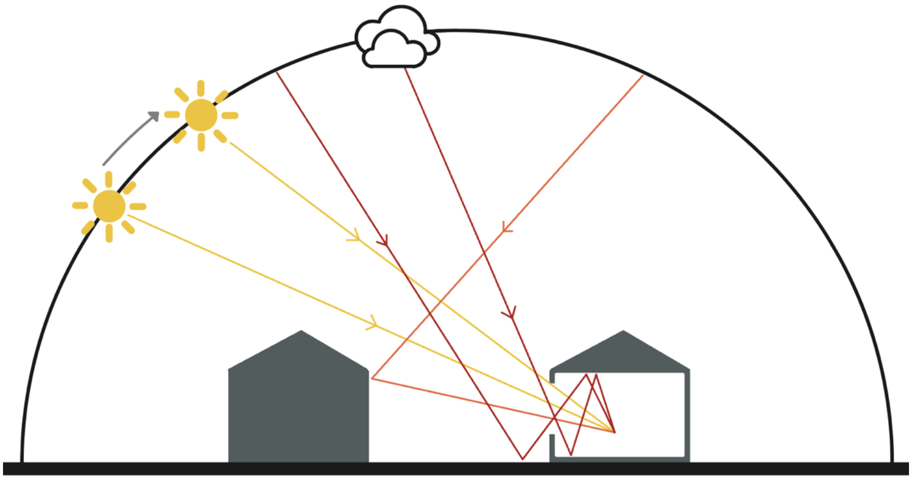
A first suggestion on how to make Climate-Based Daylight Modelling through Radiance simple and available to the Danish building industry and how to validate Climate-Based Daylight Modelling.

- Master Thesis -



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AALBORG UNIVERSITY
STUDENT REPORT

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Abstract

A method on how to make climate-based daylight modelling (CBDM) accessible to the Danish building industry has been proposed in this thesis. Accessible being twofold: user-friendly without the necessity of expert knowledge and inexpensive. This could enhance the use of CBDM in the industry.

The proposed method includes three main investigated aspects supported by a literature study of annual daylight metrics and a thorough investigation of Radiance. Radiance was chosen as a focal point, as it is considered to provide the true results in CBDM, due to its extensive validation showing its ability to provide accurate physically realistic results.

Firstly, the Radiance 3- and 4-Phase Methods were chosen for calculation of yearly indoor illuminance estimations based on typical meteorological year (TMY) weather data. The methods were found to be the most agile and fast for the investigation of dynamic solar shading and various fenestration systems.

The second aspect in this thesis regarding the proposed method of making CBDM accessible includes the choice of parameter settings. The ambient parameters have a major impact on the accuracy of the simulation results. The suggested settings are based on a literature review of previous studies.

The third aspect is the principle of how to incorporate Radiance CBDM with thermal comfort and energy use simulations in BSim. This compilation allowing for integrated design should enhance the accuracy of the estimation of the building performance. Such a compilation makes it possible to take the effect of daylighting including dynamic solar shading into account for the use of artificial lighting and heat loads for thermal simulations. This allows for the potential of lowering energy use and enhancing the indoor climate of building designs.

Furthermore, a study to map existing datasets for validation of climate-based daylight modelling tools and parameter settings is included. This is to provide the industry with recommendations for future practice, where no benchmark model or method is well-known or available. The study identifies the difficulties in the acquisition of existing datasets for validation and their uncertainties or deficiencies. The study also guided the process of verifying the proposed method to use for general CBDM. The proposed method has been tested and comparatively verified against two Radiance methods.

Preface

This thesis has been written to fulfil the requirements of the master's program Indoor Environmental and Energy Engineering at Aalborg University. The thesis was carried out from September 2021 to October 2023 prolonged due to personal circumstances.

Sparked by an interest in daylighting and problem solving the theme of the struggle in the industry including annual daylighting in the design phase and documentation of buildings arose. Annual daylight simulation in compilation with thermal comfort and energy use simulations are limited in the industry and only accessible to large companies which can afford expensive software. Hoping this thesis will contribute to future accessible tools and clearer guidelines ensuring better daylighting design not as an afterthought but as a part of integrated design. This could lead to buildings performing closer to the estimations based on simulation thereby creating more sustainable buildings.

This has led to an extensive literature review on methods, metrics and validation of climate-based daylight modelling and existing software for the simulation of this. The thesis covers the use and methods of Radiance. Furthermore, suggested methods for climate-based daylight modelling have been clarified along with the current and future integration of Radiance with other software.

Special thanks to Christian Grau Sørensen, Leader of the IT Lab of the Division of Energy and Sustainability in Buildings at BUILD, Aalborg University Copenhagen for IT support and guidance on coding. Also a special thanks to Louise Østergaard Pedersen from Artelia Group for providing data.

Reading guide

This thesis consists of eight main parts in the report. First, the introduction including the research questions and the methodology is presented. This is followed by the literature review including four chapters on annual daylight simulation metrics, validation of climate-based daylight modelling, software and methods of climate-based daylight modelling, and the Radiance software suite.

Then a part illustrates the suggested method of climate-based daylight modelling for the Danish building industry to use. It is suggested to integrate the method with thermal comfort and energy use simulations in an accessible tool. Accessibility is understood as inexpensive and simple for the user. The suggested method is tested and comparatively verified.

Finally, the report is concluded with a discussion and a conclusion. In addition to the main report, two appendices are included in this document. Appendix B is to support the report and Appendix A is a description of the digital Appendices uploaded separately.

Glossary

BESTEST	Balance Evaluation Systems Test
BSDF	Bidirectional Scattering Distribution Function
CBDM	Climate-Based Daylight Modelling
CFS	Complicated Fenestration Systems
DDS	Dynamic Daylight Simulation
DRY	Danish Reference Year
EPW	Energy Plus Weather
MBE	Mean Bias Error
MF	Multiplication Factor
NZEB	Net Zero Energy Building
OLS	Optical light shelf
BRE	British Building Research Establishment
BRE-IDMP	British Building Research Establishment - International Daylight Measurement Programme
BREEAM	Building Research Establishment Environmental Assessment Methodology
CIBSE	Chartered Institution of Building Services Engineers
CIE	International Commission on Illumination
IES	Illuminating Engineering Society of North America
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
LPBS	Physics Laboratory of Building and Systems at University of Reunion
NRC	National Research Council Canada
ASE	Annual Sunlight Exposure
cDA	Continuous Daylight Autonomy
DA	Daylight Autonomy
DC	Daylight Coefficients
sDA	Spatial Daylight Autonomy
TAI	Total Annual Illumination
UDI	Useful Daylight Illuminance
$\mathbf{S}$	Sky Vector Matrix
$\mathbf{C_{DC}}$	Daylight Coefficients Matrix
$\mathbf{E}$	Internal Illuminance Matrix
$\mathbf{V}$	View Matrix
$\mathbf{T}$	Transmission Matrix
$\mathbf{D}$	Daylight Matrix
$\mathbf{F}$	Facade Matrix
$\mathbf{d}$	Direct Component
$\mathbf{ds}$	Direct Sun

Contents

Introduction 1

The Danish building industry is moving towards climate-based daylight modelling (CBDM) along with the rest of the world. CBDM is understood in this project as the definition:

> "Climate-based daylight modelling (CBDM) is the prediction of any luminous quantity (illuminance and/or luminance) using realistic sun and sky conditions derived from standardised climate data. CBDM evaluations are usually carried out for a full year at a time-step of an hour or less in order to capture the daily and seasonal dynamics of natural daylight." [Mardaljevic, 2015]

CBDM can improve the building performance. Utilizing daylighting reduces the energy use and improves the indoor environment enhancing the health and efficiency of occupants. [Wurtman, 1968] [Harb et al., 2014] [van Bommel and van den Beld, 2004]

A large part of new buildings underperform in comparison with their documentation. In the design phase of buildings one of the major difficulties, that occurs is ensuring the use of similar settings for facade properties throughout all the documentation and the building process known as integrated design. [Karlsen et al., 2016] This is due to the use of multiple tools to investigate energy use, thermal indoor environment and daylight. Therefore there is no control over the similarity in the facade solutions such as the settings for glazing and shading. This is especially the case for solar shading control, which has a major influence on the building performance with respect to energy use, thermal comfort and daylight.

It is difficult to find design solutions with low energy use for heating and artificial lighting combined with a good indoor climate meaning close to no overheating hours, efficient daylight without glare and outlook for the occupants. In the Danish climate, it is preferable to bring down the solar heat gain in the summer to avoid the need for cooling whereas the opposite is preferable in the winter to bring down the energy use for heating. [Karlsen et al., 2016] Therefore, climate-based indoor modelling is necessary to provide documentation for the performance of the building with respect to thermal climate and energy but should also include the daylight and especially static and dynamic shading devices as this has a major impact on the user comfort besides the energy use.

This project will focus on CBDM as there is less of a common practice in this field. As CBDM is considerably new to the building industry, the common practice is still using simplified methods to evaluate sufficient daylight such as daylight factor (DF). Annual daylight metrics give a more accurate daylight estimate. Dealing with the complexity of fenestration systems needs further implementation of these advanced methods in available programs. [Buenoa et al., 2015] Small engineering companies cannot afford the software needed to perform CBDM, therefore the Danish building industry needs inexpensive software.

The scope of the topic of this project is the following aspects surrounding CBDM:

- Climate-based daylight metrics
- Climate-based daylight modelling tools and calculation methods
- Validation of climate-based daylight modelling
- Accessible CBDM in combination with energy and thermal comfort simulations

Firstly to find an accessible solution for the industry to perform CBDM in combination with energy and thermal comfort simulations the metrics, calculation methods, current software and how they are validated must be mapped out. This way the gap can be identified and what to build on to solve it. The scope was determined based on the research question, see section 1.1.

The project has a practical industry focus and does not explore the psychological effects of the quality of indoor climate or the effect of specific types of building envelopes. This includes types of shading, glazing or other important design choices.

Previous studies have found there are difficulties in the process designers encounter with combining CBDM and indoor climate simulations including both passive and dynamic shading systems. CBDM allows for the use of dynamic solar shading. This can be an advantage when designing buildings with lower energy use, less overheating and higher daylight supplies resulting in higher occupant comfort. [Nielsen et al., 2011]

It has been suggested that there is a need for software that links energy use, indoor climate and annual daylight simulations; CBDM, as the interaction between daylight and indoor climate, is a key element in designing Zero Energy Buildings. A software tool using the same 3D building model will minimize errors as the windows, shading, control strategy for dynamic shading and weather data will be identical. [Rasmussen and Pedersen, 2019]

Previous studies show that daylight and solar shading should be evaluated by multiple factors. The most commonly used annual daylight metric is a variation of spatial daylight autonomy, sDA, which is seen in BREEAM [BREEAM 3.0, 2018], LEED [LEED v4, 2017], and the Danish Building regulation [BR18 - 18 Guidance, 2021] following the European Standard. [DS/EN 17037, 2018] Furthermore, glare is often evaluated as well as outlook. The daylight and the facade construction also affect the thermal solar gain and thereby both thermal comfort and energy use for heating. [Rasmussen and Pedersen, 2019] [Karlsen et al., 2016]

So many different software tools exist to help in the design phase or for documentation of the performance of new buildings. However, it is not transparent or clear which tools to choose and very few are capable of all the necessary simulations based on annual weather models.

Software currently available does pose difficulties in combining energy use, indoor climate simulations and CBDM. The available software is either very complicated to use, expensive, very slow at simulating or does not allow simulations of the three aspects in the same software. Furthermore, a lot of the software has limitations when it comes to windows and shading devices especially when considering dynamic solar shading. Another option often used is choosing a simpler method for daylight analysis. By not doing annual simulations the effect of the variation in the climate throughout the four seasons is neglected and results are less accurate. Or simply use multiple tools often resulting in design mistakes. [Rasmussen and Pedersen, 2019] [Karlsen et al., 2016]

Furthermore, there is no common practice in validating CBDM. Therefore, it is difficult to evaluate which method or tool to choose for annual daylight simulations.

With the industry having an available tool, which combines energy use, thermal climate and annual daylight simulation, new buildings would perform better. The industry would find a common practice which included CBDM allowing for dynamic shading and predicting the effect thereof in all three aspects. Thereby, the performance of the buildings would hopefully be closer to the simulation results. Also, it would be easier to find an optimum for the specific climate ensuring a lower energy use. Resulting in more environmentally sustainable buildings and more socially sustainable buildings due to the improved thermal indoor climate and daylight.

1.1 Research question

How can the building industry improve on using climate-based daylight modelling (CBDM) in combination with thermal indoor environment and energy use simulations?

1. How to determine CBDM?
   a) Which metrics should the Danish building industry use for CBDM?
   b) How should CBDM tools or simulation parameters be validated in future work?
   c) Which software tool to choose when performing CBDM?
   d) What calculation method is generally preferred when considering speed and accuracy?
2. How can CBDM become more accessible to the Danish building industry in combination with thermal comfort and energy use simulations?

This project made preliminary work to suggest a method to simplify and combine simulations of climate-based daylight, energy use, and thermal indoor environment in the same simulation tool. This will ensure better simulations of solar shading and its influence, especially dynamic shading devices. Said tool is available to the building industry as a requirement meaning it is inexpensive and simple to use. This work includes suggestions for CBDM simulation methods and parameter settings. Utilizing Radiance for the daylight computation to be incorporated with existing software like BSim which does energy use and indoor climate simulations.

Furthermore, a study to map existing datasets for validation of climate-based daylight modelling tools or parameter settings is included. This is to provide the industry with recommendations for future practice where no benchmark model or method is well-known or available.

The outline of the thesis follows the succession of the research questions:

- CBDM metrics

- CBDM Validation
- CBDM tools including Radiance methods
- CBDM setup for integration with thermal comfort and energy use simulations

1.2 Methodology

The research methodology consists of several interconnected components, including an extensive literature review, an investigation into Radiance, and the execution of simulations with subsequent verification against results from the 17$^{\text{th}}$ International Radiance Workshop based on cases from SBI 26. [Brembilla, 2018a][SBI 2013:26, 2013] These steps collectively form the foundation upon which this study builds its analyses and findings.

1.2.1 Literature review

The foundation of this research lies in a comprehensive literature review conducted to explore and combine existing knowledge related to the primary aspects: of CBDM metrics, methods, and validation. The literature review aimed to achieve the following objectives:

- To identify the key theories, concepts, and methodologies relevant to CBDM and validation hereof.
- To establish a conceptual framework for understanding the fundamental principles and existing challenges associated with CBDM.

The literature review provided theoretical insights and facilitated the understanding of the research related to the industry. It served towards developing the research focus and guiding the subsequent phases of the research.

Understanding of Radiance

To effectively address the aspects of CBDM methods, it was imperative to gain a deep understanding of Radiance, which serves as a central component in this study. This involved the following steps:

- Set up of an external server and installing Radiance; a widely used software tool for CBDM, which is seen as the ultimate truth.
- Exploring the features, capabilities, and limitations of the program through practical experimentation.
- Engaging with relevant documentation and resources to ensure a thorough comprehension of the functionalities and applications of Radiance.
- Collaborating with experts to exchange knowledge and insights related to the coding of Radiance.
- The understanding of Radiance was essential in enabling the successful execution of simulations, as it allowed for the configuration of parameters and settings essential to the research.

1.2.2 Simulation and comparative verification of results

The creation and execution of CBDM through Radiance was essential to test the proposed method and parameter settings for the industry. This involved:

- Defining the specific simulation scenarios and parameters by the research objectives.
- Conducting CBDM through Radiance.
- Ensuring the suggested method and parameter settings give accurate results by comparative verification against the Radiance Workshop results. [Brembilla, 2018a]

The choice of verification method was chosen based on the literature review and accessible data. Verification against validated simulation methods was important as it ensured the credibility of the simulation settings.

In summary, this thesis used a methodology that began with an in-depth literature review, progressed through the acquisition of knowledge about Radiance, and culminated in the execution of simulations with a comparative verification against the results from the 17$^{\text{th}}$ International Radiance Workshop. [Brembilla, 2018a] This approach was fundamental in achieving the research objectives, enhancing the reliability of the findings, and contributing to the advancement of knowledge in the field of study.

2 CBDM Metrics & Criteria

The name Climate-Based Daylight Modelling (CBDM) was introduced in 2006 though the possibility of dynamic annual daylight predictions had been possible since 2000. [Mardaljevic, 2006] [Reinhart and Herkel, 2000] CBDM and annual daylight metrics were introduced to replace the still widely used Daylight Factor (static metric) to enhance daylighting design. [Mardaljevic, 2006]

The Daylight Factor is widely used based on its simplicity in calculation and it is easily understood by a design team. However, it has been argued that it does not create good daylighting but may only enhance an understanding of "the more light the better". It does not take glare issues, direction or fluctuations in the weather into account. [Reinhart et al., 2006]

This idea of the more the better comes from the objective of bringing down energy use of artificial lighting. The other factor which is less documented is the biological effects of daylighting. However, research suggests that daylighting has positive health benefits to us. [Wurtman, 1975] [Wurtman, 1968] [Harb et al., 2015] It has also been shown that natural daylight is preferred over artificial lighting. [Escuyer and Fontoynont, 2001]

For better daylighting, both amount, distribution, color and glare are important factors. CBDM does not consider color but the amount, distribution and glare depending on the chosen metrics. However, it gives a more reliable result than the Daylight Factor as it considers the sun and sky conditions from meteorological datasets for the building site. [Karlsen, 2016]

Besides the choice of metric two factors are essential for annual daylight metrics; evaluation area and time step. Which plane is considered relevant comes down to the use of the room and possibly the criteria the result is evaluated up against. This is typically either floor space or a work plane sometimes a percentage or specified piece of the area of the room. The time step is typically one of two: all daylight hours throughout a year or the occupied hours of the space. [Reinhart et al., 2006]

Six annual daylight metrics or dynamic daylight metrics are described in this chapter: DA, cDA, UDI, sDA, ASE and TAI. All illuminance levels referred to in this chapter are based solely on daylight.

2.1 DA - Daylight Autonomy

Daylight Autonomy or DA is a percentage of annual daylight hours where a specific point in a room has an illuminance level above a given value. [Reinhart et al., 2006] The user is free to determine this value though 300 lux, DA_{300}, is the most commonly used. A visual example of DA_{300} results appear in figure 2.1

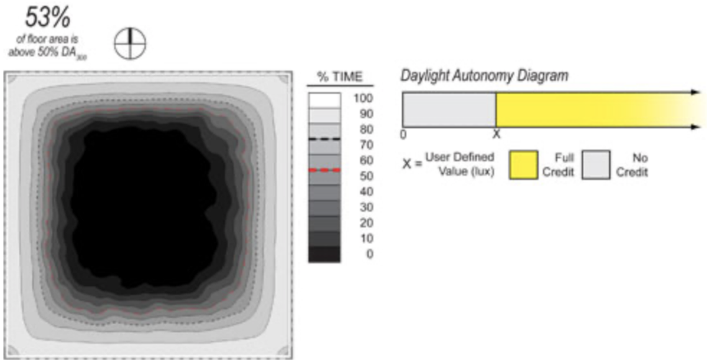


Figure 2.1: The graphs show an example of a Daylight Autonomy threshold of 300 lux, DA_{300}. The graphical percent values represent the percentage of the floor area that exceeds 300 lux for at least 50 % of the time. [New Buildings Institute, 2021a]

DA originated from a Swiss norm and was later redefined by Reinhart and Walkenhorst. [Association Suisse Des Electriciens, 1989] [Reinhart and Walkenhorst, 2001] In 2006 the prediction of movable shading devices was included and the metric is known as 'Effective' Daylight Autonomy. [Reinhart and Andersen, 2006]

2.2 cDA - Continuous Daylight Autonomy

Continuous Daylight Autonomy or cDA is based on DA with the addition of partial credits of illuminance levels below the given threshold. Is the illuminance level at a given point 50 % of the threshold at a time step then half a credit (0.5) is given. [Reinhart et al., 2006] A visual example of cDA_{300} results appear in figure 2.2.

