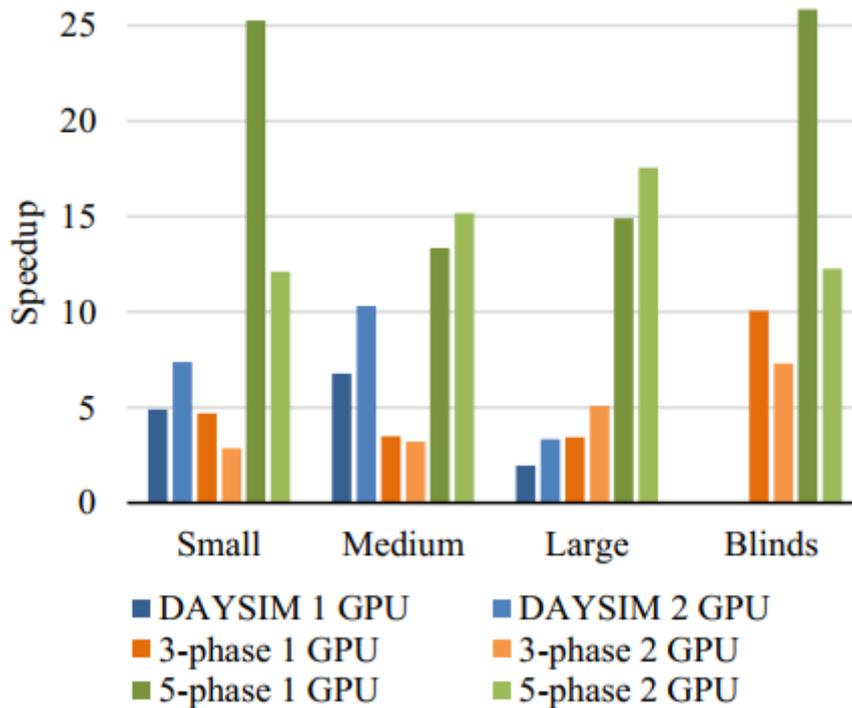


Figure 9.4-3 “Speedup factors for each method using one or two Tesla K40 accelerators. DAYSIM speedups for the blinds model not shown because the results are not useable” [42]

## 9.5 Appendix: Verification of simulation tool

In the Table 9.5-1, Table 9.5-2 and Table 9.5-3 Diva4rhino is verification against three rooms a simple room, simple room with obstruction and simple room with borrowed light. All three rooms where test against results from Radiance, Daysim and Velux daylight visualizer from daylight calculation in practices [6]. All the simulation tools set up high calculation accuracy. Diva4rhino show approximate testing results and daylight distribution on the calculation grid for the three different cases. The average daylight factor for the simple room with obstructions has low average results which results in a high percent variation even though the number different was the same as for the simple room and therefor the verification of simple room with obstructions was also accepted.

Room and area of interest	Simple room - Daylight factor			
Program	DIVA4Rhino	Radiance	Daysim	Velux Daylight visualizer
Average	3,2	3,3	3,4	3,0
% different in Average DF	0,0%	6,1%	8,8%	-3,3%
Median	2,1	2,3	2,2	1,9
Minimum	0,9	0,9	0,8	0,7
Max	12,1	12,9	13,6	12,6
Uniformity (minimum / average)	0,3	0,3	0,2	0,2
Uniformity (Max / average)	0,1	0,1	0,1	0,1
Calculation accuracy	High	High	High	High

Table 9.5-1 show verification of Diva4rhino of simple room against testing results from daylight calculation in practices [110]. All the simulation tools set up high calculation accuracy.

Room and area of interest	Simple room with obstruction- Daylight factor			
Program	DIVA4Rhino	Radiance	Daysim	Velux Daylight visualizer
Average	0,6	0,8	0,8	0,7
% different in Average DF	0,0%	25,0%	25,0%	14,3%
Median	0,5	0,5	0,5	0,4
Minimum	0,2	0,2	0,2	0,2
Max	1,9	3,1	3,1	3,0
Uniformity (minimum / average)	0,3	0,3	0,3	0,3
Uniformity (Max / average)	0,1	0,1	0,1	0,1
Calculation accuracy	High	High	High	High

Table 9.5-2 show verification of Diva4rhino of simple room with obstruction against testing results from daylight calculation in practices [110]. All the simulation tools set up high calculation accuracy.

