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Daylight calculations in practice

An investigation of the ability of nine daylight simulation programs to calculate the daylight factor in five typical rooms

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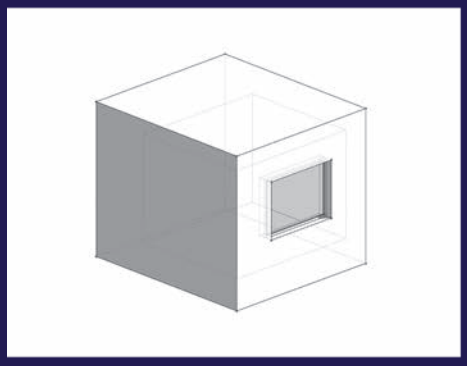
DANISH BUILDING RESEARCH INSTITUTE
AALBORG UNIVERSITY COPENHAGEN

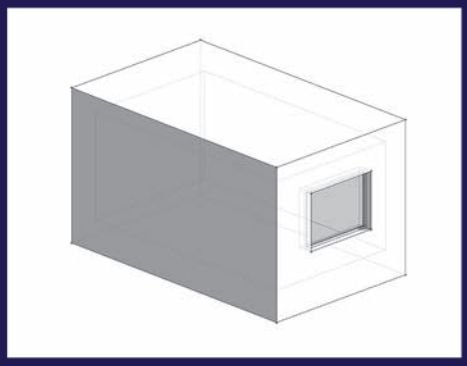
DAYLIGHT CALCULATIONS IN PRACTICE

AN INVESTIGATION OF THE ABILITY OF NINE DAYLIGHT SIMULATION PROGRAMS TO CALCULATE THE DAYLIGHT FACTOR IN FIVE TYPICAL ROOMS

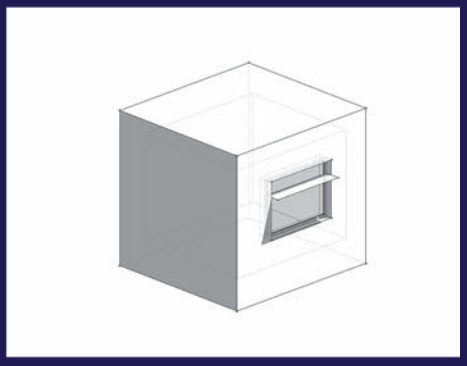
SBI 2013:26



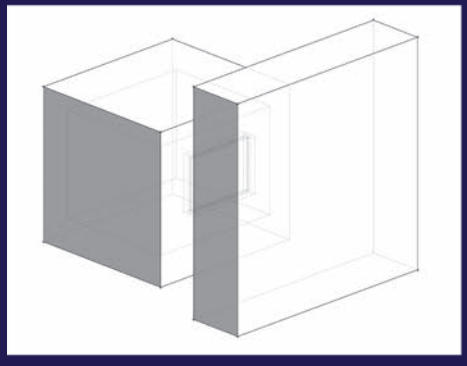
SIMPLE ROOM



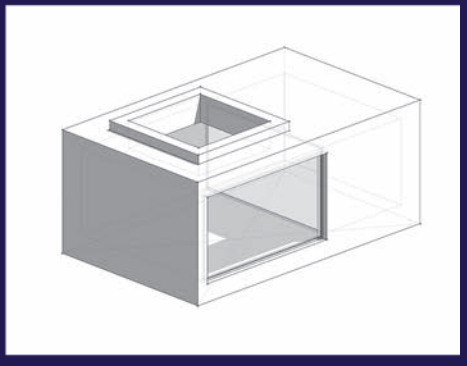
DEEP ROOM



ROOM WITH LIGHT SHELF



ROOM WITH OBSTRUCTION



ROOM WITH BORROWED LIGHT

Daylight calculations in practice

An investigation of the ability of nine daylight simulation programs to calculate the daylight factor in five typical rooms

Anne Iversen
Nicolas Roy
Mette Hvass
Michael Jørgensen
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The project is supported by

COWIfonden

VELUX®

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Preface

This report presents the results of a project initiated by COWI and the Danish Building Research institute (SBi), Aalborg University. The project focused on daylight calculations in practice and was conducted by researchers from SBi, Aarhus University (AU-ASE) and the Technical University of Denmark (DTU) as well as consultants and architects from COWI, VELUX, Alectia and Arkitema. The following persons formed the core group:

Kjeld Johnsen, SBi Aalborg University
Anne Iversen, SBi Aalborg University
Mette Hvass, COWI
Michael Jørgensen, COWI
Nicolas Roy, VELUX
Jens Christoffersen, VELUX
Glenn Elmbæk, Arkitema
Werner Osterhaus, Aarhus University
Steffen Petersen, Aarhus University/Alectia
Christian Anker Hviid, DTU/Alectia

The COWI foundation and VELUX supported the project. The aim of the project was to obtain a better understanding of what daylight calculations show and also to gain knowledge of how the different daylight simulation programs perform compared with each other. Furthermore the aim was to provide knowledge of how to build up the 3D models that were to be daylight-analysed.

The report describes an investigation of the ability of nine simulation programs to calculate the daylight factor on a working plane in five typical rooms.

The core group would like to thank the participants in the two workshops held in relation to the project. The participants came from ARUP London, the School of Architecture in Copenhagen, Rambøll, Grontmij, Esbensen, DTU, Niras, Alectia, Danske Ark, CCO Architects, Schmidt Hammer Lassen Architects, Aarhus University, VHR Holding and the Danish Centre for Light. A special thanks to the speakers; Nanet Krogsbæk Mathiasen from the School of Architecture Copenhagen, Francesco Anselmo from ARUP London, Glenn Elmbæk from Arkitema, Steffen Petersen from Alectia/AU-ASE and Mette Hvass from COWI.

Danish Building Research Institute, Aalborg University
Energy and Environment
September 2013

Søren Aggerholm
Research Director

Main findings

This report investigates the performance and accuracy of nine different simulation programs commonly used by professionals and researchers in the field of architecture and engineering. The programs are compared based on their ability to calculate the daylight factor on a working plane and the depth of daylight penetration.

The programs investigated are: Radiance, Daysim, VELUX Daylight Visualizer, DIAlux, Ecotect, Ecotect/Radiance, IESve, LightCalc and Relux. The results from Relux are based on two approaches; radiosity and raytracing, and therefore ten and not nine simulation programs are listed in the simulation and analysis sheets.

For the simulations five different types of rooms were investigated:
Room 1 – Simple room
Room 2 – Deep room
Room 3 – Room with obstruction *)
Room 4 – Room with light shelf
Room 5 – Room with borrowed light

*) (meaning obstructed daylight access from buildings opposite)

The table below gives an overview of the capability for each simulation program to calculate the daylight factor for the five room types investigated.

Table 1: Capability of each program to calculate daylight factor levels in the five room types. Yes=capable, No=not capable.

	Radiance	Desktop Radiance	Daysim	Velux Daylight Visualizer	DIALux	Ecotect	IESVE	LightCalc	Relux Radiosity	Relux Raytracing
1. Simple room	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
2. Deep room	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
3. Room with obstruction	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
4. Room with light shelve	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
5. Room with borrowed light	yes	yes	yes	yes	yes	no	yes	no	no	yes

The programs compared in the analysis of the different room types corresponded to the ones with a ‘yes’ in Table 1. For these programs, it was found that the different simulation programs gave similar results, see Table 2.
The standard deviation of the average daylight factor for the different simulation programs ranged from ±5.1 % to ±13.6 %. The smallest standard deviations of ±5.1 %; ±6.6 % and ±7.4 % were obtained for the most simple rooms; Room 1, Room 2 and Room 4. Whereas the more complex rooms, Room 3 and Room 5 had standard deviations of ±10.3 % and ±13.6 % respectively.

Table 2: Variation in average daylight factor [%] for the different simulation programs for each of the simulated rooms.