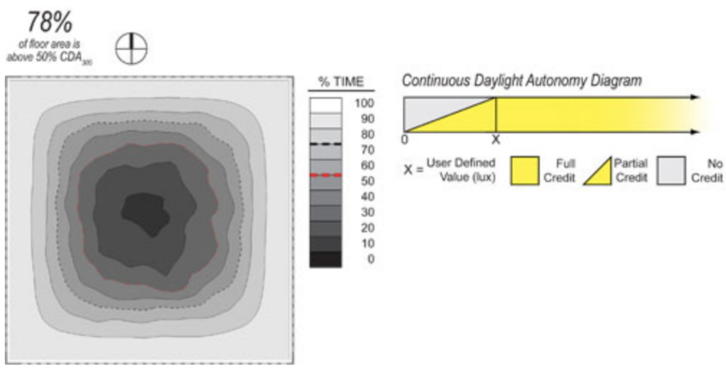


Figure 2.2: The graphs are an example of a Continuous Daylight Autonomy threshold of 300 lux, cDA_{300}. The graphical percent values represent the percentage of the floor area that exceeds 300 lux for at least 50 % of the time giving partial credit for time steps below 300 lux. [New Buildings Institute, 2021c]

2.3 UDI - Useful Daylight Illuminance

Useful Daylight Illuminance or UDI is another modification of Daylight Autonomy where hourly occupancy time values are grouped by three ranges which by default are: 0-100 lux, 100-2,000 lux and >2,000 lux. Only values in the middle range are considered and given full credits. The upper limit is a way to indicate that high illumination levels often result in issues with glare or overheating. However, there is limited research to support the value of 2,000 lux. [Mardaljevic et al., 2012] [Reinhart et al., 2006]

UDI was proposed by Mardaljevic and Nabil in 2005. [Nabil and Mardaljevic, 2005] A visual example of UDI results appear in figure 2.3.

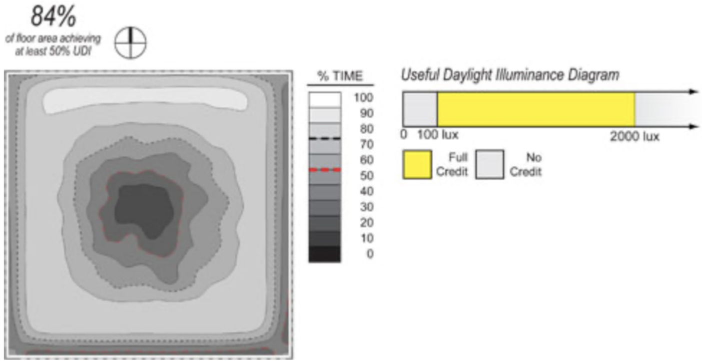


Figure 2.3: The graphs are an example of Useful Daylight Illuminance results. The graphical percent values represent the percentage of the floor area that meets the UDI criteria at least 50 % of the time. [New Buildings Institute, 2021b]

2.4 sDA - Spatial Daylight Autonomy

Spatial Daylight Autonomy or sDA is a metric defined to ensure sufficient daylight in a space. It is defined as $DA_{300/50\%}$, which was stated by the Illuminating Engineering Society (IES) and used as a daylight indicator in LEED. [IES - The Daylight Metrics Committee, 2012] Meaning the luminous level has to be above 300 lux at least 50 % of the time the space is occupied, typically 8 am-6 pm.

2.5 ASE - Annual Sunlight Exposure

Annual Sunlight Exposure or ASE is a term for the percentage of a space which receives excessive amounts of direct sunlight. This is defined by an illuminance of 1,000 lux or more for more than 250 occupied hours per year. This can cause glare or increase the need for cooling. Some note the hours with illuminance levels above 1,000 lux as glare hours. [Kusumadjaja, 2019]

2.6 TAI - Total Annual Illuminance

Total Annual Illuminance or TAI differs from the other climate-based daylight metrics by being a term of the sum of the actual illuminance in a space in the occupied hours. The other metrics bin absolute values into percentages. It is also known as Annual Daylight Exposure, ADE and is expressed in the unit klx hrs. [Brembilla and Mardaljevic, 2019]

2.7 Criteria

In Denmark, sufficient daylight in work spaces such as offices, classrooms, kitchens etc. can be proven in different manors. This project focuses on the second method suggested in the Danish Building Regulations, which is the more advanced method, the first method being the 10% rule. With the second method, documentation of internal illuminance of at least 300 lux in more than half of the relevant floor area in at least half of the daylight hours has to be provided through simulation (sDA). [BR18 - 18, 2021]

The relevant floor area for offices does not include the space 0.5 m along the walls. If the layout including the work spaces are known the area can be limited further. The reference plane in which the illuminance level is documented is positioned 0.85 m above the floor for workspaces, see figure 2.4. [BR18 - 18 Guidance, 2021]

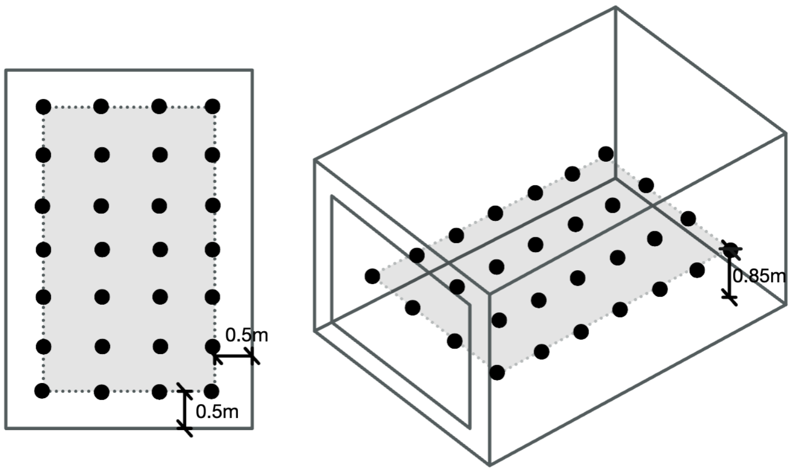


Figure 2.4: Illustration of the relevant floor area divided into measurement/calculation/reference points.

The daylight hours in a year is defined as half of the hours in a year with the highest amount of daylight based on weather data from the Danish Reference Year. [Wang et al., 2013] [BR18 - 18 Guidance, 2021]

Though the standard does require the use of hourly-based weather data and validated software, there are no requirements on the sky model used in the software. It is not specified whether the validation has to be experimental or comparable, though it is suggested the software can be validated against the CIE 171:2006 Test Cases. [CIE 171:2006, 2006] The same applies to software used for daylight factor calculation. [DS/EN 17037, 2018]

It is allowed to utilize a different method to show a space has sufficient daylight, where the Daylight Factor is accepted. Due to this exception, the Danish building industry still uses this method.

2.8 Choice of dynamic daylight metric

Of the climate-based daylight metrics mentioned; UDI gives a better indication of useful daylight in a space. UDI divides the illuminance levels into groups which might indicate the amount of hours without sufficient daylight and the amount of hours with excessive amounts of daylight. Whereas, sDA is simpler and only indicates hours with daylight above a certain amount in the space. It does not consider glare. However, as sDA is chosen by the Danish Building Regulation as the current criteria this project will include this metric for evaluation of daylight performance in buildings. [BR18 - 18, 2021] [Karlsen, 2016]

The advantage of sDA is that it is an easily comparable climate-based daylight metric as the result is expressed as a single percentage number. Therefore, listing it as a criterion that has to be met is convenient. Furthermore, it is easy for engineers or architects to explain this factor to a project manager or builder. ASE and UDI or TAI may be relevant metrics for validation as well when considering a more holistic approach including a form of glare assessment. [Brembilla, 2017]

CBDM Validation 3

Before the 21st century scale models were considered the benchmark for daylight modelling. [Mardaljevic, 2001] Since then computer modelling has taken over as the more common practice than scale models as they are faster and cheaper. For energy simulations, the building industry has a common practice using the BESTEST suite as a benchmark for validation. [Judkoff and Neymark, 1995] For climate-based daylight simulations such a benchmark is missing as common practice. [Mardaljevic, 2001] [Osborne and Donn, 2011]

Validation of simulation tools is iinortant to determine the accuracy and thereby the applicability of results. Most CBDM validation being software or simulation settings are mainly dknownby comparative validation against Radiance which is seen as the "ground truth" in annual daylighting simulation. [McNeil, 2019] This is the common practice for validation of software as seen in table 4.2. Experimental validation does eliminate some uncertainties and is therefore preferable. It would eliminate uncertainty errors caused by Radiance. However the uncertainty of the use of the sky model sconsistsists based on the climate in which simulations are made differing from where the dataset was made. If a dataset and 3D model were available and straightforward to use it might become the common practice instead.

Currently, only researchers use experimental validation though most researchers choose comparative validon. Multiple of Radiance CBDM calculation methods have been validated experimentally, see table 4.1.

The Chartered Institution of Building Services Engineers (CIBSE) panel is currently working on formulating a benchmark for daylighting software accreditation. [Mardaljevic and Prost, 2023] In 2006 they came out with an initial attempt though it has since been suspended. [CIBSE, 2006]

3.1 Comparative validation

Cosupportsve validation pose some difficulties and uncertainties. How closely can the settings and models align so that only the calculation algorithms or parameter settings are evaluated? Or ensure that the various aspects are evaluated individually? When making comparisons between various software a guideline should exist to ensure a certain quality of the accreditation. Radiance is seen as the ground truth and is therefore often used for comparative validation of CBDM software.

There are multiple categories of design choices though; which have an impact on the validation. There is no guideline currently and the CBDM comparative validation existing is therefore varied and comparison directly between different studies is therefore difficult.

These categories are:

- Radiance calculation method of the "benchmark"
- Choice of sky model and discretization
- Time step and period
- Parameter settings
- Output metrics

Originally brute force was used, then the 4-component method and later the 3-Phase Method have been used to compare against. Choice of sky model and discretization and how it affects the accuracy is elaborated in section 5.2.3. The parameter settings has a major impact on the accuracy. When comparing to software using other calculation methods it is therefore difficult to align the accuracy as they may not have similar settings.

To ensure a robust validation multiple outputs or metrics should be considered. Metrics based on averaged total illuminance might currently be preferable over metrics using spatial distribution. [Brembilla, 2017] Various methods have shown significant deviations on results based on direct sunlight and spatial distribution, especially the metric ASE. It is uncertain which method is more accurate as there are know uncertainties in this aspect of the Radiance benchmark predictions. [Brembilla and Mardaljevic, 2019]

3.2 Experimental validation

In 2012 Jake Osborne proposed a suit used for the validation of climate-based daylight simulations similar to the BESTEST suite for energy simulations. The proposed suite consist of three datasets; the CIE 171:2006 Test Cases to assess the accuracy of lighting computer programs, measured data from the 71T test-bed at Lawrence Berkeley National Laboratory (LBNL), and measured data from the Université de La Réunion's Laboratoire de Physique du Bâtiment et des Systèmes (LPBS). The two latter to represent real physical aspects and challenges of CBDM. A flaw of the suite which Osborne points out is that the suite is not able to test the sky model accuracy for multiple locations as this will need future work. [Osborne and Donn, 2011] [CIE 171:2006, 2006]

This combination of test cases and datasets covers a wide range of simulation scenarios for simulations using weather data such as DRY and the Perez Sky model. [Wang et al., 2013] If the simulation support the use of the more complex patch-based sky the BRE-IDMP dataset should be used instead of the two latter mentioned datasets in combination with the CIE 171:2006 Test Cases. [Osborne, 2012] The Perez model is based on a single diffuse horizontal value and determines the illuminance distribution of the sky from this. Whereas the patch-based sky in the BRE-IDMP dataset is based on 150 illuminance measurements. The Perez sky model will loose detail in sky conditions with partial clouds where there is variation in brightness across the sky. To make up for this the time step in the measurements of the LBNL and LPBS is lowered to one minute intervals compared to the 15 minute intervals in the BRE-IDMP dataset. Osborne [2012] [Mardaljevic, 2001]

In 2009 Christoph Reinhart pointed out that though the British Building Research Establishment (BRE) has been offering a large dataset of solar and indoor illuminance not many apart from John Mardaljevic have used this as a validation dataset. [Reinhart and Breton, 2009] [Mardaljevic, 2001] Reinhart used a different dataset from the National Research Council Canada (NRC) to compare the performance of Autodesk® 3ds Max® Design 2009 and Daysim 3.0. This dataset has multiple test cases which are more complicated than the BRE dataset, however, it does not include sky luminance distribution only direct and diffuse irRadiance. [Reinhart and Breton, 2009]

For a dataset to be valid to use for future validation against it the accuracy of the dataset must be determined. A common method of determining this is by finding the Mean Bias Error (MBE) which is a measure of the average deviation between the measured and simulated dataset. Previous validation studies suggest a MBE is acceptable within ±20% but a MBE of ±5% is preferable. [Reinhart and Breton, 2009] [Osborne and Donn, 2011] They suggest a MBE of ±5% ensures that design decisions will be based on reality rather than wild simulation errors. The threshold has to be low enough for the dataset to be reliable but high enough to be practically obtainable. [Osborne and Donn, 2011]

Though there have been suggested multiple dataset for validation of daylight analysis programs, there is still no proper benchmark or common practice for validating climate based daylight models against one another. The industry is missing this benchmark of a dataset to compare against or to add to the CIE Test Cases which seems to be the most widely used. For example to determine settings of reflectance, accuracy or dynamic shading.

The investigated studies in this chapter all utilise Radiance for validation against field measurements. Table 3.1 illustrates which situations the various dataset represents.

Table 3.1: Design parameters validated through Radiance against measurements by a selection of previous studies. The studies in grey text include limited datasets.

study/source	dataset	multi-oriented openings	light shelf	internal shading	external shading	dynamic shading	sky model	indoor measurement points×instants	access
[CIE 171:2006, 2006]	CIE 171:2006	×			×		CIE skies		[CIE, 2006]
[Mardaljevic, 2001]	BRE-IDMP		×				Tregenza 145-patch	12×754	john@mardaljevic.com
[Reinhart and Breton, 2009]	NCR Daylight Lab		×	×	×	×	Perez sky model	15×16710 5×3145	[NRC, 2022]
[Osborne and Donn, 2011]	LBNL 71T Test Bed			×		×	Perez sky model	6×7200	[LBNL, 2023]
[McNeil and Lee, 2012]	LBNL OLS Test Space		×				Perez sky model	6×34800+	[LBNL, 2023]
[Geisler-Moroder et al., 2017]	LBNL FLEXLAB			×	×	×	Perez sky model	12×25000	[LBNL, 2023]
[Ng et al., 2001]	ACM, Singapore	×		×			CIE overcast sky	12×32	edwardng@cuhk.edu.hk
[Reinhart and Walkenhorst, 2001]	Fraunhofer Test Office				×	×	Perez sky model	7×10097	christoph.reinhart@nrc.ca
[Reinhart and Andersen, 2006]	NRC Daylight Lab			×			Perez sky model	5×24252	christoph.reinhart@nrc.ca
[Osborne and Donn, 2011]	LPBS NZEB	×			×		Perez sky model	14×1200	
[Karlsen et al., 2016]	The Cube			×	×	×	Perez sky model	8×1500+	line_roseth@hotmail.com
[Karlsen, 2016]	Team Office Oslo	×			×		Perez sky model	11×2000+	line_roseth@hotmail.com
[Campano et al., 2018]	Seville Test Module						Perez sky model	8×38000+	mcampano@us.es
[Kharvari, 2020a]	Carleton University				×		CIE overcast sky	35×4	[Kharvari, 2020b]

Few of the datasets were made with the focus of future use, however, both LBNL, BRE and NRC had this intention with their measurements. Their data should be accessible through their departments or the corresponding author of the mentioned articles in table 3.1. Though how well, documented the selection of the data is, is uncertain. The datasets shown in grey text in table 3.1 are deemed insufficient for general use for CBDM validation. They can be used for specific studies of various types of shading though.

In the following it is elaborated what each of the datasets involve.

3.2.1 CIE 171:2006

CIE 171:2006 Test Cases are used to validate new simulation tools and their performance. The test cases separately tests different aspects of a lighting simulation. These test cases are mostly mathematical theoretical scenarios which eliminates uncertainties. A couple of simple experimental cases are included with limited uncertainties. However, they do not represent complicated real life scenarios. During these tests does give some indication of the performance of a lighting simulation tool. It is useful for scoping where the software program performs well and where it has its limitations for example in regards to direct and indirect sun light, and thereby finding the domain of the applicability of the program. [CIE 171:2006, 2006] [Maamari et al., 2006]

The CIE Test Cases do not validate how the program performs in comparison to real weather conditions or with complicated or adjustable geometry. Hence this method is tailored toward software developers or for comparisons of multiple simulation tools or for optimizing simulation settings in a program. The test cases does have some limitations to validate daylight distribution when it comes to how materials reflect and redirect light, obstruction of light by complicated geometry and exterior environmental conditions. [Maamari et al., 2006]

Though more than 15 lighting analysis programs have been validated against these test cases or a selection hereof, no further work has been done correcting or updating the CIE 171:2006 Test Cases since they were made. Though there are known errors in the test cases. Ian Ashdown suggested being aware of the known errors when using the cases for validation. He listed the known errors found in various validations. [Ashdown, 2016]

An example of one of these errors is for test case 5.8 where CIE 717:2006 states: [CIE 171:2006, 2006]

> "*The test case geometry is a square room of dimensions* $4m \times 4m \times 4m$ *(*$S_T = 96m^2$*), with all surfaces being uniform diffusers and spectrally neutral. An isotropic point light source is positioned at the centre of the room with an output flux (f) of* $10000lm$*.*
>
> *The reflectance is the same for all interior surfaces and varies from* 0% *to* 95%*.*"

Figure 3.1 illustrates the square room illuminated by an isotropic point light source in its centre. The problem is the choice of a box rather than a sphere. This results in lower illuminances at the corners and where the surfaces meet due to inter-reflections between the surfaces. This makes it difficult to compare results between programs as the mesh size or other specifications are needed. [Ashdown, 2016]

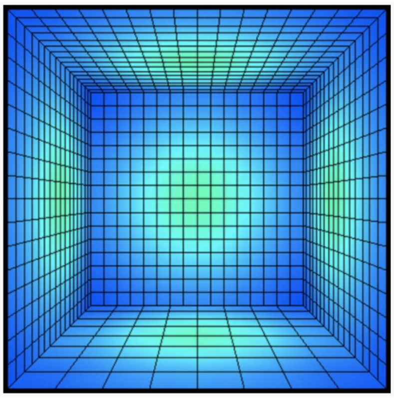


Figure 3.1: Example room with 10% surface reflectance. Illuminance values range from the room corners to the centre of room surfaces. [Ashdown, 2016]

3.2.2 BRE-IDMP

The Building Research Establishment – International Daylight Measurement Programme (BRE-IDMP) dataset has been suggested as a benchmark for illuminance prediction simulations including both daylight and artificial light. [Mardaljevic, 2001] However, it is not used in common practice. The main issue with the dataset is that it has a detailed patch-based sky model which may not be supported by the software. Most daylight simulation tools use a sky model like the Perez sky model based on weather data like DRY. [Osborne and Donn, 2011]

The dataset is measured at the Building Research Establishment (BRE), Garston, UK. It consists of two sets of measured data. One set includes sky illuminance the other indoor illuminance of a room with clear glazing and a room with different innovative glazing systems positioned underneath the roof where the sky measurements were done. Combined these two sets are known as the BRE-IDMP validation dataset.

With the measurement data, the original Radiance simulation model is included. The data provided includes the following files:

- brelum-table-3.12.xlsx
- con_r_w_g2_ex.rad
- meas_rz
- pcell05.hdr
- pcell05.vf
- scene.oct

The Excel file includes all the measurements of both sky and room illuminance, time, temperature and humidity. The rendering of the office mentioned above is shown in figure 3.2.

The accuracy of the dataset is very high though several potentially unreliable measurement combinations appear in comparison with the Radiance simulation. It is suggested that they could occur due to either small geometrical miss-placements of the window panes, bright low-hanging clouds, fast-moving clouds or variation in the reflectance of the external ground due to rain or snow. [Mardaljevic, 2001]

Figure 3.2: Radiance rendering of the 3D model of the room used for measurements in the BRE-IDMP dataset [Mardaljevic, 2000a] mentioned in the article. [Mardaljevic, 2001]

3.2.3 NRC Daylight Laboratory

The daylight laboratory of the National Research Council Canada (NRC) is located in Ottawa, Canada. Two of the datasets in table 3.1 consist of measurements from this facility. The first set by Reinhart and Breton consists of measured direct and diffuse outdoor irRadiance and indoor and outdoor illuminace. The measurements represent five different test cases with varying complexity. The five test cases are illustrated in figure 3.3 along with a rendering of test case 1. [Reinhart and Breton, 2009]

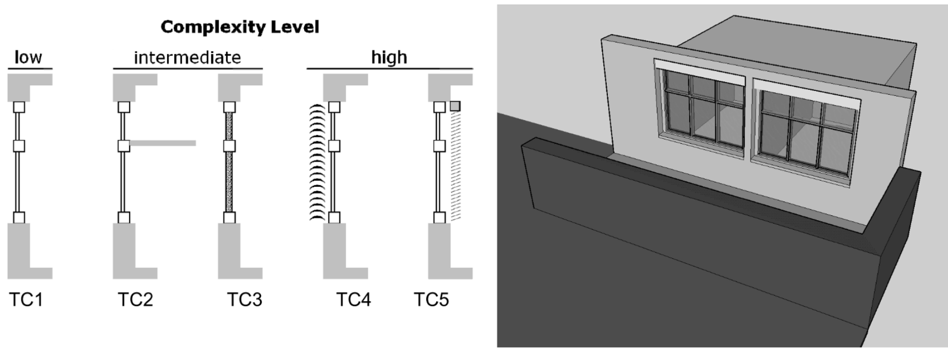


Figure 3.3: On the left the five test cases and on the right a rendering of test case 1 (TC1). [Reinhart and Breton, 2009]

The earlier study by Reinhart and Andersen 3.1 explored a translucent panel, see figure 3.4. [Reinhart and Andersen, 2006]

Figure 3.4: On the left the window with translucent panels and a small regular window pane for outlook, on the right a photo of the exterior of the room. [Reinhart and Andersen, 2006]

3.2.4 LBNL 71T Test Bed

This dataset is from Lawrence Berkeley National Laboratory (LBNL) from their test bed facility 71T. LBNL is located in Berkeley just northeast out of San Francisco. This dataset contains measurements of the sky illumination and of a simple room with only one opening in a wall, see figure 3.5. The room was tested with various shading designs creating more complex daylight distributions, which is something the CIE 171:2006 Test Cases are missing. Furthermore, this dataset allows for the implementation of the Perez sky model with varying sky conditions. [Osborne and Donn, 2011]

Figure 3.5: Pictures of the LBNL 71T test-bed facility. [Osborne and Donn, 2011]

For this dataset uncertainties when comparing to a daylight simulation are based on physical measurements of the geometry, placement of measurement equipment, material details and reflectances, precision of measurements of illuminance, temperature and humidity, details of the surroundings and what unreliable data to discard.