Room and area of interest	Simple room with borrowed light - Daylight factor			
Program	DIVA4Rhino	Radiance	Daysim	Velux Daylight visualizer
Average	2,1	2,1	2,1	2,2
% different in Average DF	0,0%	0,0%	0,0%	4,5%
Median	1,7	1,8	1,8	2,0
Minimum	0,7	0,7	0,7	0,6
Max	5,6	5,0	5,0	5,0
Uniformity (minimum / average)	0,3	0,3	0,3	0,3
Uniformity (Max / average)	0,1	0,1	0,1	0,1
Calculation accuracy	High	High	High	High

Table 9.5-3 show verification of Diva4rhino of simple room with borrowed light against testing results from daylight calculation in practices [110]. All the simulation tools set up high calculation accuracy.

## 9.5.1 Appendix - Reference simple room

Reference room is used to verify the Diva for Rhino model

SBi 2013:20 Daylight calculation in practices is used to verify the Diva for Rhino model [111].

Floor plan illustration

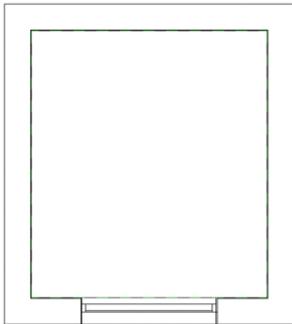


Figure 9.5-1 Floor plan

3D illustration

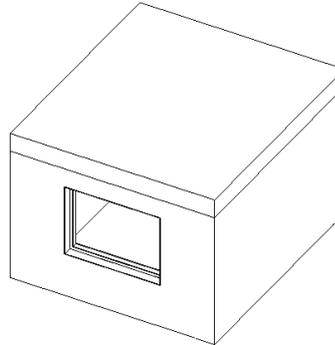


Figure 9.5-2 3D view

	Office room
Room volume [m <sup>3</sup> ]	39,2
Floor area [m <sup>2</sup> ]	14
Width [m]	3,5
Hight [m]	2,8
Depth [m]	4
Wall thickness [m]	0,4

Table 9.5-4 Room properties

	Office window
Window area [m <sup>2</sup> ]	3
Glazed area [m <sup>2</sup> ]	2,6
Window hole width [m]	2
Window hole height [m]	1,5
Window frame thickness [m]	0,06
Window wall/back	0,9

Table 9.5-5 Window properties

Surface	Surface reflectance value [111]
Ceiling	0,70
Interior walls	0,40
Floor	0,10
Window lighting, inside	0,70
Window lighting, outside	0,30
Window frames	0,80
Significant neighbouring obstructions	0,30
Urban neighbourhood	0,10
Window	Glazing properties [111]
Check window glazing's consisting surfaces	Model as one layer
LT-value: Light transmittance: Outside glass layer	0,76
LT-value: Light transmittance: inside glass layer	0,85
Grid settings [6]	Value [111]
Spacing -> resolution defined in SBI 272	0,25
Edge (Excepted from the calculation area)	0,5
Height above the floor (Office)	0,85 m
Min/Max ratio	1

Table 9.5-6 Optical material properties

## 9.5.2 Appendix - Reference simple room with obstruction

Reference room is used to verify the Diva for Rhino model

SBi 2013:20 Daylight calculation in practices is used to verify the Diva for Rhino model [111].