3.2.5 LBNL test facility with OLS

Another set of measurements was made at a test facility at Lawrence Berkeley National Laboratory with an optical light shelf (OLS) installed. [McNeil and Lee, 2012]

Pictures of the test space appear in figure 3.6

Figure 3.6: On the left is a side view of the OLS, in the middle an angled view of the OLS, and to the right a fish-eye picture of the test space. [McNeil and Lee, 2012]

3.2.6 LBNL FLEXLAB

This dataset includes measurements at a new Facility for Low Energy Experiments in Buildings (FLEXLAB) at Lawrence Berkeley National Laboratory, see figure 3.7. [Geisler-Moroder et al., 2017]

Further information on the measurements can be found in the report "*Technology Assessments of High Performance Envelope with Optimized Lighting, Solar Control, and Daylighting Energy Technologies Area*". [Lee et al., 2016]

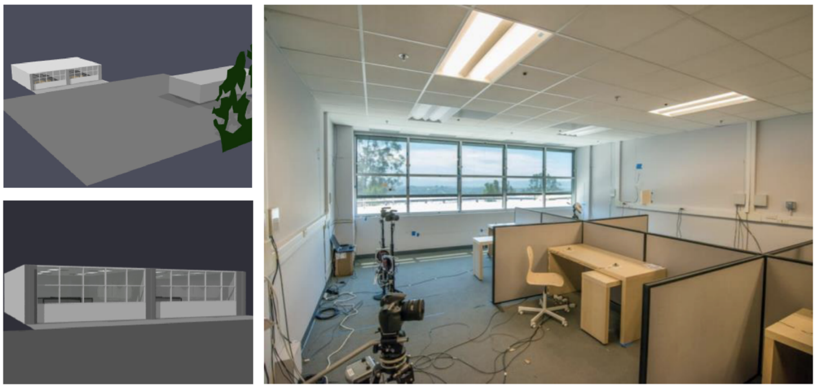


Figure 3.7: On the left are Radiance renderings of the 3D model, and to the right is a picture of the LBNL FLEXLAB. [Geisler-Moroder et al., 2017]

3.2.7 Additional datasets

The additional datasets mentioned in table 3.1 are shown here. However, this study found these datasets of less relevance due to the size of the datasets. Further information on these can be found in the articles which are cited.

ACM, Singapore

Measurements were made in a salon at the Asian Civilisation Museum ACM in Singapore which is shown in figure 3.8. [Ng et al., 2001]

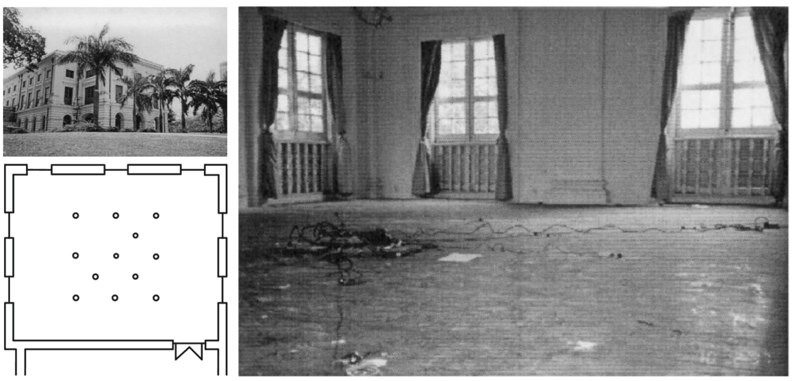


Figure 3.8: On the top left is the ACM from the outside, on the bottom left is a plan drawing of the salon including sensor points, and on the right a photo from inside the salon. [Ng et al., 2001]

Fraunhofer test office

Measurements were made at the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany. The office appears in figure 3.9. [Reinhart and Walkenhorst, 2001]

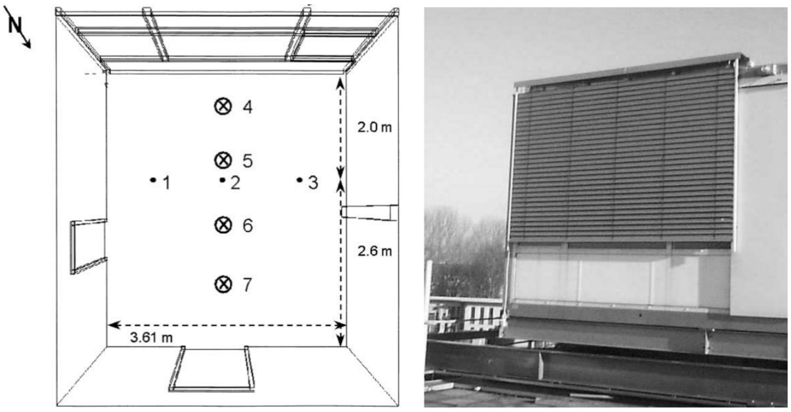


Figure 3.9: On the left an illustration of the test office including sensor points, and on the right a photo from outside showing the external blinds. [Reinhart and Walkenhorst, 2001]

LPBS Net Zero Energy Building

Laboratoire de Physique du Bâtiment et des Systèmes (LPBS) is on Réunion island which is located east of Madagascar in the Indian Ocean but is a French region. [Osborne and Donn, 2011] The building used for measurements is a complicated Net Zero Energy Building (NZEB), see figure 3.10.

Figure 3.10: Rendering of the 3D model of LPBS Net Zero Energy Building. On the left are details of the classroom. [Osborne and Donn, 2011]

The Cube

Measurements for this dataset were conducted at Aalborg University, Aalborg, Denmark. The test facility The Cube appears in figure 3.11. [Karlsen et al., 2016] Further information on the measurements can be found in the PhD dissertation by Line Karlsen. [Karlsen, 2016]

Figure 3.11: On the top left is a sketch of the external shading, on the bottom left is a sketch of the interior and on the middle and the right pictures of the Cube without and with external shading. [Karlsen et al., 2016] [Karlsen, 2016]

Team Office Oslo

Measurements were made in a team office on the 15th floor in Oslo, Norway. Sketches of said test space appear in figure 3.12. [Karlsen, 2016]

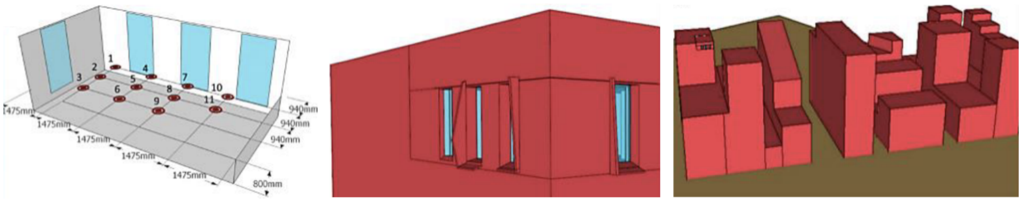


Figure 3.12: Sketches of the interior on the left, the facade in the middle and the location in relation to the surrounding buildings on the right of the team office in Oslo. [Karlsen, 2016]

Seville Test module

Measurements were made in one of the four test cells at Seville University, Spain. The test module appears in figure 3.13. [Campano et al., 2018]

Figure 3.13: On the top left a photo from inside the test room, on the bottom left an illustration of the test room including sensor points, and on the right a photo from outside. [Campano et al., 2018]

Carleton University

The dataset of measurements from Carleton University, Ottowa, Canada, was done in a room with one opening with single glazing. The dataset is limited as it only includes a single sky and illumination condition. [Kharvari, 2020a]

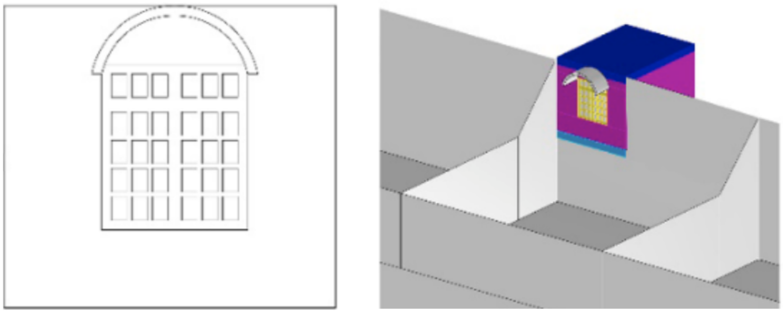


Figure 3.14: On the left a drawing of the window details on the right a rendering of the model. [Kharvari, 2020a]

The study aimed to find the most accurate Radiance parameter settings and create a validated model for future studies on daylight. The available material includes the Rhino and Honeybee models and the measured illuminances, which are freely accessible. [Kharvari, 2020b]

3.3 Discussion of validation of CBDM

Validation of CBDM is crucial for the method to have any use in the building industry. The choice of comparative or experimental comes down to the use. Experimental validation is preferable due to accuracy and limiting uncertainties. However, it is time-consuming and expensive. Until a benchmark of a validation suite is available this method is primarily for researchers.

Software developers use comparative validation or validation against the CIE 171:2006 Test Cases, if any, as this is cheaper. [CIE 171:2006, 2006] See table 4.2. Engineers and architects in the building industry are left with the difficulty of choosing appropriate software and parameter settings for CBDM. If a benchmark for validation were to arise in the future providing a list of accredited software followed by a more specified guideline by the authorities on settings, then the industry would get more aligned and utilize CBDM more. If said software is available for free.

The guidelines might state the benchmark to compare against along with design and parameter settings such as ambient bounces, sky model and discretization and which output metric to use. As long as these are open choices to be made by the individual user, results should be used with caution for inter-model comparison or compliance with building regulation codes.

The choice of a validation set for an experimental validation benchmark should possibly consist of a combination of the CIE 171:2006 Test Cases and a set of measured data. To both test individual parts of the calculation algorithm and also the accuracy when simulating the complexity of real daylight. Such a suite could contain the BRE-IDMP dataset as it is the most extensive with sky luminance distribution. However, such data is not generally available for other sites as sky scanners are rare and some software use sky models. Radiance simulations based on sky models have been shown to lead to satisfying results. [Reinhart and Andersen, 2006]

If CBDM using sky models based on direct and diffuse illuminances is acceptable as studies have shown then datasets from NRC Daylight Lab or LBNL are recommendable. [Reinhart and Breton, 2009] [Geisler-Moroder et al., 2017] The difficulty in using a sky model is that it becomes difficult to differentiate between errors based on the sky model and the simulation algorithm. [Reinhart and Andersen, 2006] A further advantage of these datasets is the use of internal, external and dynamic shading which is a reality in modern building design. The NRC Daylight Lab dataset was created based on having a CBDM dataset for distribution to software engineers. [Reinhart and Breton, 2009] The BRE-IDMP dataset is available for educational use, however, for commercial use it has to be extensively approved.[1]

Another consideration when comparing useful datasets is the measurement instances. For annual metrics measurements of every hour of the year with daylight might be preferable though it is difficult and impractical. A smaller time-step of say every minute or every 15 minutes measured over several days may be sufficient. [Reinhart and Breton, 2009] [Osborne and Donn, 2011]

[1] private correspondence with John Mardaljevic

4 CBDM Tools & Methods

Simulations are replacing most scale model approaches in the industry when it comes to daylight analysis. [Reinhart and Fitz, 2004]

There is a collection of tools for Climate-Based Daylight Modelling, CBDM, but no clear guidance or comparison of these. CBDM has been possible since 1982 in a limited form though it was properly developed in the 90's, where Radiance was utilized for annual daylight simulations based on dynamic sun and sky conditions. It got the name climate-based daylight modelling in 2006. [Mardaljevic, 2000b] [Reinhart and Herkel, 2000] [Brembilla, 2017]

The key challenges with CBDM tools have been identified as accuracy, generality and practicality. Results have to be accurate though found in a reasonable time, the tool has to be generalized to handle complex situations with a user-friendly interface, and it has to be validated to apply to the industry. [Ward, 1994]

Radiance is considered the Benchmark for daylight simulations. [Brembilla, 2017] Radiance is free software. However, Radiance is rarely used in the industry as a stand-alone program due to the lack of a visual user interface. It runs in a UNIX-based environment on Linux® or Mac OS® making it quite inaccessible. Software engineers have incorporated it as a calculation core through other tools which are more user-friendly in this form a version for Windows® is available. See the digitally attached Appendix *Subramaniam, 2017 - Appendix F* referred to in Appendix A for some modifications to be aware of if running Radiance on Windows®. A study from 2004 showed that Radiance compatible tools are the most predominant in the industry for climate-based daylight modelling. Radiance is the preferred underlying algorithm for simulations though the interfaces may differ due to the ability to create physically accurate rendering. [Reinhart and Fitz, 2004]

On this basis, Radiance was chosen as the focal of this project. This chapter mainly focuses on tools that utilize Radiance programs as a backward ray tracing engine for daylight simulations as Radiance is the most versatile and precise engine. [Brembilla and Mardaljevic, 2019] Furthermore, Radiance is well-validated both experimentally and comparatively.

4.1 Radiance

Radiance is an experimentally validated daylighting simulation tool, see table 4.1. Radiance has the advantage over other daylight calculation or rendering tools, in that it has very few geometry and material limitations. Furthermore, the simulations are based on the physical properties of daylight. Radiance can be used to simulate spectral Radiance (luminance and color), irradiance (illuminance and color) and glare indices. [McNeil, 2019]

Radiance traditionally uses backward ray tracing as a rendering technique. Backward ray tracing calculates the distribution of rays from a view point rather than the light source as forward ray tracing. The method is faster than forward ray tracing as the number of rays is limited to the ones reaching the view point. Both reflection, transmission and refraction of surfaces are supported which allows for simulation of complex materials. Since 2015 bi-directional ray tracing (photon mapping) has also been possible with Radiance. A more thorough description of Radiance and ray tracing techniques appears in chapter 5. [SBI 2013:26, 2013] [Watt, 2000]

4.1.1 Calculation Methods

Table 4.1 indicates some common Radiance calculation methods and their respective experimental or comparative validation. These methods are described in this section.

Table 4.1: Common Radiance calculation methods. Validations before 2006 were performed for clear glazing.

calculation method	**Radiance command**	**experimental validation**	**comparative validation**
4-component	*rtrace*	[Mardaljevic, 2000b]	[Reinhart and Herkel, 2000] [Mardaljevic and Prost, 2023]
DAYSIM	*rtrace*	[Reinhart and Walkenhorst, 2001] [Reinhart and Andersen, 2006]	[Brembilla, 2017]
2-Phase	*rcontrib*		[Brembilla, 2017]
3-Phase	*rcontrib*	[McNeil and Lee, 2012]	[Brembilla, 2017]
4-Phase	*rcontrib*	[Wang et al., 2016a][Wang et al., 2016b]	
2-Phase DDS	*rcontrib*	[Reinhart and Breton, 2009]	[Bourgeois et al., 2008]
5-Phase	*rcontrib*	[Geisler-Moroder et al., 2017]	[Brembilla, 2017]
6-Phase	*rcontrib*	[Wang et al., 2016a][Wang et al., 2016b]	
Photon Mapping	*mkpmap+rcontrib*	[Schregle and Wienold, 2004]*	

* Experimental validation in model with artificial lighting. All other experimental validations on this list was conducted with measurements of sky and sun illuminance.

The 4-component method is considered the benchmark of CBDM. [Brembilla, 2017] It was thoroughly experimentally validated in 2000 though the name of the method was given later. [Mardaljevic, 2000b] The 4-component method uses backward ray tracing to collect the contribution of four different components. The four components are respectively: direct and indirect sunlight, and direct and indirect skylight.

The direct sunlight is found in a deterministic way determined from the closest of 2056 sky patches to the actual sun position. For further explanation of sky discretizations see figure 5.8 in section 5.2.3.

The direct skylight is similarly found in a deterministic calculation by the distribution of 900 light sources distributed over 145 rectangular sky patches, see figure 5.8.

The indirect components are determined by stochastic calculation from 145 circular sky patches, see figure 5.8. Indirect sunlight is found from the reflected contribution from one of 145 points in the sky being closest to the actual sun's position.

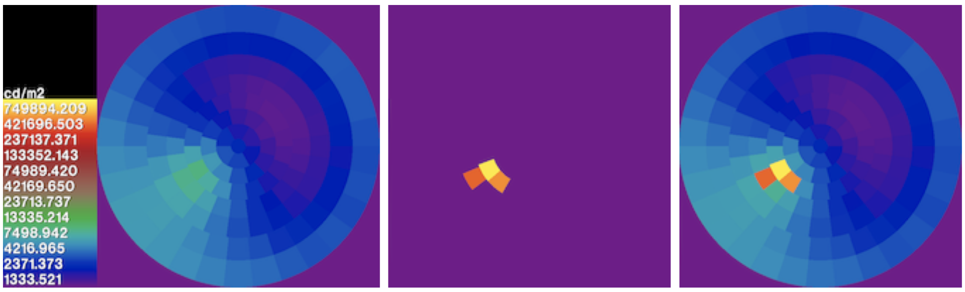
Once the daylight coefficients of the four components have been found by iteration of the three calculation methods the resulting illumination values of the sensor points are found by matrix multiplication.

The hybrid of deterministic ray tracing and Monte Carlo stochastic method is due to efficiency and accuracy. [Ward, 1994]

> "The deterministic approach will never render all of the interactions and details we wish to see, and the stochastic approach takes forever to reach a reasonably noise-free solution. What we want is a technique that captures the best of both worlds, rendering all important phenomena, yet finishing in a reasonable time with a manageable amount of noise" [Ward and Shakespeare, 2021]

Another Radiance calculation method is known as DAYSIM. DAYSIM is also the name of the software that contains a user interface. DAYSIM uses a modified version of the same ray tracing engine command, *rtrace*, as the 4-component method making the simulation faster. The daylight coefficients found include both direct sunlight and indirect light components. [Brembilla, 2017]

Another Radiance command, *rcontrib*, calculates daylight coefficients through backward ray tracing by calculating the sun and sky contributions as one. Here the sun illuminance is assigned to the three sun patches closest to the sun position, see figure 4.1. The command was first introduced in 2005 as *rtcontrib*. [Brembilla, 2017]



(a) Diffuse (b) Direct (c) Global

Figure 4.1: The intensity of (a) a diffuse sky (b) direct sun (c) global combination of diffuse sky and direct sun in 145 Tregenza patches. [Jacobs, 2010]

The command *rcontrib* is the basis for the six methods:

- 2-Phase Method
- 3-Phase Method
- 4-Phase Method
- 2-Phase DDS Method
- 5-Phase Method
- 6-Phase Method

The six methods are indicated in figure 4.2 and 4.3.