Floor plan illustration

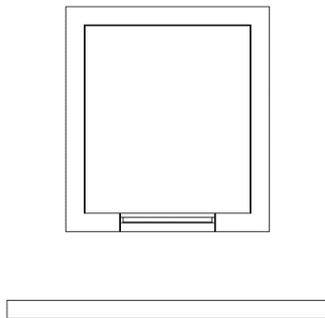


Figure 9.5-3 Floor plan

3D illustration

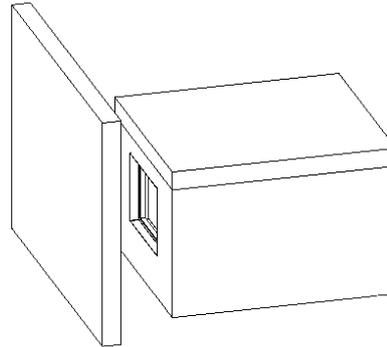


Figure 9.5-4 3D view

	Office room
Room volume [m <sup>3</sup> ]	39,2
Floor area [m <sup>2</sup> ]	14
Width [m]	3,5
Hight [m]	2,8
Depth [m]	4
Wall thickness [m]	0,4

Table 9.5-7 Room properties

	Office window
Window area [m <sup>2</sup> ]	3
Glazed area [m <sup>2</sup> ]	2,6
Window hole width [m]	2
Window hole height [m]	1,5
Window frame thickness [m]	0,06
Window wall/back	0,9

Table 9.5-8 Window properties

Surface	Surface reflectance value [111]
Ceiling	0,70
Interior walls	0,40
Floor	0,10
Window lighting, inside	0,70
Window lighting, outside	0,30
Window frames	0,80
Significant neighbouring obstructions	0,30
Urban neighbourhood	0,10
Window	Glazing properties [111]
Check window glazing's consisting surfaces	Model as one layer
LT-value: Light transmittance: Outside glass layer	0,76
LT-value: Light transmittance: inside glass layer	0,85
Grid settings [6]	Value [111]
Spacing -> resolution defined in SBI 272	0,25
Edge (Excepted from the calculation area)	0,5
Height above the floor (Office)	0,85 m
Min/Max ratio	1

Table 9.5-9 Optical material properties

### 9.5.3 Appendix - Reference simple room with borrowed light

Reference room is used to verify the Diva for Rhino model

SBi 2013:20 Daylight calculation in practices is used to verify the Diva for Rhino model [111].

Floor plan illustration

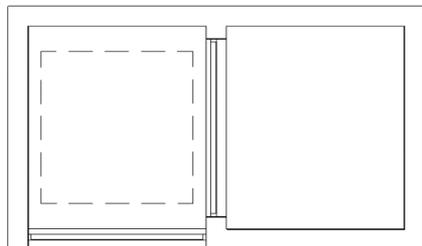


Figure 9.5-5 Floor plan

3D illustration

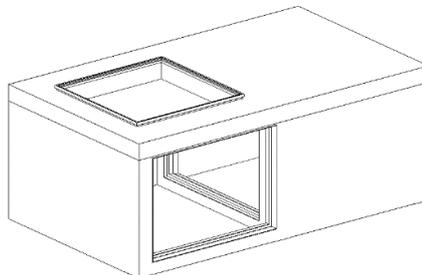


Figure 9.5-6 3D view

Two similar office room	
Room volume [m <sup>3</sup> ]	39,2 x2
Floor area [m <sup>2</sup> ]	14 x2
Width [m]	3,5
Height [m]	2,8
Depth [m]	4
Wall thickness [m]	0,4

Table 9.5-10 Room properties

	Office window	Skylight
Window area [m <sup>2</sup> ]	8,87	8,698
Glazed area [m <sup>2</sup> ]	8,044	8,004
Window hole width [m]	3,5	3
Window hole height [m]	2,5	3
Window frame thickness [m]	0,06	0,06
Window wall/back [m]	0,9	0,9

Table 9.5-11 Window properties

Surface	Surface reflectance value [111]
Ceiling	0,70
Interior walls	0,40
Floor	0,10
Window lighting, inside	0,70
Window lighting, outside	0,30
Window frames	0,80
Significant neighbouring obstructions	0,30
Urban neighbourhood	0,10
Window	Glazing properties [111]
Check window glazing's consisting surfaces	Model as one layer
LT-value: Light transmittance: Outside glass layer	0,76
LT-value: Light transmittance: inside glass layer	0,85
Grid settings [6]	Value [111]
Spacing -> resolution defined in SBI 272	0,25
Edge (Excepted from the calculation area)	0,5
Height above the floor (Office)	0,85 m
Min/Max ratio	1

Table 9.5-12 Optical material properties

## 9.5.4 Appendix Radiance parameter

Radiance Raytracing have 18 adjustable parameters<sup>3</sup>. Diva for Rhino calculate all radiance parameter but to optimise the user-friendliness only five parameters can be adjusted, and these five parameters shown in Table 9.5-13.