The first three methods 2-, 3-, and 4-Phase Method all have the same essential three steps: Flux-Transfer calculations (A), Sky-vector calculations (B), and Calculation of results (C). See figure 4.2

The Flux-Transfer calculations (A) trace the path of light from an indoor space to the sky by constructing flux-transfer matrices. The calculation of sky-vectors (B) is an estimation of the brightness of the sky. Finally, by relating the brightness of the sky by multiplication to the brightness inside the space, adding and transforming the matrices from the first two steps illuminance and luminance values are generated giving the results (C). [Subramaniam, 2017]

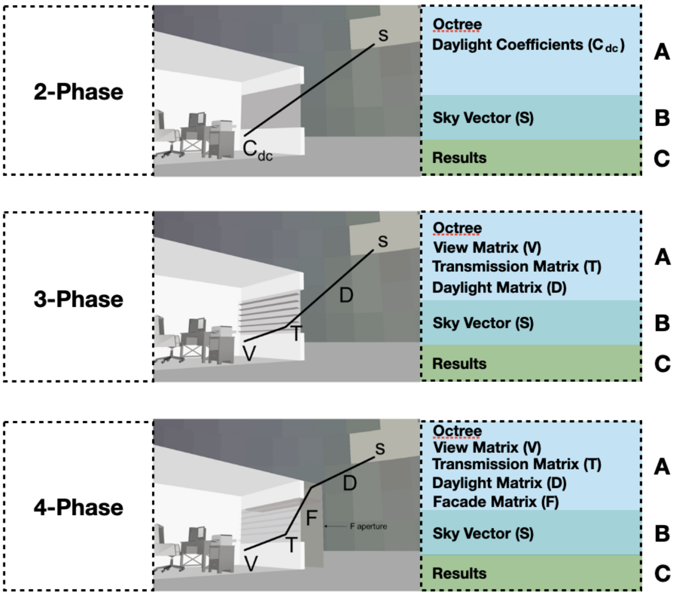


Figure 4.2: Schematic overview of the 2-Phase, 3-Phase and the 4-Phase Method. Each method has three steps as indicated: (A) Flux-Transfer Calculation, (B) Sky Vector Calculations and (C) Calculation of Results. Each notation in the illustrations represents a matrix. [Subramaniam, 2017]

The difference between these three methods is in the first step (A). In the 2-Phase Method only a matrix of Daylight Coefficients (Cdc) is calculated, see section 5.1.1. In the 3-Phase and 4-Phase Method, multiple matrices are calculated: View Matrix, Transmission Matrix and Daylight Matrix. In the 4-Phase Method, an additional matrix called the Facade matrix is added. [Subramaniam, 2017] See figure 4.2.

Furthermore, the 2-Phase Method does the Flux-Transfer (A) and Sky-vector (B) calculations in one for faster simulation. The 3- and 4-Phase Methods involve two separate ray tracing processes: one from the sensor points to the fenestration system (A) and one from the fenestration system to the sky (B). This separation allows for simulations of complicated fenestration systems (CFS). CFS means window technology including a layer with changing properties or a layer of a non-transparent material such as a light shelf. This includes shading devices such as venetian blinds or other dynamic internal or external shading, electrochromic glazing and light pipes amongst others. [Buenoa et al., 2015] [Ward et al., 2011] [Brembilla, 2017]

The Transmission Matrix is used to define the optical behaviour of the fenestration system: How angle-dependent light is transmitted and reflected by using a Bidirectional Scattering Distribution Function (BSDF). Scattering means the combination of transmittance and reflectance. BSDF thereby describes how light interacts with a given material. [McNeil et al., 2013] The 4-Phase Method includes a matrix for external shading systems which are non-planar to the window such as overhangs or fins: Facade Matrix (F). [Ward et al., 2011] Brembilla [2017]

The additional three methods of backwards ray tracing which Radiance can perform; 2-Phase DDS Method, 5- and 6-Phase Method, are built on each of the first three described methods respectively. The initial calculation results are the same, To improve the results two additional independent components are simulated beside the Main Simulation: Direct component and Accurate direct-sun. The direct component is then subtracted and the accurate direct-sun results are added as indicated in figure 4.3. This use of a more accurate direct-sun contribution results in better and more accurate spatial resolution results. [Subramaniam, 2017] Brembilla [2017]

The sun's position is approximated to three or four sky patches in the first three calculation methods. For the more accurate direct-sun calculation of the last three methods, more sun coefficients are calculated for the sky to minimize the errors occurring due to the inaccuracy in results of the first three methods including direct sun near a sensor point. [Subramaniam, 2017]

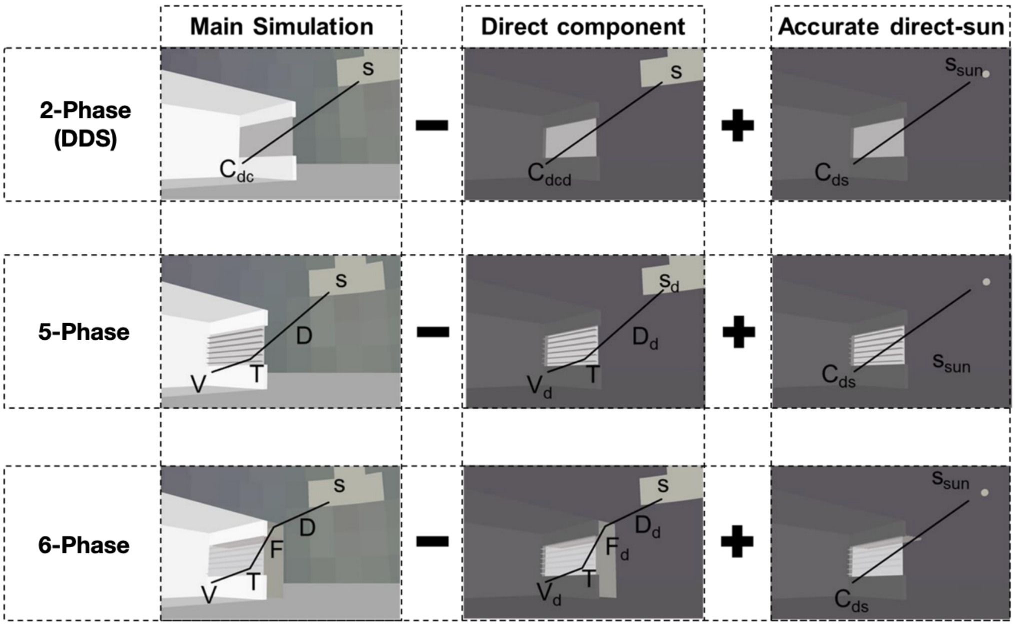


Figure 4.3: Schematic overview of the 2-Phase DDS Method, the Five-Phase Method and the Six-Phase Method. The "Main Simulation" refer to the Two-Phase Method (top), Three-Phase Method (middle) and the Four-Phase Method (bottom). The three new methods involve additional steps that improve the accuracy of the first three methods respectively. The + and – signs in the above image indicate how the results from each stage are added and subtracted from one another. [Subramaniam, 2017]

The discretization of the sky and the sun's position affect the accuracy of each of the methods. Further explanation on how and why the sky is divided is found in section 5.2.3.

In 2015 an extension allowing for Radiance to perform Photon Mapping was included. Photon mapping involves a combination of forward and backward ray tracing for faster simulation. The extension works in combination with one of the mentioned methods. The extension adds a forward ray tracing step and assigns flux values to the surfaces. Further description is found in chapter 5. Radiance photon mapping has some limitations in the current integration, however. It only complies with the daylight coefficient method; 2-Phase and 2-Phase DDS. It does not work with the original Radiance programs handling CFS or BSDF: *mkillum* and *genBSDF*. Therefore it does not work with the 3-, 4-, 5- or 6-Phase Method. However, photon mapping is a faster method which makes it possible to visualize and calculate lighting effects from caustics, reflections on curved specular surfaces and daylight redirecting systems without BSDFs. [Schregle et al., 2015a] [Schregle et al., 2015b]

4.2 Choice of CBDM method

An advantage of the 3-, 4-, 5- and 6-Phase Methods is that multiple fenestration systems can be evaluated without running the entire simulation again by replacing the Transmission Matrix. The 2-phase and 2-phase DDS methods are not compatible with CFS they are fast, however, for CBDM of rooms with one simple opening, they can be combined with Photon Mapping. [Brembilla, 2017] [Schregle et al., 2015b]

A suggestion for when to use each of the different methods of backward ray tracing and photon mapping is illustrated in figure 4.4. [Subramaniam, 2017] [Schregle et al., 2015b]

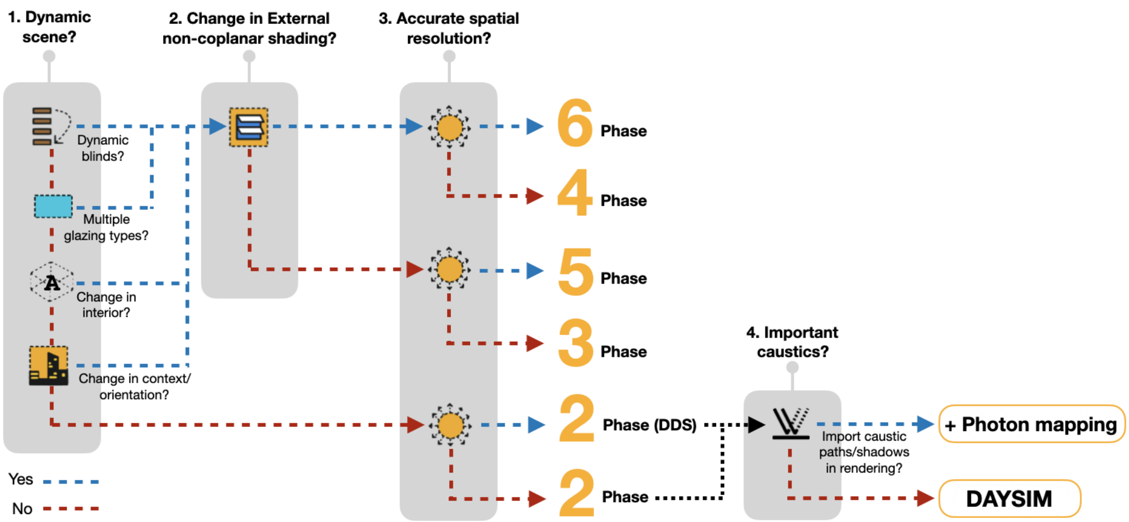


Figure 4.4: Decision tree for determining the appropriate Radiance backward ray tracing method for CBDM based on a graphic by Mostapha Sadeghipour Roudsari [Subramaniam, 2017] with the addition of photon mapping. [Schregle et al., 2015b]

Figure 4.4 presents four main questions:

1. Is the scene dynamic? Are investigations of any of the following relevant:
   - dynamic shading
   - multiple types of glazing or mullions
   - interior layout, furnishings or surface materials
   - surroundings or orientation of the building
2. Is multiple choices of geometries/ placements of external non-coplanar shading being investigated?

3. Is the quality of rendering output important, especially in terms of shades?
4. Are there important shades or caustics for the rendering?

The various choices mostly represent the different matrices in the various models. Meaning, does a building model have dynamic shading or if multiple glazing types are to be evaluated while the rest of the model stays the same, then the 3- or 5-Phase Method would be the appropriate choice depending on how accurate the need for the direct sunlight is in the rendering. The methods would have the advantage that once the first simulation is computed only the transmission matrix has to be replaced to compute new results for comparison.

For small simple models without CFS all the methods will produce useful accurate results. Only varying slightly in accuracy and simulation time. If only CBDM values are relevant and not accurate images then the 3-phase or 4-Phase Method is preferred for fast results. For climate-based daylight metrics using the more accurate sun component has a minor effect on the accuracy compared to the additional simulation time and is therefore not recommended. The 5- and 6-Phase Method are more relevant in cases where the precision of shadows and their edges are relevant for the rendering images. [Jones, 2017]

The advantage of DAYSIM, 2-phase and 2-phase DDS are the speed especially the two latter in combination with photon mapping. The disadvantage, however, is a lack of accuracy in dark spaces and an entirely new simulation has to be run respectively to investigate multiple design solutions.

For annual daylight metric results the 3- and 4-Phase Methods seem to be most applicable in simulation time and setup while being accurate. Both methods allow for faster computation of dynamic shading than DAYSIM, 2-phase and 2-phase DDS.

For the most precise and realistic rendering the 5- and 6-Phase Methods should be chosen if various design choices are to be investigated. However, if a real representation of objects which are highly reluctant to cause caustics then 2-phase DDS combined with Photon Mapping is the optimal choice.

4.3 Radiance correlation with other software

Multiple software has integrated Radiance for rendering or for calculating daylight illumination giving Radiance a graphical user interface. The U.S. Department of Energy keeps a dynamic list of these tools. [DOE, 2014] Furthermore, the International Building Performance Simulation Association – USA has an energy use software tool directory where some Radiance-based tools appear. [IBPSA, 2023]

Part of this list of software that utilizes Radiance for annual daylighting simulations appears in table 4.2.

The software tools listed in the lower section in table 4.2 additionally include the option of energy use and thermal simulations.

Table 4.2: A collection of tools providing a graphical user interface for Radiance-based annual daylight simulations. [Brembilla, 2017] Software in the lower section also includes options for thermal calculations, some through their coupled software, while the top section only performs CBDM.

software	Radiance calculation method	comparative validation	availability
Accelerad	DAYSIM, 3- and 5-phase	[Jones, 2017]	free
Autodesk Ecotect	DAYSIM	[Vangimalla et al., 2011]	discontinued
DAYSIM	DAYSIM	[Brembilla, 2017]	free [1]
EvalDRC	photon mapping		in-house [2]
Groundhog	2-phase		free [3]
LightStanza	3- and 5-phase	[Sunger and Vaidya, 2019]*	$
LiVi	2-phase		free [4]
ArtLight	3-phase	[Hauer and Geisler-Moroder, 2017]	in-house [5] [6]
ClimateStudio		[Aguilar-Carrasco et al., 2023]	$ [7]
DALEC	3-phase	[Werner et al., 2016]	free online [8]
DIVA-for-Rhino	DAYSIM	[Aguilar-Carrasco et al., 2023]	discontinued
FENER	3-phase	[Buenoa et al., 2015]	free
Honeybee + Ladybug	DAYSIM, 3- and 5-phase	[Kharvari, 2020a]	free [7]
IDA ICE	3-phase	[Solvang et al., 2020][EQUA, 2023]	$
IESVE	2-phase	[IES, 2023]	$
OpenStudio	3-phase	[Muhammad and Aliyu, 2021]*	free
Trimble® Sefaira	DAYSIM		$ [3]
TypeDLT	3-phase		free [6]

* experimental validation
[1] the graphical interface is discontinued - require a third party software [Reinhart, 2013]
[2] at Lucerne University of Applied Sciences and Arts, CC Envelopes and Solar Energy
[3] Requires SketchUp which is not free software
[4] part of the VI-suite for Blender which is free open-source
[5] at the University of Innsbruck, Institute for Construction and Material Science
[6] Requires TRNSYS which is not free software
[7] Requires Revit and Rhino with Grasshopper which is not free software
[8] https://dalec.zumtobel.com/#room

In table 4.2 the availability of the software tools appear. A minor selection of the tools is truly available for free. Some are free extensions though the main software is costly. Also, comparative validations are listed. The Danish building regulations state that software used for CBDM compliance documentation has to be validated. Where no citation appears no validation has been found. [BR18 - 18 Guidance, 2021]

In the following, some of the commonly used tools in the Danish building industry are elaborated on including DAYSIM, Honeybee, DIVA-for-Rhino, ClimateStudio and VELUX Daylight Visualizer. The latter does not appear in table 4.2 as it does not utilize Radiance.

4.3.1 DAYSIM

DAYSIM calculates both daylight autonomy (DA) and useful daylight illuminance (UDI). As mentioned DAYSIM is based on the backward ray tracing engine of Radiance in the current version using a slightly modified version of the *rtrace* command with the DDS method added for more accurate direct sun contributions. This engine is slightly faster than traditional Radiance calculation. The program was the first to give a graphic and easy-to-use interface to the end-user and has been experimentally validated. [Reinhart and Walkenhorst, 2001] [Reinhart et al., 2006] [Subramaniam, 2017] [Brembilla and Mardaljevic, 2019]

DAYSIM has some fixed simulation settings which limit the control for the user slightly. The choice of materials is only a fraction of the ones supported by Radiance. DAYSIM uses the simple Trengenza sky discretization of 145 sky patches and does not allow the user to choose a more accurate discretization. Whereas in the DDS method, more accurate choices are possible for the direct sun contribution. However, DAYSIM has a user behaviour model that predicts occupant use of electrical lighting and shading controls. [Reinhart, 2010] [Brembilla and Mardaljevic, 2019]

DAYSIM is used by a lot of other programs for CBDM, however, it should be noted that some of these programs may include results of other metrics and here caution is necessary:

> "Metrics based on direct sunlight – such as ASE – are not as accurate, due to the simultaneous presence of four suns in the sky at any given daytime, which lead to the creation of unrealistic solar patterns on the working plane. For the same reason, any evaluation that strictly depends on the sun angle and intensity should not be based on the results obtained from DAYSIM's interpolated mode." [Brembilla, 2017]

4.3.2 Honeybee

Honeybee legacy and HoneybeePlus are extensions to Grasshopper in Rhinoceros3D. Honeybee legacy is based on DAYSIM for CBDM whereas HoneybeePlus uses the 3- and 5-Phase Method directly from Radiance.

Requirements to run Honeybee are Revit with Rhino and Grasshopper. Honeybee legacy needs Ladybug as well. Each of the programs is licensed making it very inaccessible and expensive.

4.3.3 DIVA-for-Rhino & ClimateStudio

DIVA-for-Rhino was recently replaced by ClimateStudio which besides doing faster and more accurate daylight simulations also utilizes EnergyPlus to include thermal analysis. [Solemma LLC, 2021] DIVA-for-Rhino was based on DAYSIM.

ClimateStudio uses Radiance with progressive path-tracing. By performing a set of calculation passes of only a few light paths at a time. The accuracy of each pass is thereby very low. The result is updated for each pass and convergence is found a lot faster than traditional Radiance methods as a lot less ray-traces are calculated. Resulting in seemingly accurate results. [Solemma LLC, 2023]

DIVA-for-Rhino and ClimateStudio have been validated using CIE 171:2006 Test Cases. [CIE 171:2006, 2006] Though comparative validation is still needed to evaluate how the accuracy of ClimateStudio is affected by the progressive path-tracing technique. The lack thereof does make it uncertain whether ClimateStudio is an appropriate tool for documentation. [Aguilar-Carrasco et al., 2023]

Requirements to run ClimateStudio are similar to DIVA-for-Rhino and Honeybee: Revit with Rhino and Grasshopper. Each of the programs is licensed making it very inaccessible.

4.3.4 VELUX Daylight Visualizer

VELUX Daylight Visualizer is a popular software in Denmark. The program was updated in 2023 to now perform CBDM. The program calculates the three climate-based daylight metrics sDA, UDI and Total Annual Illumination (TAI). [Roy, 2022]

The validation report is yet to be released so the information on the program is limited. However, it does not utilize Radiance for simulations. The climate-based daylight modelling is made by Luxion. The program uses bi-directional ray tracing with photon mapping algorithms. [VELUX, 2023] [Roy, 2023]

Photon mapping is faster than backward ray tracing and is more accurate in some complex lighting scenes e.g. including light pipes. [SBI 2013:26, 2013]

This simulation tool has some limitations and a lot of the parameters for the simulation are locked and unknown by the user. Without access to the validation report, this study cannot draw any further conclusions on the performance of Daylight Visualizer. That is for future work. VELUX Daylight Visualizer is available for free, however, it does not incorporate thermal climate simulations.

The metric sDA should be used with caution in challenging zones. VELUX Daylight Visualizer may give misleading results of this metric in shaded areas as the photon mapping of the indirect sun and skylight can cause severe miss calculations. [Mardaljevic and Prost, 2023]

4.4 Reflection on CBDM methods

For climate-based daylight modelling, Radiance is seen as the ultimate truth. This is due to the accurate ability to create renderings, illuminance values or contour plots representing the visual quality and illuminance of a build environment. Often highlighted as the advantage over other daylighting tools is the ability to handle almost any geometry and material type and how daylight is reflected and refracted by the surfaces. On the other hand, the many choices and settings without a user interface require a major know-how of the user.

This is likely the reason why multiple software tools utilize the Radiance calculation algorithms though giving it an intuitive user interface and a limited set of choices for the user. For research full flexibility and complexity is preferable whereas for engineers and architects in the building industry functionality is desirable. This is the reason for the simplicity of available software giving Radiance a user interface. Some settings are locked and chosen by the software developer to simplify the tool.

For compliance with the Danish Building Regulations CBDM has to be performed through a validated software. It is not specified whether the validation has to be experimental or comparative. Few of these tools are validated and free for use. Amongst those only two also allow for thermal comfort and energy simulations: DALEC and FENER. See table 4.2. DALEC has a major limitation in that it cannot import 3D models and can only set up simple rectangular rooms with an opening on one wall. FENER has not been investigated thoroughly in this study. FENER does however have some limitations to the energy model limited to one thermal zone without humidity calculations. An advantage of FENER is the support of dynamic solar shading control. Since all the programs are based on Radiance which is heavily experimental and comparatively validated software, all the programs could be argued to satisfy the Danish Building Regulations requirement.

If the cost is of no importance then ClimateStudio seems to be a good choice for combining CBDM, thermal comfort and energy simulations. However, the tool still needs comparative or experimental validation to evaluate the accuracy. Honeybee is also costly in acquiring Revit and Rhino and does require the user to build the simulation from components. IDA ICE could be another choice though the tool is quite complicated and is mainly used for research. Most other tools listed in table 4.2 are based on open-source or involve visual coding requiring the user to have a lot of know-how to provide usable results.

Based on this research no inexpensive existing software which combines CBDM, thermal comfort and energy use simulation can be recommended for the building industry. Such an accessible and functional tool is still missing. Having the CBDM component based on Radiance seems a good choice as it is a well-documented software with high-fidelity of reality.

Using Radiance for CBDM the choice of calculation method comes down to multiple aspects. For a tool for general use in the building industry for assisting with design choices and compliance documentation of the building regulations, the following should be considered. If caustics or dark rooms are important then photon mapping and the 2-Phase Method are desirable. For most cases, however, the 3- or 4-Phase Method is preferable, especially for the comparison of various design solutions of shades, glazing types and orientation. If accurate representation of shadows are important in renderings then the 5- and 6-Phase Method should be chosen.

Radiance 5

This project is based on a pre-release of Radiance version 5.4a (2023-07-16). [McNeil, 2019] The latest official release is 5.3 which was released in September 2020.

Radiance is a collection of well over fifty programs which run either interactively or in batch mode. [Mardaljevic, 2001] The programs has a wide range of functions such as object modelling, conversion of data, calculations, analysis, rendering, image processing and display. Together the package is a sophisticated program for lighting analysis and visualization. See a list of the programs along with a short description in Appendix B. [Ward and Shakespeare, 2021]

The advantage of Radiance is its flexibility and ability to accurately simulate light behaviour in complicated environments. Both represented by accurate numerical results and renderings which looks like replicas of photographs. [Ward and Shakespeare, 2021]

Like other daylight simulation programs Radiance needs three main components: data on the building and its surroundings, sky condition information including a sky model and the calculation method to predict indoor illuminance distribution, see this illustrated in figure 5.1.

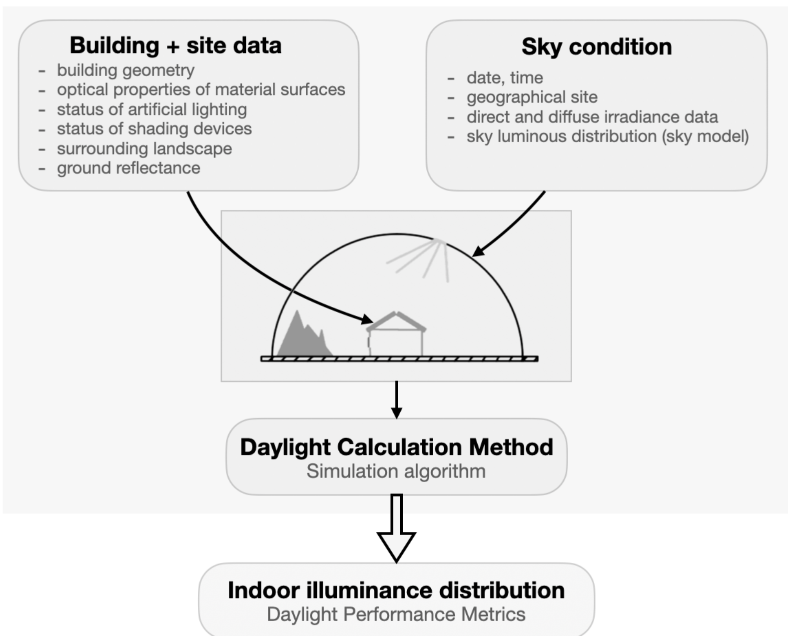


Figure 5.1: Information required to perform CBDM with Radiance. [Reinhart, 2010] [Ayoub, 2019]

The following sections describes the ways of Radiance in more detail.

5.1 Radiance ray tracing methods

This section elaborates on the principles behind the nine Radiance CBDM methods explained in section 4.1.1. The three principles are the Daylight Coefficient method, backward ray tracing, and photon mapping.

5.1.1 Daylight Coefficient Method

The daylight coefficient method was proposed in 1983 by Tregenza and Waters. [Tregenza and Waters, 1983] The method is based on the assumption that the indoor and outdoor illumination are directly proportional by a constant factor. If both the indoor working plane and the outdoor sky are described by subdivisions of finite elements then indoor illuminances can be predicted for various sky conditions by a matrix multiplication, see equation (5.1). [Brembilla and Mardaljevic, 2019]

$$\mathrm{E} = DC \times S \tag{5.1}$$

E being the internal illuminances, **DC** is the daylight coefficients and **S** the sky matrix. The constant factors are determined by a daylight simulation tool such as Radiance by deterministic algorithm or stochastic sampling and then grouped in the **DC** matrix. Indoor illuminances can then easily be iterated for a full year if the sky matrix includes hourly values for a year of the typical sky luminance distribution.

Equation (5.1) represents the Radiance 2-Phase Method graphically illustrated in figure 4.2.

5.1.2 Backward ray tracing

> "Ray tracing is a rendering technique based on the calculation of the distribution of a large number of rays emitted in a scene – either from light sources (forward ray tracing) or a view point (backward ray tracing). Backward ray tracing is a faster method than forward ray tracing because it only calculates rays reaching the view point. On the other hand, it is less or not suitable for use in cases where light sources are hard to find in the scenes, i.e. narrow light well, or light pipe. Ray tracing algorithms support reflection, transmission and refraction properties of surfaces, which permits the use of complex materials in simulations." [SBI 2013:26, 2013]

Figure 5.2 illustrates the principle of backward ray tracing from daylight and artificial lighting. When determining climate-based daylight metrics instead of rendering images the view point is replaced by measurement points where the rays are traced from.

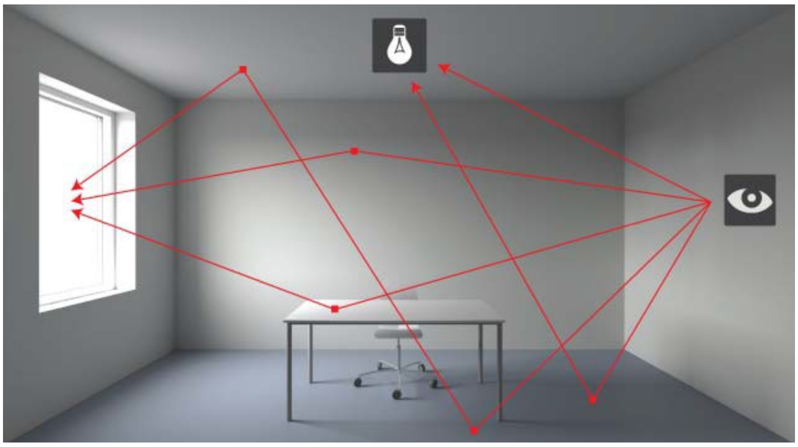


Figure 5.2: Illustration of the backward ray tracing method. [SBI 2013:26, 2013]

Due to the use of backward ray tracing Radiance is capable of replicating real-life diffuse inter-reflections between surfaces, instead of defining an ambient light without a source. [Jacobs, 2012]

5.1.3 Photon Mapping

Photon mapping is a two-pass rendering technique using a bi-directional form of ray tracing. The method was developed by Henrik Jensen in 1995. [Jensen, 1996] First a photon map is created by tracing photons emitted from light sources with forward ray tracing and storing the flux in the surfaces. The second pass involves backwards ray tracing applied from the view point towards the surfaces which is used to render the final image. The concept of photon mapping is illustrated in figure 5.3. With bi-directional ray tracing all possible light transport paths are accounted for, even illuminance from rays which are not directly intercepted by the view point. [Jensen, 1996] [SBI 2013:26, 2013] [Schregle, 2019]

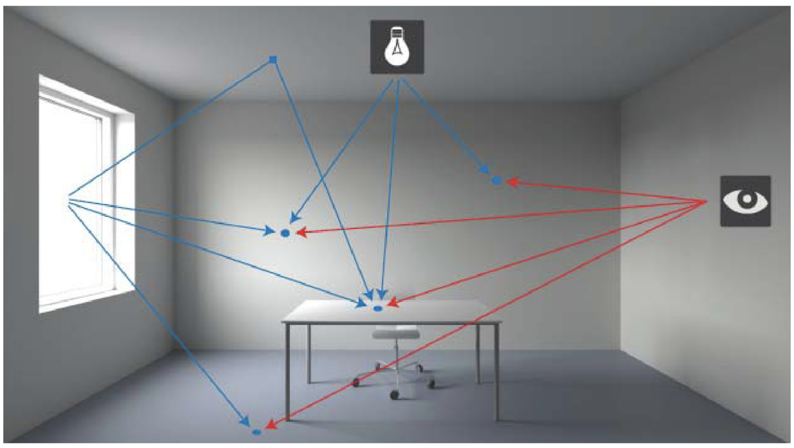


Figure 5.3: Simplified illustration of photon mapping. [SBI 2013:26, 2013]

The result of the first pass alone is a view-independent representation of the indirect illumination in the scene. Due to this, the same geometry (as the photon map is stored with the geometry) can be used for renderings from multiple view points. [Schregle, 2019]

Besides handling indirect diffuse illumination it handles caustics better than backward ray tracing alone. Meaning the technique is better at handling transparent materials within the scene such as glass, water or highly reflective surfaces. Caustics are bright-colored highlights on diffuse surfaces created by specular reflections and refractions. Furthermore, the technique is faster than using backward ray tracing. [Schregle, 2019]

The Radiance photon map extension has been included in the suite since the release of Radiance 5.0 in 2015. [Schregle, 2015] [McNeil, 2019]

5.2 Program structure

The geometric scene including geometry and materials is compiled into an octree. An octree is nested octants which subdivides the space to efficiently trace rays. Once the octree is compiled a hybrid of deterministic ray tracing and Monte Carlo method is used for the simulation. The calculation has three main parts: the direct component, the specular indirect component, and the diffuse indirect component. Depending on the settings results can then be given as numbers and rendered images. [Ward and Shakespeare, 2021]

An example of the overall structure of a standard Radiance simulation is illustrated in figure 5.4.

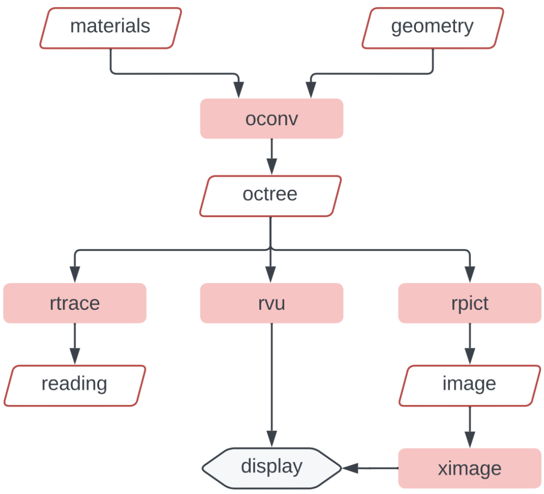


Figure 5.4: The main components of the Radiance rendering system. The parallelograms indicate files, the rectangles indicate Radiance programs, and the hexagon indicates an action. [Jacobs, 2012]

5.2.1 Materials

Radiance supports a wide variety of materials. Among the more than 20 types of material are four different types of artificial light, glass, metal, plastic and mirror. The materials have different colors and ways of handling Radiance; how the rays are refracted, reflected (divided in RGB), absorbed, emitted or transmitted. The roughness and thickness of the surface are included. It even includes how highlights on the surface of said material will appear once rendered.

For any surface to appear in a rendering the surfaces have to be defined first. Radiance does not include a predefined catalogue of materials. The tutorials provide a small selection but for the most accurate CBDM, the user should provide as detailed information on the materials as possible as the reflectance of the surfaces has a major impact on the results. [Jacobs, 2012] [Subramaniam, 2017] [Osborne and Donn, 2011]

Texture
The texture, meaning the perturbation in the surface normal, is defined either by a function or data.

Pattern
Adding a pattern modifies the reflectance of the given material. The patterns are either color patterns or monochromatic.

Mixtures
It is possible to mix two materials as a "foreground" and "background". However, light sources cannot be included.

5.2.2 Geometry

Geometries in Radiance are built by the basic geometric shapes or choices: source, polygon, sphere, cone, cylinder, ring, mesh and instance. Any geometry is described through these shapes and their position in a three-dimensional coordinate system.

Beware when a CAD file is translated to Radiance it does not handle solid models but only surface models.

To define a geometry various generators are used. Some create geometric shapes like a box, a 3-dimensional prism or a shape defined by mathematical functions. Once geometric shapes or surfaces are defined and assigned a material another generator *xform* can be used to modify the size, location and orientation of the entire scene or a single object. Though simple this allows for the creation of very complicated scenes.

> "for accurate results, the surrounding geometry and reflectances have a significant impact on simulation accuracy." [Osborne and Donn, 2011]

Therefore, when using Radiance for CBDM a surface should be defined as the local ground plane for creating an accurate ground reflectance. This ensures that the local environment of surrounding structures is taken into account as well as the sky brightness. If this plane is not included then the ground brightness will only be a function of the diffuse horizontal irradiance and the "average ground reflectivity". Even if surrounding structures appear in the model they will not affect the ground brightness and Radiance will then overestimate the irRadiance entering the simulated scene. The ground plane should not be excessively large as the resolution of an ambient calculation is dependent on the global dimensions of the scene. [Mardaljevic, 1999]

5.2.3 Skies

To simulate daylight a sky model is necessary to describe the luminance distribution of the sky. The simplest form is a Uniform Luminance Model representing an overcast sky of constant brightness. If it is not completely overcast the light from the sky will have two components: diffuse and direct sun light. [Mardaljevic, 1999]

To describe the luminance distribution of a sky the angles shown in figure 5.5 are used to define the position of the sun and a sky element in relation to each other.

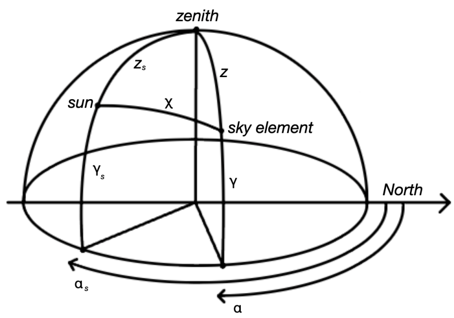


Figure 5.5: Angles describing the position of the sun and a sky element. [ISO 15469, 2004]

The common way to describe sky models are by numerical functions of the altitude and the azimuth over the hemisphere (a half globe from the horizon). Some models accept climate data to normalize the luminance distribution and some accept time and location. [Brembilla, 2017]

Radiance has two programs for sky generation: *gensky* and *gendaylit*. The *gensky* program produces sky luminance distributions based on four different models: [ISO 15469, 2004]

- **Uniform luminance model**
  an overcast sky with uniform brightness
- **CIE overcast sky model**
  an overcast sky darkest at the horizon and gradually brighter towards the zenith
- **CIE clear sky model**
  accounts for the direct sunlight and the ambient sky with horizon brightening
- **CIE (Matsuura) intermediate sky model**
  lower circumsolar luminances than the clear sky model without horizon brightening

It has been proven as early as 1901 that even an overcast sky is darker towards the horizon and gradually brighter towards the zenith. [Ward and Shakespeare, 2021] Therefore a Uniform Luminance Model is a poor representation and is not a good choice for daylight modelling. The distribution of the CIE overcast, clear and intermediate sky models are illustrated in figure 5.6. To create these distributions time and location has to be specified. They are all quite narrow models in the aspect that they each represent a segment of weather conditions. It should be noted that the *gensky* program has not been updated to include the modifications made to the CIE sky models in 2003. [ISO 15469, 2004] [Marsh, 2020]

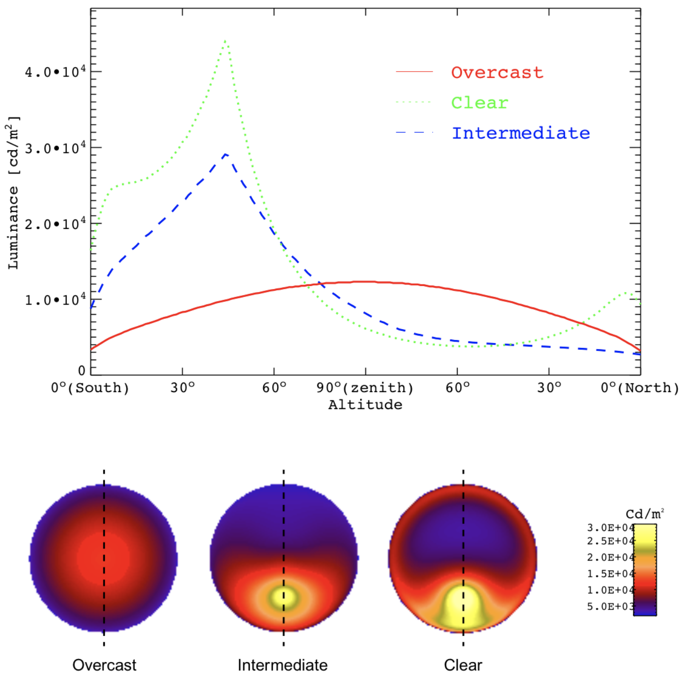


Figure 5.6: Luminance profile and maps for the tree CIE sky models. [Mardaljevic, 1999]

The *gendaylit* program generates sky luminance distributions based on the **Perez All-Weather model**. [Perez et al., 1993] The model is a generalization of the CIE clear sky model formula. As indicated by the name this model has the advantage of covering various types of skies; from overcast to clear. The model was devised on data of over 16.000 all-sky scans from the Lawrence Berkeley National Laboratory in California. [Perez et al., 1993] The model calculates the mean luminous efficacy of diffuse and direct sunlight and of the luminous distribution for a considered sky condition. Based on inputs of date, time, site, direct and diffuse solar illuminance or irRadiance, and, humidity the model estimates the distributions in the circumsolar region and the gradient near the horizon and takes light backscattered from the earth into account. [Reinhart, 2010] [McNeil, 2020a] The main simplification in the model is the use of a single diffuse horizontal value, which will cause the lack of details in skies with partial cloud cover, where one direction is brighter than another. [Osborne and Donn, 2011] The Perez All-Weather model has the lowest uncertainty of the current models and is the most precise. [Mardaljevic, 1999] [Alshaibani et al., 2020] [Reinhart and Andersen, 2006] Though more precise models are still needed. [Alshaibani et al., 2020]

The *gendaylit* program can generate skies based on four different sets of information provided about radiation: [McNeil, 2020a]

- direct normal and diffuse horizontal irRadiance $[\mathrm{W/m^2}]$
- directs horizontal and diffuse horizontal irRadiance $[\mathrm{W/m^2}]$
- direct normal and diffuse horizontal illuminance $[\mathrm{lm/m^2}]$
- global horizontal irRadiance $[\mathrm{W/m^2}]$

The pairs of a direct and a diffuse component are recommended for the most accurate results. [McNeil, 2020b] A practical advantage of the Perez All-Weather sky model is that all the inputs needed are available for free for multiple sites around the globe as they are all included in standard climate files. The program *epw2wea* extracts location, direct normal radiation and horizontal diffuse radiation from Energy Plus Weather (EPW) data files so it is compatible with Radiance. [Subramaniam, 2017]

For CBDM in Denmark the weather file used is the Design Reference Year, DRY 2013. [Wang et al., 2013] DRY is based on ten years of data and combined into a representation of typical Danish weather. In relation to light distribution throughout the year the following information is given in the dataset: global, diffuse and direct normal irradiance, relative humidity, and global, diffuse and direct normal illuminance. [Nielsen, 2019] The country is divided into six zones for this data which is shown in figure 5.7, which also indicates the total global radiation of the reference year. For simulating hourly skies throughout a year in Radiance using the *gendaylit* program any of the three sets of data with a direct and a diffuse component can be utilized.

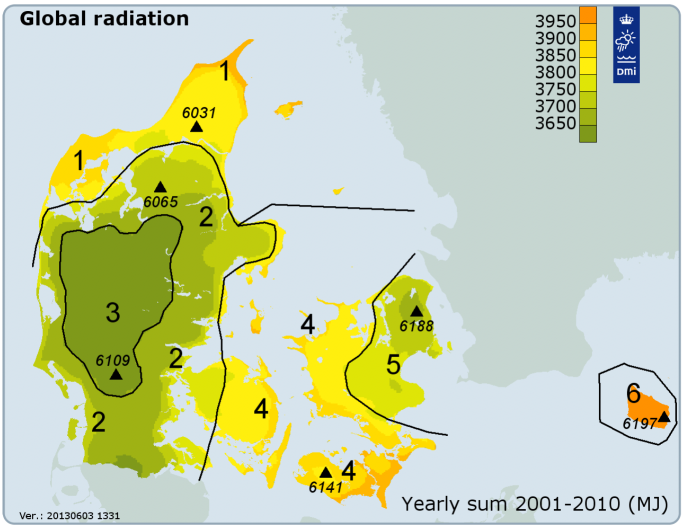


Figure 5.7: Map indicating the six zones for global radiation and the yearly sum of global radiation in each zone in MJ. [Wang et al., 2013]

Subdivision of the sky

As mentioned in section 5.1.1 in order to make efficient daylight simulations the sky is described as a discretized hemispherical sky in subdivisions of finite elements. Tregenza first proposed a subdivision of the sky of 151 circular patches, see figure 5.8 (a). [Tregenza, 1983] Later he suggested sky model scheme of 145 patches, see figure 5.8 (b). The position of the center of these patches was used by Klems, who changed the shapes to trapezoidal-like patches with numbers in order to cover the whole hemisphere continuously, see figure 5.8 (c). [Klems, 1993] This model was subsequently adopted by Reinhart and Herkel. [Reinhart and Herkel, 2000] Reinhart later refined the model for more accurate simulations by subdividing each of the 145 patches in 4, 9 and 16 patches apart from the zenith and the ground ones. These models are known as Multiplication Factor (MF), the divisions are illustrated in figure 5.8 (e), (f) and (g) including their names respectively.