Radiance - Parameters	Default	Explanation
-ab (ambient bounces)	2	Number of diffuse bounces in the indirect calculation. Reflectance required to reach the area of interest. 0 value no contribution of indirect light.
-aa (ambient accuracy)	1000	Set the maximum indirect irradiance interpolation error permitted. Lower values give high accuracy and normally values between 1 and 0.1 are used. No interpolations when setting value is zero.
-ar (ambient resolution)	20	Avoid overloading the program by determining the maximum density of ambient values and exclude small geometric details.
-ad (ambient divisions)	300	Sampling rays send to hemisphere from area of interest which increase the accuracy if the simulation. Zero no indirect calculation
-as (ambient super-samples)	0,1	Extra rays used to sample areas in the hemisphere. Sampling shadow boundaries.

Table 9.5-13 Radiance parameters with default diva value and explanation [112][113][114]

The simulation quality and simulation execution time are influencing by the radiance parameters and the values should therefore chose in accordance to the level of detail that is needed for a model as shown in Table 9.5-14. Higher values can add but the simulation quality will not just continues increase with higher radiance parameters.

Simulation quality	Radiance - Parameters				
	-ab	-ad	-as	-ar	-aa
Low quality (initial simulation)	2	512	128	16	0,25
Medium quality	3	2048	2048	64	0,20
High quality (final simulation)	6	4096	4096	128	0,10

Table 9.5-14 Radiance - parameters and rendering quality [112][113][114]

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<sup>3</sup> Detailed description of Radiance Raytracing 18 parameters  
[http://radsite.lbl.gov/radiance/man\\_html/rtrace.1.html](http://radsite.lbl.gov/radiance/man_html/rtrace.1.html)

Room	Simple room - Daylight factor					
Program	DIVA4Rhino			Radiance	Daysim	Daylight visualizer
Average	2,7	3,0	3,1	3,3	3,4	3,0
% different in Average DF	-14,8%	-3,3%	0,0%	6,1%	8,8%	-3,3%
Median	1,9	1,9	2,1	2,3	2,2	1,9
Minimum	0,6	0,6	0,9	0,9	0,8	0,7
Max	10,3	11,8	12,1	12,9	13,6	12,6
Uniformity (minimum / average)	0,2	0,2	0,3	0,3	0,2	0,2
Uniformity (Max / average)	0,1	0,0	0,1	0,1	0,1	0,1
Radiance Parameter settings	Low	Medium	High	High	High	High

Table 9.5-15 show radiance - parameters and rendering quality and then verified against testing results from daylight calculation in practices [110]. The percent different in average daylight factor is setup against Diva4Rhino high radiance parameter settings.

Table 9.5-16 show how the five different radiance parameters influencing the execution time. By using high quality setting the execution time increase drastically.

-ab	doubling value can double the rendering time
-aa	doubling value approximately quadruples rendering time
-ar	effect depends on scene, can quadruple time for double value
-ad	doubling value may double rendering time
-as	effectively adds to -ad parameter and its cost

Table 9.5-16 Radiance-parameters effect on execution time [112][113][114]

Diva for rhino have these remaining radiance parameters that cannot be editing but default parameter shown in Table 9.5-17.

-dc (direct certainty)	0.75	-ps (pixel sampling rate)	2
-dj (source jitter)	0.7	-pt (sampling threshold)	0.05
-dp (direct pertest density)	2048	-pj (anti-aliasing jitter)	0.9
-dr (direct relays)	3	-st (specular threshold)	0.01
-ds (source substructuring)	0.2	-lr (limit reflection)	12
-dt (direct thresholding)	0.05	-lw (limit weight)	0.0005
-sj (specular jitter)	1		

Table 9.5-17 Diva remaining parameters [113][143]