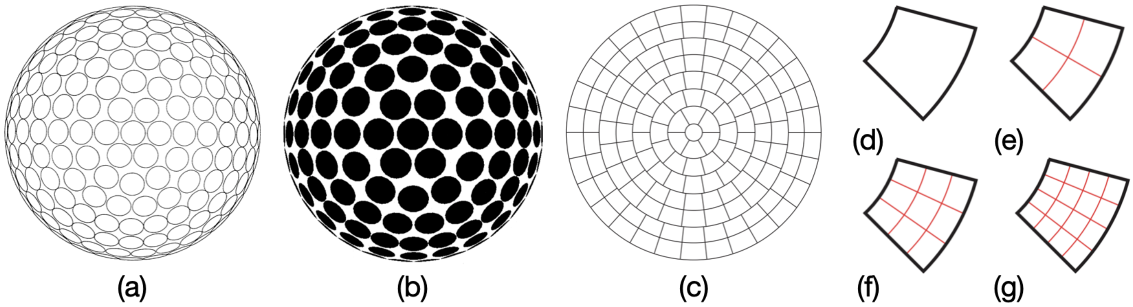


Figure 5.8: Discretized sky models: (a) Tregenza scheme of 151 patches, (b) Tregenza scheme of 145 patches, (C) Klems dome without numbers, (d) Tregenza patch referred to as MF:1, (e) MF:2, (f) MF:3, and (g) MF:4 [Tregenza, 1983] [Klems, 1993] [Reinhart and Herkel, 2000] [Brembilla, 2017]

Each of the sky models include one or three additional patches representing the ground.

Sun position

The sun position must be defined for the direct Radiance component. The different Radiance calculation methods has different ways to describe this. Some of the methods can be combined with simpler or more accurate ways of describing the sun position.

The sun position is described by one of the discretized sky models mentioned above with the middle of each patch representing a possible sun position. See figure 5.9 for examples hereof. The sun illuminance can then either be assigned to the nearest point to its actual position on the hemisphere at a given time step or be distributed to the nearest sky patches by interpolation. The amount of possible sun positions can vary between 145 and 5185.

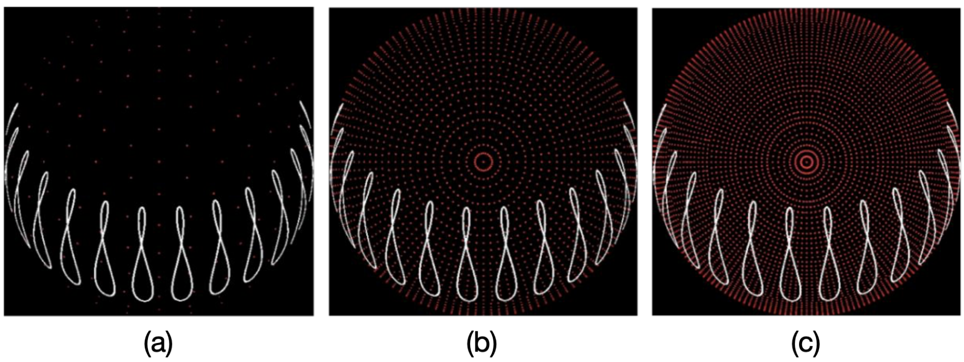


Figure 5.9: Sun positions indicated by red dots for (a) MF:1 (145 positions) (b) MF:4 (2305 positions) and (c) MF:6 (5185 positions) and the actual sun position for a year for a given place indicated by the white line. [Subramaniam and Mistrick, 2017]

5.2.4 Sensor points

When doing CBDM a set of sensor points must be defined as where the indoor illuminance is investigated. Typically these points are chosen in the working plane. For proving sufficient daylight in buildings in Denmark the sensor points are predefined, see section 2.7. [BR18 - 18 Guidance, 2021]

In Radiance sensor points are defined in a text file and then fed to the octree.

5.2.5 Rendering

Radiance can render images in multiple ways. Figure 5.10 illustrates a flow chart of when to use which command for scene viewing.

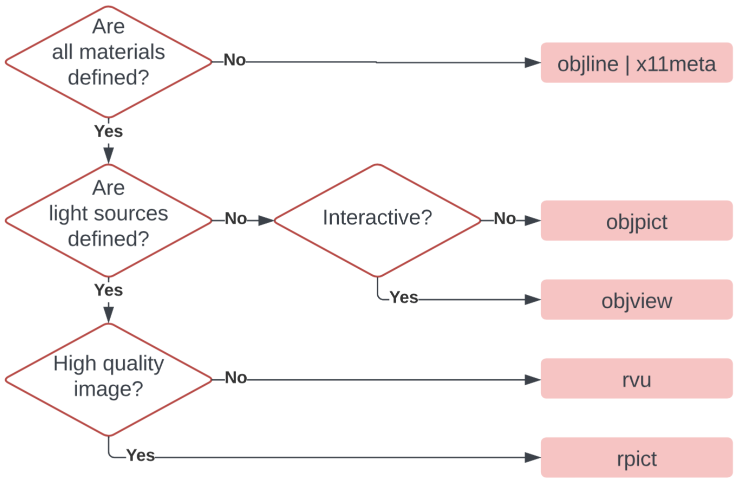


Figure 5.10: Flowchart of various Radiance commands to view a scene. [Jacobs, 2012]

While working on the project setting up the geometry and such the first three commands; *objline*, *objpict*, and, *objview*, indicated in figure 5.10 are useful. Once the whole scene and parameter settings are ready *rvu* is useful for spotting errors and needed adjustments or optimizing view point as it is interactive and fast. *rpict* is used for high-quality images for results.

5.2.6 Simulation and rendering commands and parameter settings

The Radiance programs for rendering or calculating indoor illuminance have close to 40 different settings. Finding the optimal parameter settings would take infinite time with such a high amount of parameters. Besides the optimal settings depend on the individual case. Therefore this project focuses on some main parameters for annual daylight simulations.

The main Radiance programs for rendering or calculating internal illuminance are listed here:

- *rtrace* Computation of individual Radiance or irRadiance values
- *rpict* Rendering of scene images based on ray tracing
- *rvu* Interactive scene viewing, progressively refined image
- *rcontrib* Luminous coefficient computation for surfaces
- *rfluxmtx* Computation of flux transfer matrices through *rcontrib*
- *mkpmap* Generation of Radiance photon map can be combined with any of the above programs apart from *rfluxmtx*

Further description of each program can be found in Appendix B. Which of the two main programs for backward ray tracing are used in the various CBDM methods appear in table 4.1.

For illuminance calculations and rendering the key simulation parameters evolve around the ambient parameters. These control the depth that is to say the number of reflections and the resolution of the inter-reflection calculation. The most important ambient parameters are listed here: [Mardaljevic, 1999]

- **ab** ambient bounces
- **aa** ambient accuracy
- **ar** ambient resolution
- **ad** ambient division
- **as** ambient super-samples
- **am** max photon search radius (only used for photon mapping)

In table 5.1 a collection of parameter settings appears. The settings are a collection of the default values in some Radiance programs, useful ranges suggested by Radiance, and previous studies. Further suggested settings for rendering with the Radiance program *rpict* are given with the program. [LBNL, 2020]

The suggested ranges given by Radiance and the Radiance tutorial which appear in table 5.1 are the following: [McNeil, 2019] [Jacobs, 2012]

- **Minimum** for fastest, crudest rendering.
- **Fast** for reasonably fast rendering.
- **Accurate** for reasonably accurate rendering (artificial lighting)
- **Very Accurate** for accurate rendering or complicated scenes (daylighting)
- **Maximum** for the ultimate in accuracy. Avoid due to rendering time.

Table 5.1: Radiance ambient parameter settings from previous studies or program recommendations.

parameter	**ab**	**aa**	**ar**	**ad**	**as**	**lr**	**lw**	**source***
Default *rvu*	0	0.3	32	256	64	6	0.001	R, J
Default *rpict*	0	0.2	64	512	128	7	0.0001	R
Default *rtrace*	0	0.1	256	1024	512	10	0.0001	R
Default *rcontrib* (*d***)	1	0	256	350	0	10	0.002	R
Minimum	0	0.5	8	0	0	0	0.05	R, J, K
Fast	0	0.2	32	32	32	4	0.01	R, J, K
Accurate	2	0.15	128	512	256	8	0.002	R, J, K
Very Accurate	5	0.08	512	2048	512	*d*	*d*	J
Maximum (IIII)	8	0	0	4096	1024	16	0	R, J, K
Maximum I	8	0.1	256	4096	1024	16	0	K
Maximum II	8	0.05	512	4096	1024	16	0	K
Maximum III	8	0.01	1024	4096	1024	16	0	K
Maximum-ab 10 I	10	0.1	256	4096	1024	16	0	K
Maximum-ab 10 II	10	0.05	512	4096	1024	16	0	K
Maximum-ab 10 III	10	0.01	1024	4096	1024	16	0	K
Maximum-ab 10 IIII	10	0	0	4096	1024	16	0	K
rtrace	6	0.05	*v****	2500	100	10	0.0005	O
4-cm	5	0.2	128	2048	256	6	0.05	B
4-cm for PSS	7	0.15	512	2048	256	6	0	B
DAYSIM v4	5	0.2	512	4096	512	6	0.04	B
2-ph	5	0	0	89600	64	6	0.05	B
3-ph (vmx)	5	*d*	*d*	22400	*d*	*d*	0.05	B
3-ph (dmx)	2	*d*	*d*	22400	*d*	*d*	0.05	B
5-ph	1	*d*	*d*	22400	*d*	*d*	0.05	B
Illuminance	4	*d*	*d*	5000	*d*	*d*	0.0002	S
Views	4	*d*	*d*	1000	*d*	*d*	0.001	S
V Matrix (SensorPoints)	12	0		60,000	0		1e-42	M
T Matrix (BSDF)	5	0		700	0		3e-6	M
D Matrix	4	0	*d*	2000	0	*d*	1e-8	M
Daysim 3.2	7	0.05	300	1500	100	10	0.004	C
DAYSIM	8	0.05	300	4096	20	6	0.001	T
3-/5-PM	8	0	256	50000	0	-10	0.00002	T

*****Source indicates the origin of the parameter settings along with other studies that have used said settings.
R Radiance default settings or suggestions [McNeil, 2019]
J Radiance tutorial suggestions [Jacobs, 2012]
S Radiance tutorial suggestions [Subramaniam, 2017]
M Study by Lawrence Berkeley National Laboratory [McNeil and Lee, 2012]
O Study by Victoria University [Osborne, 2012]
K Study by Carleton University [Kharvari, 2020a]
B Study by Loughborough University [Brembilla, 2017]
C Study by University of Seville, Spain [Campano et al., 2018]
T Study by Massachusetts Institute of Technology [Jones, 2017]
*******d* indicates default setting corresponding with *rcontrib*
*******variable based on equation, see "Appendix 1" in the thesis by Jake Osbourne [Osborne, 2012]

Recommended ranges for additional parameters appear in table 5.2. [McNeil, 2019]

Table 5.2: Recommended Radiance parameter settings. [McNeil, 2019]

Parameter	**ps**	**pt**	**pj**	**dj**	**ds**	**dt**	**dc**	**dr**	**dp**	**sj**	**st**	**lr**	**lw**
Minimum	16	1	0	0	0	1	0	0	32	0	1	0	0.05
Fast	8	0.15	0.6	0	0.5	0.5	0.25	1	64	0.3	0.85	4	0.01
Accurate	4	0.05	0.9	0.7	0.15	0.05	0.5	3	512	0.7	0.15	8	0.002
Maximum	1	0	1	1	0.02	0	1	6	0	1	0	16	0

As a standard, the parameter max photon search radius, **am**, is set to zero in all Radiance programs. The parameter is only changed when using photon mapping through the program *mkpmap*. The program stores photon values in surfaces which the rendering or illuminance calculation programs can then trace directly from the surfaces. When using photon mapping the ambient bounce for the backward ray tracing step is set to one as the photon values are already stored in the surrounding surfaces additional bounces are not necessary.

Table 5.3 indicates important parameter settings and ranges when using photon mapping. [Schregle, 2019]

Table 5.3: Recommended Radiance settings for photon mapping.

paramter	**ab**	**am**	**apD**	**apm**	**apP**	**dp**	**ds**	**source***
Default *rpict*	0	0	-	-	-	512	0.25	R
Default *mkpmap*	-	-	0.25	5000	0.25	1000	0.01	R
Typical ranges	1	100-1000	0.1-1.0	1000-5000	0.25-0.5	1000-100000	0.0001-0.01	Sc

*Source indicates the origin of the parameter settings.
R Radiance default settings [McNeil, 2019]
Sc Radiance user manual suggestions [Schregle, 2019]

5.3 Recommendation of parameter settings

Most studies rely on settings from previous studies or industry-accepted values which are taught at universities. [Kharvari, 2020a] Based on research this paper suggests the use of two different settings as a guideline. One being less accurate though having a faster simulation time. This way the faster simulation can be used early on in a project for indications and comparisons of various designs and more accurate results can be simulated for documentation of a final or a few designs.

Based on the need for a certain accuracy in simulations and low simulation time two of the general recommended settings from the Radiance website have been chosen. [McNeil, 2019][Jacobs, 2012] Based on earlier studies of the accuracy and simulation time these settings seem to meet both criteria. [Kharvari, 2020a] Further accuracy is too time-consuming and less accuracy has results which are too unreliable. The chosen settings are denoted *Accurate* and *Maximum (IIII)* in table 5.1.

When using photon mapping this study suggests using the ranges shown in table 5.3 due to limited research on these parameters.

6 CBDM setup for integration with thermal comfort & energy use simulations

Integrated design allowing for CBDM, thermal comfort and energy simulations in the same tool enhances the design process. It makes it possible to utilize dynamic shading for optimising the indoor climate by improving thermal and visual comfort and lowering energy use. [Buenoa et al., 2015] Having such a tool accessible to any engineer or architect would enhance its use in the Danish building industry. Accessible is here defined as inexpensive and simple so expert knowledge is unnecessary.

This chapter focuses on a suggestion on how an inexpensive tool integrating these three aspects could be developed in the future. This work focuses on the CBDM through Radiance to be integrated with an existing inexpensive tool that performs thermal comfort and energy use simulations. A suggestion of the calculation method, parameter settings and user choices appears in the following. Furthermore, the suggested methods for CBDM have been tested and compared with CBDM results from a presentation at the 17$^{\text{th}}$ International Radiance Workshop. [Brembilla, 2018a]

In table 4.2 multiple tools, which can perform both thermal comfort and energy use simulations and CBDM, are listed. The most common of these in Denmark are ClimateStudio for use amongst engineers and IDA ICE for research purposes. Both tools are costly and IDA ICE is too complicated for general use.

In Denmark an inexpensive tool for thermal comfort and energy use simulations is available; BSim. [BUILD, 2020] The energy use does not cover the entire building though it indicates the effect of design choices on a room basis. For example, energy use for artificial lighting, and ventilation for air circulation, heating and cooling are included. The tool can perform daylight analysis though not CBDM. Currently, the software includes calculations of the daylight metric Daylight Factor.

Preparations have been made to export the 3D model from BSim to Radiance, so integrating Radiance for CBDM in BSim could be a solution to making integrated design accessible. The following is based on a proposal of how to couple Radiance CBDM with BSim.

For a tool which can perform both CBDM, thermal comfort and energy simulations to be functional it has to be simple for the user to handle. Simple and clear choices are key. To incorporate CBDM through Radiance into an existing tool; BSim, the principle of the workflow, the layout of the dialogue boxes to incode, and the simulation method and settings have been suggested. The principle of the simulation process is shown in figure 6.1. The design and workflow appear in further detail in figure 6.2 and 6.3.

After setting up the model in BSim and running initial thermal comfort simulations climate based daylight modelling is run incorporating the solar shading control calculated based on the thermal simulation. Once the CBDM results are calculated through Radiance the use of artificial lighting is adjusted based on inefficient daylight supply and the occupancy schedule. Furthermore, the user will be presented with the choice of adding solar shading control based on excessive daylight causing discomfort due to glare to the BSim model. The thermal indoor climate and energy use are then recalculated, see figure 6.1.

When daylight is evaluated through Radiance results appear in terms of the metric spatial daylight autonomy, sDA. Results are also calculated for the metrics UDI, TAI and ASE. These results are not initially presented but can be found in the time schedule with all results from the thermal simulation, see figure 6.1.

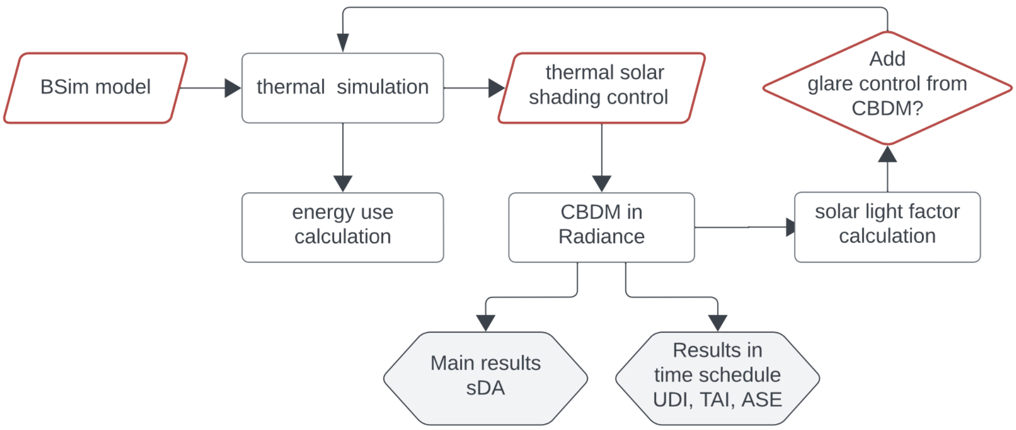


Figure 6.1: Principle of Radiance implementation with BSim.

When opening the dialog box for daylighting in BSim the choice of calculation method is automatically chosen based on whether the model includes external non-coplanar shading. If so, then the 4-Phase Method is used, otherwise the 3-Phase Method is used. This choice has been made based on the research of Radiance CBDM methods presented in chapter 4. This is shown in figure 6.2.

The user is presented with a choice of the accuracy of the annual daylight simulation and the distribution of sensor points. The results are presented as an sDA value in percentage and shown graphically to identify areas of the room with inefficient daylight. The graphical representation of the results indicates how much of the daylight hours in a year the illuminance is above 300 lux, see figure 6.2. The results can be shown including glare control of the solar shading or without. This project does not go into further detail on this.

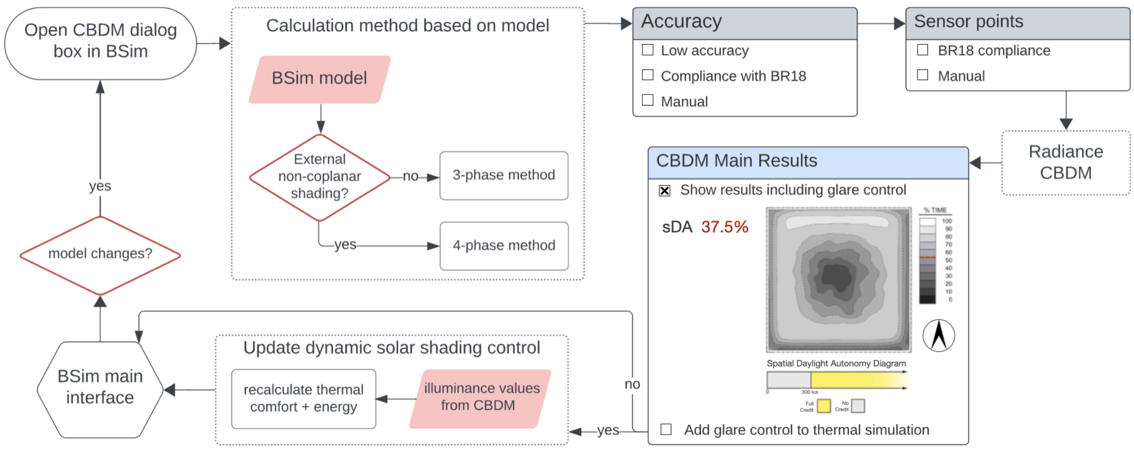


Figure 6.2: Radiance CBDM through BSim workflow including processes and user dialogue boxes.

Once the initial simulation of CBDM is performed getting additional results due to model adjustments is faster due to the choice of calculation method. If the glazing or internal shading is changed the transmission matrix is updated and results are recalculated. The time-consuming ray tracing processes do not need to be repeated.

The dialogue boxes with user choices are shown in further detail in figure 6.3. For accuracy, the user gets three choices: a fast simulation of lower accuracy, a suggested setting for compliance with the Danish Building Regulations, BR18, and manual parameter setting. [BR18 - 18 Guidance, 2021] Reflectance of surfaces has a major impact on CBDM metrics and therefore the user gets the choice of using the standard values of BR18 or the properties of the materials in the 3D model. [Osborne and Donn, 2011]

The user choices for the position of sensor points appear in figure 6.3. Again compliance with BR18 is an option with the choice of distance between the points of up to 1 m and a relation between the longest and shortest side of each division of at least 0.7. [BR18 - 18 Guidance, 2021] Additionally the sensor grid can be created manually.

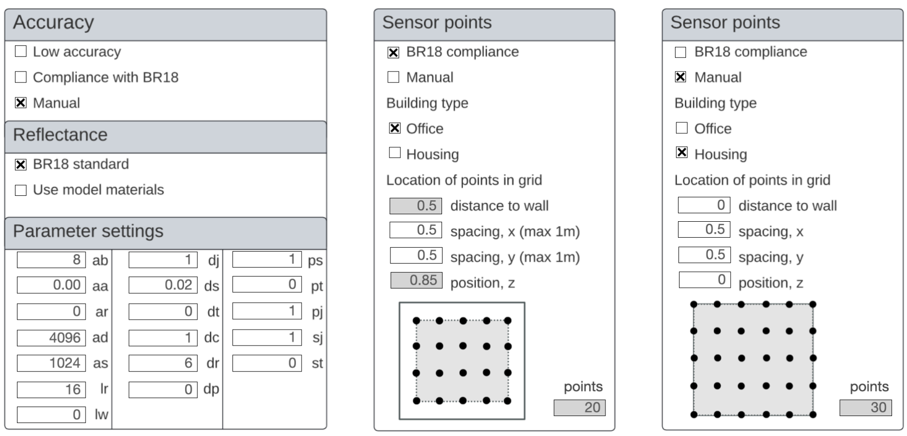


Figure 6.3: Details of the dialog boxes for accuracy and sensor points.

6.1 CBDM with Radiance

To demonstrate that the proposed method and parameter settings are applicable to the industry for compliance with BR18 a test case has been used to show that it provides accurate results. The results have then been verified by comparison with results from a presentation at the 17th International Radiance Workshop. [Brembilla, 2018a] The voice recording of the presentation "Competition Results and Discussion" can be found on the official Radiance website. [Brembilla, 2018b]

The chosen data for comparison include results in the form of various annual daylight metrics for three cases. The cases represent three typical rooms from SBI 26. [SBI 2013:26, 2013] The data includes results from the 4-Component Method; the "truth" of annual daylight simulations along with simulation results based on the 3-Phase Method. Comparison against the results presented at the Radiance Workshop can identify whether the chosen parameter settings leads to in usable results. [Brembilla, 2018a]

6.1.1 Method

The calculation methods and parameter settings chosen are based on the research of this project described in chapter 4 and 5.

To accommodate for the possibility of CBDM with dynamic shading devises and exploration of multiple design choices Radiance 3-phase and 4-Phase Methods have been chosen, see figure 4.4. This is seen as a common need in the industry. Design choices can include geometry including static external shading, orientation and material choices for example. If external shading such as side fins or overhang appear in the model the additional F-matrix of the 4-Phase Method will be included in the simulation. Otherwise the 3-Phase Method is used as standard.

The parameter settings have been chosen to have 2 default settings and the option of custom settings for expert users. The first chosen setting, *low accuracy*, is for fast simulation to get quick estimations in the early design phase. The second option, *compliance with BR18*, is a suggested standard parameter setting for the industry to use when documenting sufficient daylight in spaces in terms of the annual daylight metric sDA.

The chosen parameter settings appear in table 6.1. They are based on the official Radiance standard recommended settings from table 5.1: *Accurate* and *Maximum IIII*.

Table 6.1: Chosen Radiance settings.

parameter	ps	pt	pj	dj	ds	dt	dc	dr	dp	sj	st	ab	aa	ar	ad	as	lr	lw
Low accuracy	4	0.05	0.9	0.7	0.15	0.05	0.5	3	512	0.7	0.15	2	0.15	128	512	256	8	0.002
Compliance with BR18	1	0	1	1	0.02	0	1	6	0	1	0	8	0	0	4096	1024	16	0

Besides determining sDA also the annual daylight metrics $UDI_{300\text{-}3000}$, DA_{300}, and ASE are calculated.

The case model, described in the following section, does not include any external non-coplanar shading only the 3-Phase Method has been simulated. The 4-Phase Method would give the exact same results in this case.

The scripts used to perform CBDM through Radiance are included in the digital appendix mentioned in the Appendix A along with the files used. The bidirectional scattering distribution function (BSDF) xml file was created through the program Window 7. [LBNL, 2023] It is possible to do this through the Radiance command *genBSDF* and incorporate it in the simulation code.

BSim was used for making the 3D model. Utilizing the existing export function to Radiance geometry and material files.

6.1.2 Case

As a case study to test the chosen simulation settings, a typical room was chosen from a previous investigation of simulation programs to calculate the daylight factor. [SBI 2013:26, 2013] The rooms in the report were made for comparison of daylight simulation software. The advantage of the cases is the simplicity ensuring errors are due to the simulation method versus the construction or interpretation of the model. The room chosen represents a deep room, see figure 6.4.

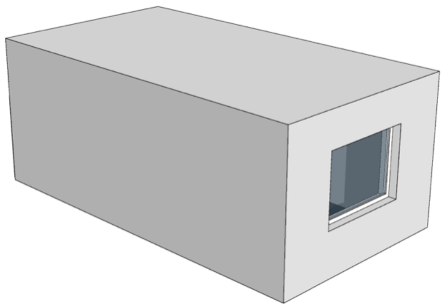


Figure 6.4: Illustration of the chosen deep room. [SBI 2013:26, 2013]

The model also has a ground plane of 50 m×50 m. Additional information on the geometry can be found in SBI 26. [SBI 2013:26, 2013] The reflectances of the surfaces in the model appear in table 6.2

Table 6.2: Surface reflectances in the case model. [SBI 2013:26, 2013]

	reflectance (r)	**light transmittance (LT)**
ground	0.1	
external walls	0.3	
floor	0.1	
internal walls	0.4	
ceiling	0.7	
window frame	0.8	
side of window opening, internal	0.7	
side of window opening, external	0.3	
window glazing		0.76

6.1.3 Results

Using the BSim extension to create the material and geometry files had some minor issues. The geometry part was fine, though for the method used the window glazing was moved to a separate file. This could be avoided by changing the code. The issues were related to the materials. For convenience, these were also moved to a separate text file. However, setting up the materials in BSim to be transferable to Radiance is tedious and inconvenient. For some element types, it is not possible to set the surface reflectance.

The CBDM results from the 3-Phase Method with the suggested parameter settings appear in table 6.3.

Table 6.3: CBDM results for the deep room. [Brembilla, 2018a]

$\mathbf{UDI_{300\text{-}3000lx}}$	$\mathbf{DA_{300lx}}$	$\mathbf{sDA_{300lx/50\%}}$	$\mathbf{ASE_{1000lx}}$
27.1%	30.6%	32.9%	41.2%

The case does not meet the Danish building regulations requirement of spatial daylight autonomy, sDA, being above 50 %. In this case 30.6 % of the reference plane has an illuminance of over 300 lux in more than 50 % of the occupancy hours of a year. Likewise is the useful daylight illuminance, UDI, and daylight autonomy, DA, low. These results were expected based on the room geometry; a deep room with a single comparatively small window opening. However, the window is south facing and the window has no shading devices so the annual sunlight exposure, ASE, is fairly high.

6.2 Comparative verification

The values used for comparison appear in table 6.4. The data is from the 17th International Radiance Workshop and is based on the 4-Component Method (4-PM) and the 3-Phase Method (3-PM). [Brembilla, 2018a]

Table 6.4: CBDM results from the Radiance Workshop presentation. [Brembilla, 2018a]

Metric values	$\mathbf{UDI_{300\text{-}3000lx}}$	$\mathbf{DA_{300lx}}$	$\mathbf{sDA_{300lx/50\%}}$	$\mathbf{ASE_{1000lx}}$
4-CM by Eleonora	37.5%	42.4%	31.0%	16.5%
3-PM by James & Ruth	32%	36%	37%	25%
3-PM by Abel & Bruno	36%	43%	30%	43%

The results from the Radiance Workshop differ from one another. The workshop intended to highlight how much impact the way the user uses Radiance settings has on the output. The 4-Component method is seen as the benchmark. The two sets of results from the 3-Phase Method have been included to compare against the same calculation method where only the parameter settings differ. The results from this project are illustrated alongside the three sets of values used for comparison in figure 6.5.

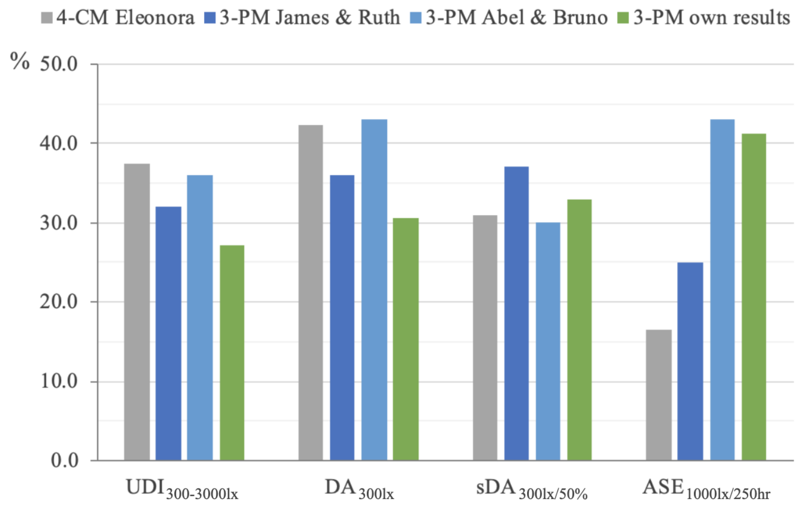


Figure 6.5: Results graphically illustrated with the values used for comparison.

The relative error between the simulated results and the values from the Radiance Workshop appears in table 6.5 including the average error.

Table 6.5: Error of results compared to those from the Radiance Workshop. [Brembilla, 2018a]

Relative error	**$UDI_{300\text{-}3000lx}$**	**DA_{300lx}**	**$sDA_{300lx/50\%}$**	**ASE_{1000lx}**
4-CM by Eleonora	-28%	-28%	6%	150%
3-PM by James & Ruth	-15%	-15%	-11%	65%
3-PM by Abel & Bruno	-25%	-29%	10%	-4%
average error	-23%	-24%	2%	70%

As the values from the Radiance Workshop differ from one another there is a variation in the error results. The relative errors seem reasonable for UDI, DA and sDA where they are in the interval of 6-29 %. sDA produces the most agreeable results. For Annual Sunlight Exposure, ASE, the relative error is significant, especially in comparison to the 4-Component method.

In previous studies, an allowance for CBDM to have an error of ±20 % has been used as an acceptable range. [Reinhart and Andersen, 2006]

Discussion 7

The project proposes a method to make climate-based daylight modelling accessible to the Danish building industry. The method itself, the verification of the method and various sources of error in CBDM are discussed in the following.

7.1 Results

The results of CBDM using Radiance to perform the 3-Phase Method are given in table 6.3. Four metrics were calculated. The case which has been simulated is a deep room of 7 m with a single south-facing window of 3 m^2 with no shading. The results showed inefficient hours with sufficient daylight with an sDA below the threshold of 50 % according to the Danish building regulations. [BR18 - 18, 2021] The insufficient distribution of daylight was expected due to the depth of the room and the position of the window.

Furthermore, the results showed a large number of hours with potential problems of glare issues and overheating causing the need for cooling which would increase energy use. The annual sunlight exposure, ASE, the result was at 41 %. However, the choice of case was not to meet requirements but to verify the chosen simulation settings could produce applicable results for the industry.

7.1.1 Comparative verification

The simulation results were compared against values from simulations based on the same case by two different Radiance CBDM methods: the 4-Component Method and the 3-Phase Method. The most agreeable results were found to be spatial daylight autonomy, sDA, and the metric results deviating the most were annual sunlight exposure, ASE. This corresponds with the findings of previous studies comparing different CBDM methods using Radiance. [Brembilla, 2017]

The large variation in ASE results is probably due to the metric being highly influenced by direct sunlight. The two calculation methods deal with the direct sunlight component differently. Also, this component is highly sensitive to the choice of sky discretization. Since the choice of multiplication factor may be different for each of the simulations the ASE results are reasonably unreliable. [Brembilla, 2017]

The daylight distribution in deep rooms is more sensitive to the inter-reflection of surfaces as less direct sunlight reaches the back of the room. Therefore the surface reflectances and ambient parameters can have a significant influence on the CBDM results, as is the case in this study. The reflectances were the same so in the comparative verification only the parameter settings were a factor. The considered metrics based on global, averaged illuminance are UDI, DA and sDA. These metrics have relative errors within ±30 %. It could be argued to be sufficient to verify the simulation settings as there is no specified range, though for validation it has been suggested to accept an error of ±20 %. [Brembilla, 2017]

Based on that it could be argued that further investigation on the parameter settings is necessary. However, the relative error of the metric sDA is within ±11 % and only SI6% in comparison to the 4-Component Method value. As the metric needed for compliance with the Danish building regulation is sDA it could be argued the settings are sufficiently accurate for recommendation as the Danish industry standard.

7.1.2 Simulation parameters

The choice of simulation parameters was purely based on the literature review. Better setting combinations are possible for general use. A method to investigate this further could be to run multiple setting combinations as done by Kharvari. [Kharvari, 2020a] Using experimental data provides a real-life result to compare with. Though it often introduces various unknown or uncertain sources of error. Another method could be to perform a comparative validation against the Radiance 4-Component Method. Using the five typical rooms of SBI 26 as they represent typical geometric difficulties would be a way to generalize the results. [SBI 2013:26, 2013]

7.1.3 Method

For simplicity, for the user, it is essential to make some choices as the developer. Radiance is too complicated and has too many possibilities to ensure comparative results across projects from different companies. CBDM would become more streamlined if the Danish building regulations set a more specified guideline for the method and settings. However, the current regulation gives the industry the freedom of choice of validated software.

The developer should make as many choices for the user as possible, though leave the option of manual inputs for expert users. This project suggests the use of Radiance 3- and 4-Phase Methods for CBDM based on the model geometry. The advantage of the methods is that once the initial simulation has been run it is fast to test various fenestration systems including dynamic solar shading solutions and building orientations.

If Radiance photon mapping gets integrated with the 3-, 4-Phase Methods in the future, then using photon mapping in combination with the two methods would speed up the simulation times.

7.1.4 Integration of Radiance with BSim

The current method of assigning reflectances to surfaces in BSim is inconvenient and difficult. Furthermore, it currently requires the user to convert the reflectances into the grey-scale RGB which is readable to Radiance. This conversion from a single reflectance value should be incoded into BSim for this component to be effective and useful. However, the conversion from a BSim model to Radiance is not complicated so the compilation of the two programs should be smooth allowing BSim to use Radiance as a CBDM engine.

7.1.5 Model setup and weather data

The model geometry and detail level have a major impact on CBDM results. Previous research has shown that surprisingly the reflectance of internal and external surfaces is more critical than the size of window openings. [Osborne and Donn, 2011] The Danish building regulations provide standard reflectances. If the actual building elements have lower reflectances, however, the daylighting in the building might be significantly lower than predicted and documented. The regulations do not specify that manually chosen reflectances have to be validated, so this is potentially a way for architects or engineers to cheat on the daylight documentation. Based on the research indicating the major influence of reflectances further research is needed on this.

Though the European standard for CBDM does require the use of hourly-based weather data and validated software, there are no requirements for the sky model used in the software. [DS/EN 17037, 2018] This can have a great impact on the accuracy of the results. Also, the sky discretization has an impact on the accuracy. Using the Perez sky model seems to be the most common way when using TMY-type weather data and it has been shown to give accurate results. [Reinhart and Walkenhorst, 2001]

7.1.6 CBDM metrics

The replacement of the daylight metric daylight factor, DF, with annual metrics like useful daylight illuminance, UDI, was to evade the “the more the better” approach for windows, which may occur when considering DF alone. [Karlsen, 2016] This may still be relevant to investigate further. Even though sDA is now included in the Danish building regulations for daylight analysis the metric does not take glare and overheating into account.

There is still a need for further research for a proper solution to deal with this issue. As long as it is not specified by the building regulations it is not common practice for all companies to investigate thoroughly.

7.1.7 Validation of CBDM

In this study, thorough research on validation methods of CBDM was conducted. The research mainly focused on experimental validation to map out existing datasets. Having a common practice for experimental validation easily accessible would make the choice of software tool and calculation method more transparent. However, the research showed that the existing datasets are either inadequate, too complicated with too many factors for error, or inaccessible. They are hard to come by, insufficient information is available or they come with limitations on the use. Some are not for commercial use and the CIE 171:2006 which does not provide for a holistic validation has to be purchased. This limits the use of experimental validation for research projects and some software developers.

Comparative validation is therefore more used. It is more accessible and Radiance has been accepted as a benchmark since it has multiple and the most thorough experimental validation showing it is very accurate at simulating real daylight. Studies have validated Radiance with a mean bias error within ±10 % and ±20 %. [Mardaljevic, 1999] [Reinhart and Walkenhorst, 2001]

This is a compelling argument for the comparative validation of new CBDM methods, software and parameter settings to be sufficient. However, though Radiance is available expert knowledge of the program is necessary to utilize at least the most precise and most thoroughly validated method; the 4-Component Method. Most comparative validations in the industry are based on the other methods including DAYSIM, and the 3- and 5-Phase Method. These comparative validations are furthermore performed through various software providing a user-friendly interface. This introduces further factors of errors besides the already existing ones of the parameter and simulation settings.

In this study insufficient data was found for a thorough validation, therefore a comparative verification was performed against annual daylight metric results. [Brembilla and Mardaljevic, 2019] Future work of further validation of the accuracy of the chosen simulation settings should be conducted. Especially investigating how well the suggested settings deal with solar shading as this was not included in this project.

The chosen data for the comparative verification is from the conference presentation "Competition Results and Discussion". [Brembilla and Mardaljevic, 2019] The presentation was made to highlight that the Radiance CBDM results will vary due to differences in practices. The various practices here were the settings of simulations using the Radiance 3-Phase Method or 4-Component method.

Furthermore, each Radiance calculation will give a slight variation of the result even when using identical settings. This is due to the Monte Carlo sampling shown by previous research. [Kharvari, 2020a]

Conclusion 8

In this project, thorough research was conducted on the topic of climate-based daylight modelling. As Radiance is seen as the ultimate truth in the field of daylighting based on its extensive validation, this became the focal point. Annual daylight metrics and CBDM validation methods and their accessibility were investigated in the literature review besides the workings, methods and parameter choices of Radiance.

Based on the literature review a Radiance method was suggested as a standard for the Danish building industry for CBDM along with a proposed method of integration with BSim. Finally, the proposed method was tested and verified by comparison against other results based on the same method with different settings and the "truth"-method of Radiance.

Based on the research clarity and transparency of available methods and software to perform CBDM would help implement the use of CBDM in the industry. By making CBDM simple and accessible it should become more common practice even amongst engineers and architects at smaller companies.

A simple user interface with few choices is key. Therefore this study suggested the predefined parameter settings for CBDM through Radiance, shown in table 6.1. Presenting the user with the simple choice of a fast estimation, compliance with the Danish building regulations or manual inputs. A suggestion of the structure of the user interface is illustrated in figure 6.3.

For simplicity, the user is not represented with the choice of which Radiance calculation method to use. This study found the 3- and 4-Phase Method to be the most adaptable and fast for general use. The findings on calculation method choice are illustrated in figure 4.4. The advantage of these methods is the speed at which they can be used to investigate dynamic solar shading and various fenestration systems while providing accurate illuminance results.

The results have been suggested to be given in the metric spatial daylight autonomy, sDA. The metric is simple to understand and is needed to document compliance with the Danish building regulations. Furthermore, as secondary results would be provided in the form of the metrics useful daylight illuminance, UDI, total annual illuminance TAI and annual sunlight exposure, ASE. This will provide the user with a more holistic spectrum of results if interested.

For validation of CBDM tools and parameter settings experimental validation is preferable due to accuracy and uncertainties. No benchmark exists for CBDM validation. Until such procedures are available a proposal on the use of existing datasets is provided:

For experimental validation a combination of the *CIE 171:2006 Test Cases* and either *BRE-IDMP dataset* or the dataset from *NCR Daylight Lab* is recommended. [CIE 171:2006, 2006] [Mardaljevic, 2001] [Reinhart and Breton, 2009] The *BRE-IDMP* dataset is recommended for research use whereas the *NRC Daylight Lab dataset* is recommended for other purposes. Table 3.1 presents the investigated existing datasets as the creation of a new dataset is time-consuming and expensive.

Comparative validation is the current practice for software developers and it is also used amongst researchers. Again no guideline is available on the practice of ensuring accreditation quality. So comparative validation results are difficult to compare and should be made with caution and awareness of the uncertainties the method introduces. Furthermore, multiple output metrics should be considered for robustness to ensure investigation of the influence of various aspects such as calculation algorithm, parameter settings, sky model and different daylight components.

Software for CBDM should be simple, transparent and accessible to ensure proper application in the building industry. Table 4.2 shows a wide selection of software tools that use Radiance as a CBDM engine. This provides a certain level of validation. However, this study found a gap between free software that is too limited due to simplicity for the user and expensive software which requires a certain amount of know-how.

If the cost is not a question ClimateStudio possibly provides the most user-friendly tool while being versatile and fast, though the accuracy has not been validated. If an inexpensive tool is needed the industry is missing a tool which is user-friendly as the existing free software requires know-how of visual coding. This is where the proposed compilation of BSim and Radiance would fill this gap providing a simple and accessible software.

When considering the speed of CBDM the iterative method of ClimateStudio or Photon Mapping is desirable. However, when accuracy is also taken into account, and considering existing Radiance methods alone, the 3-, 4-, 5- and 6-Phase Methods are more desirable due to agility and speed when investigating dynamic solar shading or multiple fenestration systems. The choice of method comes down to the model and the design choices which the user wants to investigate. Figure 4.4 illustrates a flowchart to use for the choice of method made in this project.

As mentioned the 3- and 4-Phase Method is recommended for general use for CBDM metric results as the additional accuracy of the direct sun component provided in the 5- and 6-Phase Methods only has a significant impact on rendering results.

The proposed method has been verified against results for a typical deep room from two Radiance calculation methods. [SBI 2013:26, 2013] [Brembilla and Mardaljevic, 2019] The relative error is within $\pm 30\,\%$ for the metrics based on global, averaged illuminance showing an acceptable divergence. The metric solely based on the direct sun component has a higher error of up to $\pm 150\,\%$. To use this metric further investigation is needed. Future work with a more thorough validation of the chosen parameters would be beneficial to confirm the method and settings work well for general CBDM.

The aim was to provide a method to make climate-based daylight modelling more accessible to the Danish building industry in combination with thermal comfort and energy use simulations. This could improve the integrated design and thereby lower energy use while creating a better indoor climate. Therefore a method of integration of Radiance and BSim has been proposed. The principle of the integration is illustrated in figure 6.1. The workflow along with user interfaces appear in figure 6.2 and 6.3.

The hope is, that the method will be fully integrated into BSim in the future, making CBDM accessible to the Danish building industry by making it inexpensive and simple to perform CBDM.

A Digital appendix

The files included in the digital appendix, uploaded separately to this report, appear in figure A.1.

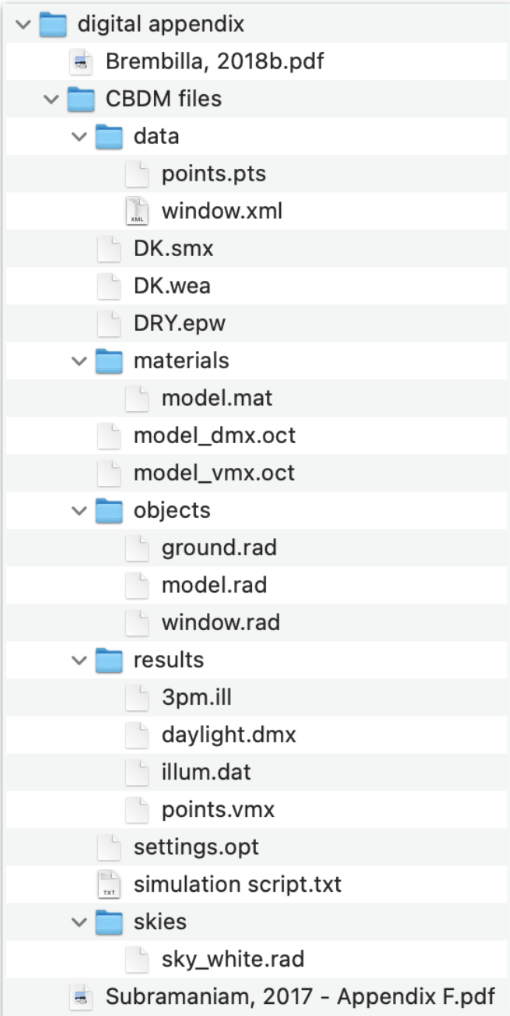


Figure A.1: File structure of digital appendix.

The digital appendix includes the files used for the climate based daylight modelling done with Radiance. Furthermore, included is the presentation from the 17$^{\text{th}}$ International Radiance Workshop with the CBDM results used for verification of the suggested simulation settings and appendix F from the Radiance tutorial *Daylighting Simulations with Radiance using Matrix-based Methods.* [Brembilla, 2018a][Subramaniam, 2017]

Description of individual Radiance programs B

This appendix includes a short description of all the individual Radiance programs. The descriptions are mainly taken directly from the Radiance site. The full description for each program can be downloaded in pdf's found on the website. [McNeil, 2020b] A few of the commonly used programs on this list has a longer description taken from *Rendering with Radiance* or *Daylighting Simulations with Radiance using Matrix-based Methods*. [Ward and Shakespeare, 2021] [Subramaniam, 2017] The commonly used programs for annual daylight simulations are marked in red. The programs are grouped below by their function.

Scene preparation / processing

- ies2rad - convert IES luminaire data to Radiance description
- mgf2meta - convert Materials and Geometry Format file to Metafile graphics
- mgf2rad - convert Materials and Geometry Format file to Radiance description
- obj2rad - convert Wavefront .obj file to Radiance description
- obj2mesh - create a compiled Radiance mesh file from Wavefront .OBJ input
- tmesh2rad - convert a triangular mesh to a Radiance scene description

Radiance geometry generators

- genblinds - generate a Radiance description of venetian blinds
- genbox - generate a Radiance description of a box: Creates a parallelepiped with sharp, beveled, or rounded corners.
- genBSDF - generate Bidirectional Scattering Distribution Function (BSDF) description of Radiance definitions from Radiance or MGF input: For example, it can convert a venetian blind defined in terms of Radiance polygon primitives into an equivalent BSDF.
- genclock - generate a Radiance description of a clock
- genprism - generate a Radiance description of a prism: Creates a truncated prism, extruded from a specified polygon along a given vector. Optionally rounds corners.
- genrev - generate a Radiance description of surface of revolution: Generates a surface of revolution based on a user-defined function and a desired resolution. The resulting object is built out of stacked cones.
- gensky - generate a Radiance scene description of a CIE standard sky for a specific time or altitude/azimuth angles: Generates a description of a clear, intermediate, overcast, or uniform sky, with or without a sun. The location details and irradiation values (for a single point-of-time) from a WEA file can be included as input parameters for gensky.

- gendaylit - generate a Radiance scene description of the daylit sources using Perez models for diffuse and direct components that are similar to gensky
- gensurf - generate a Radiance description of a curved surface: Generates a general parametric surface patch from a user-defined function or dataset. The object is created from optionally smoothed quadrilaterals and triangles.
- genworm - generate a Radiance description of a functional worm: Generates a variable-radius "worm" along a user-specified parametric curve in 3D space. The object is built out of cones joined by spheres.
- pkgBSDF - package BSDFs provided as XML for Radiance

Scene preparation / processing

- xform - transform a Radiance scene description: Scales, rotates, and moves Radiance objects and scene descriptions. Combined with the inline command expansion feature, permits easy creation of a scene hierarchy for easy modification and manipulation of complex environments. Also provides an array feature for repeating objects. When used without any transformation options, xform can be used to simply include a certain Radiance definition into the scene. It can also be used to replace the material definitions of surfaces in the scene with a different material.
- rcalc - record calculator: It is extremely versatile and can be used for calculations that range from simple arithmetic to complex ones such as mapping an image of the sky to a cylindrical surface. It is used in the Five-Phase Method for calculating the position of solar-discs as per the chosen number of Reinhart sky-subdivisions.
- icalc - interactive calculator
- cnt - index counter that is useful in iterating or counting through a specified number of inputs
- macbethcal - compute color compensation based on measured Macbeth chart: Calibrates color and contrast for scanned images based on a scan of the Macbeth Color Checker chart. May also be used to compute color and contrast correction for output devices such as film recorders. Output is a pixel-mapping function for pcomb or pcond.
- lampcolor - compute spectral Radiance for diffuse emitter
- ev - evaluate expressions
- neaten - neaten up output columns
- tabfunc - convert table to functions for rcalc, etc.
- total - sum up columns
- vwright - normalize a Radiance view, shift it to the right
- rcollate - resize or transpose a matrix of data values: a tool for formatting, resizing or transposing matrix data from a single file. With regards to the simulations described in this tutorial, it can be used for changing the dimensions of the results calculated through rmtxop or dctimestep.
- replmarks - replace triangular markers in a Radiance scene description: Replaces special "mark" polygons with object descriptions. Useful for separating light sources or detail geometry for manipulation in a CAD system.
- rlam - laminate records from multiple files
- pmblur - generate views for camera motion blurring
- pmdblur - generate views for combined camera motion and depth blurring

- pdfblur - generate views for depth-of-field blurring
- vwrays - compute rays for a given picture or view. Serves, when during annual daylight simmulations, two purposes that are critical to image based simulations:

  a. Generating input rays: Vwrays can accept a view specification or a pre-existing image as input and generate ray origins and directions for each pixel in that image. These rays are then specified as inputs to rfluxmtx for performing image-based simulations. The rays generated this way are somewhat analogous to the manually specified grid- points that are used in illuminance-based simulations.

  b. Computing image dimensions: When invoked with the -d option, vwrays calculates the dimensions of the image to be generated. These dimensions are required as command-line inputs for rfluxmtx.
- oconv - create an octree from a Radiance scene description. The octree format which the rendering programs use as input compiles the given scene files into an octree for efficient ray-tracing. Creating an octree is the preliminary step for annual daylighting simulations.
- getbbox - compute bounding box for Radiance scene: Computes the extents of the physical geometry present in a Radiance scene.
- mkillum - compute illum sources for a Radiance scene: Converts specified scene surfaces into illum secondary sources for more efficient rendering.
- compamb - compute good ambient value for a rad input file
- raddepend - find Radiance scene dependencies
- objview - view Radiance object(s): Can be used to interactively view a Radiance scene.
- lookamb - examine ambient file values
- rhcopy - copy ray information into a holodeck
- rhoptimize - optimize beam locations in holodeck file

Rendering

- rpict - generate a Radiance picture: This rendering program produces the highest-quality raw (unfiltered) pictures. A Radiance picture is a 2D collection of real color Radiance values, which, unlike a conventional computer graphics image, is also valuable for lighting visualization and analysis. The picture is not generally viewed until the rendering calculation is complete and the output has been passed through pfilt for exposure adjustment and antialiasing. It is the conventional Radiance ray-tracing program used for generating images from Radiance definitions.
- rvu - generate Radiance images interactively: The interactive program for scene viewing. The displayed resolution is progressively refined until the user enters a command to change the view or other rendering parameters. This is meant primarily as a quick way to preview a scene, check for inconsistencies and light placement, and select views for final, high-quality rendering with rpict.
- rview - ray-tracing program for viewing a scene interactively. When the user specifies a new perspective, rvu quickly displays a rough image on the terminal, then progressively increases the resolution as the user looks on. He can select a particular section of the image to improve, or move to a different view and start over. This mode of interaction is useful for debugging scenes as well as determining the best view for a final image.

- rcontrib - compute contribution coefficients for geometric sufaces in a Radiance scene: These surfaces are usually luminous in nature (such as the sky or electric light fixtures). Simply put it is a program that can compute the flux transfer matrix between two physical or virtual surfaces. It can also calculate the flux transfer matrix between a set of input rays (specified as a grid-points file) or surface elements and one or more surfaces.
- rtrace - trace rays in Radiance scene: This program computes individual Radiance or irRadiance values for lighting analysis or other custom applications. Input is a scene octree (as for rvu and rpict) plus the positions of the desired point calculations. This program is often called as a subprocess by other Radiance programs or scripts.
- rpiece - render pieces of a Radiance picture
- ranimate - compute a Radiance animation: This control program handles many of the administrative tasks associated with creating an animation. It coordinates one or more processes on one or more host machines, juggles files within limited disk space, and interpolates frames, even adding motion blur if desired.
- ranimove - render a Radiance animation with motion
- rholo - generate/view a Radiance holodeck
- rhpict - render a Radiance picture from a holodeck file
- bsdfview - view a BSDF representation: a viewer for BSDF files.

User interface

- rad - render a Radiance scene: This is probably the single most useful program in the entire Radiance system, since it controls scene compilation, rendering, and filtering from a single interface. Through the setting of intuitive control variables in a short ASCII file, rad sets calculation parameters and options for rvu, rpict, and pfilt, and also automatically runs mkillum and updates the octree and output pictures with changes to the scene description files.
- trad - graphical user interface to Radiance rad program: This is a graphical user interface (GUI) built on top of rad using the Tcl/Tk package. To the utility ofrad it adds process tracking, help screens, and image file conversions.
- lampcolor - compute spectral Radiance for diffuse emitter
- dayfact - compute illuminance and daylight factor on workplane: An interactive script to compute illuminance values and daylight factors on a specified work plane. Output is one or more contour line plots.
- glare - perform glare and visual comfort calculations: An interactive script that simplifies the generation and interpretation of findglare results. Produces plots and values.
- getinfo - get header information from a Radiance file
- xshowtrace - interactively show rays traced on Radiance image under X11

Viewing output

- ximage - Radiance picture display for X window system: Displays one or more Radiance pictures on an X11windows server. Provides functions to query individual and area pixel values and computes ray origins and directions for input to rtrace.
- x11meta - output metafile graphics to X11

- ra_bmp - converts Radiance images to the more commonly known bitmap (.bmp) format.

Daylight coefficients, and flux matrix tools for annual simulation

- epw2wea - extracts location details, Direct-Normal irRadiances and Diffuse-Horizontal irRadiances from EnergyPlus Weather data (EPW) files and stores them in WEA (weather file) format.
- genklemsamp - generate ray samples over specified surfaces using Klems hemispherical sampling (BSDF) basis: With the exception of the sky-vectors, Klems sampling basis are required for surfaces that is considered for creating flux-transfer matrices.
- genskyvec - compute patch Radiance averages for a specific sky: generates a point-in-time sky-vector, usually based on input from gensky or gendaylit.
- gendaymtx - generate annual perez sky matrix from a weather tape: generates a Perez Sky Model-based time-series of sky-vectors based on input from a weather tape (which is usually a WEA file generated by epw2wea).
- dctimestep - compute annual simulation time-step via matrix multiplication: is a matrix multiplication program that is optimized to perform multiplications for the Daylight coefficient method and the Three-Phase Method. Although it isn't specifically documented, dctimestep can also be used to combine F-matrices and D-matrices into a single resultant matrix.
- rfluxmtx - compute flux transfer matrices for a Radiance scene: creates flux-transfer matrices between a sending surface and one or more receiving surfaces in a Radiance scene. It simplifies the process of setting up matrix-based simulations by replicating some of the functionality of genklemsamp and invoking rcontrib in the background.
- rmtxop - concatenate, add, multiply, divide, transpose, scale, and convert matrices: can be used for matrix multiplication, addition, subtraction, transpose and scaling operations. It is especially useful when combining results from different phases in the Five-Phase Method as well as the F-matrix method.

Photon Map Tools

- mkpmap - generate Radiance photon map: Performs Monte Carlo forward path tracing from the light sources, depositing indirect ray hit points along with their energy (flux) as "photons". The resulting localised energy distribution represents a global illumination solution which is written to a file for subsequent evaluation in a backward ray-tracing pass by another program. The photon map(s) can be reused for multiple viewpoints and sensor locations as long as the geometry remains unchanged.

Analyze and convolve

- pfilt - filter a Radiance picture: Performs antialiasing and exposure adjustment. A picture is not really finished until it has passed through this filter. It is useful for post-processing raw Radiance images generated through daylighting simulations. It can be used to scale, make exposure adjustments and perform anti-aliasing modifications on Radiance images.
- falsecolor - make a false color Radiance picture: Converts a picture to a false-color representation of luminance values with a corresponding legend for easy

interpretation. (See Plate 3 for an example.) Options are included to compute contour lines and superimpose them on another (same-size) picture, change scales and interpretations, and print extrema. This program is actually implemented as a C-shell script, which calls other programs such as pcomb and pcompos.

- histo - compute 1-dimensional histogram of N data columns
- phisto - compute a luminance histogram from one or more Radiance picture
- pcond - condition a Radiance picture for output: Conditions pictures for output to specific devices, compressing the dynamic range as necessary to fit within display capabilities . Also takes calibration files from macbethcal.
- findglare - locate glare sources in a Radiance scene: An image and scene analysis program that takes a picture and/or octree and computes bright sources that would cause discomfort glare in a human observer.
- glarendx - calculate glare index: A back end to convert findglare output to one of the supported glare indices. Also called glare.
- xglaresrc - dislpay glare sources under X11
- evalglare - locate glare sources and calculate glare metrics in a Radiance image
- pcomb - combine Radiance pictures: Manipulates pixel values in arbitrary ways based on the functional programming language used throughout Radiance. Can be used to add, subtract or combine equally-sized Radiance images. Pcomb is employed in the simulations involving the correction of direct-solar aspect of the sky such as the Five-Phase Method or the Six-Phase Method.
- pcompos - composite Radiance pictures: Composites pictures together in any desired montage.
- pexpand - expand requested commands in metafile
- pextrem - find minimum and maximum values and locations in Radiance picture
- pflip - flip a Radiance picture: Flips pictures left-to-right and/or top-to-bottom.
- pinterp - interpolate/extrapolate view from pictures: Interpolates or extrapolates pictures with corresponding z-buffers as produced by rpict. Often used to compute in-between frames to speed up walkthrough animations
- protate - rotate a Radiance picture 90 degrees clockwise.
- psign - produce a Radiance picture from text.
- psort - sort primitives in metafile as requested
- pvalue - convert Radiance picture to/from alternate formats like various ASCII and rawdata formats for convenient manipulation.
- dayfact - compute illuminance and daylight factor on workplane
- normpat - normalize Radiance pictures for use as patterns.
- fieldcomb - combine to or more field frames for video animation.

Converters from Radiance

- rad2mgf - convert Radiance scene description to Materials and Geometry Format
- ra_gif - convert Radiance picture to Compuserve GIF
- ra_bmp - convert Radiance picture to/from Windows BMP image
- ra_pict - convert Radiance pictures to Macintosh PICT files
- ra_ppm - convert Radiance picture to/from a Poskanzer Portable Pixmap
- ra_ps - convert Radiance picture to a PostScript file
- ra_rgbe - change run-length encoding of a Radiance picture

- ra_t16 - convert Radiance picture to/from Targa 16 or 24-bit image file
- ra_t8 - convert Radiance picture to/from Targa 8-bit image file
- ra_tiff - convert Radiance picture to/from a TIFF color or greyscale image
- ra_xyze - convert between Radiance RGBE and XYZE formats
- ran2tiff - expose and convert a Radiance animation to TIFF frames
- normtiff - tone-map and convert Radiance picture or SGILOG TIFF to RGB TIFF

Other Output

- dgraph - do a set of graphs to a dumb terminal
- gcomp - do computations on a graph file.
- igraph - interactive graphing program

Metafile tools

- libmeta.a - simplified interface to metafile
- metafile - graphics command interface, similar to plot
- objline - create metafile line drawings of Radiance object(s)
- plotin - convert plot to metafile primitives
- psmeta - convert metafile to PostScript
- bgraph - do a set of batch graphs to a metafile
- cv - convert between metafile formats
- meta2bmp - convert metafile to Windows Bitmap (BMP) File
- meta2tga - convert metafile to Targa image format
- x11meta - output metafile graphics to X11

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