	Room 1 Simple room	Room 2 Deep room	Room 3 Obstruction*	Room 4 Light shelve**	Room 5 Borrowed light***
Max	3.5	2.1	0.9	2.6	2.4
Min	3.0	1.6	0.6	2.1	1.7
Average value	3.2	1.8	0.8	2.4	2.0
Standard deviation [DF %]	0.2	0.1	0.1	0.2	0.3
Standard deviation (+/-) [%]	±5.1	±7.4	±10.3	±6.6	±13.6
Relative difference, max vs. min [%]	15.0	22.6	28.1	18.3	31.2

*Ecotect excluded
**LightCalc excluded
***Ecotect, LightCalc and Relux Radiosity excluded

In this report, the daylight penetration depth was defined as the distance from the façade where a daylight factor of 2% is reached. Looking at the daylight penetration depth simulated with the different simulation programs, standard deviations in the range from ± 4.9% to ± 8.7% were found, see Table 3. The highest deviation was seen for the room with obstruction, which can be attributed to the different ways of the simulation programs to deal with obstructions. For the room with borrowed light, the daylight penetration depth was not considered as this room describes a room located within the building with no façade facing the exterior.

Table 3: Variation in distance [m] from facade, where 2% DF is obtained, for the investigated rooms simulated with the applied simulation programs.

	Room 1 Simple room	Room 2 Deep room	Room 3 Obstruction*	Room 4 Light shelf**	Room 5 Borrowed light***
Max	2.5	2.4	0.7	2.2	
Min	2.1	2.1	0.6	1.8	
Average value	2.3	2.2	0.7	2.0	
Standard deviation [DF]	0.1	0.1	0.1	0.1	
Standard deviation (+/-) [%]	±6.4	±4.9	±8.7	±6.7	
Relative difference, max vs. min [%]	18.1	15.9	24.9	20.6	

*Ecotect excluded

**LightCalc excluded

***Ecotect, LightCalc and Relux Radiosity excluded

Experience from the work reported in this report showed that the programs Radiance, Desktop Radiance, Daysim, Velux Daylight Visualizer, DIALux, IESve and Relux Raytracing were all capable of calculating the daylight factor levels in the five different room types within acceptable agreement.

Ecotect was capable of calculating the simple room, the deep room and the room with light shelf. The program was not capable of calculating the room with obstruction and the room with borrowed light. This fact was ascribed to the simplified calculation engine within Ecotect (split flux method) which the program applies as default for its calculations.

LightCalc was capable of calculating the daylight factor in the simple room, the deep room and the room with obstruction within good agreement. LightCalc was not capable of calculating rooms with light shelf and borrowed light. This is due to the fact that the calculation engine within LightCalc was not developed to include light shelves, and is only capable of calculating one room, and therefore cannot consider internally located rooms.

Relux radiosity was capable of calculating the four rooms; simple room, deep room, room with obstruction and room with light shelf. Relux radiosity could not calculate a room with borrowed light. This is due to the fact that it is only possible to place window openings in the facades facing the exterior. Therefore it was not possible to create a room geometry with a window placed internally in the building.

Even though Table 1 states that IESve was capable of calculating all room types, one should be aware that simulations made with the highest accuracy in IESve, have the amount of ambient bounces set to 3. For simulation programs such as Daysim and Radiance, the amount of ambient bounces was set to 7. This means that calculations made with IESve underestimates the daylight levels in more complex scenes, such as the room with obstruction, where the shadow effect from the obstruction is considered in the calculations. If rooms with obstruction are to be included in IESve and simulated correctly, the designer should therefore be aware of the need to change the default settings in the program.

The report describes a number of possible sources for these deviations. These sources can be due to the structure of the calculation programs, their capacity to simulate complex rooms/surroundings, as well as the expertise of the user.

Introduction

During the last years, there has been a growing interest in buildings lit by daylight. Apart from the aesthetic, visual and spatial qualities obtained from daylight, daylight also plays an important role in the efforts to minimise energy consumption for artificial lights.

Therefore, daylight calculations are included in the design process as a tool to predict daylight levels in buildings. On the marked today, different daylight simulation programs exist, and these programs are being used by both architects and engineers. Experience has shown that results for the same room, obtained from two daylight simulation programs can give different results. This can be due to restrictions in the program itself and/or be due to the skills of the persons setting up the models. This is crucial as daylight calculations are used to document that the demands and recommendations to daylight levels outlined by building authorities are being met, as well as to document the need for additional artificial light. A misleading daylight calculation can have consequences for the design layout of the building and for considerations on how to make use of the space in question. It is therefore important that the results of the daylight simulations are acceptable and that you as a user know the limitations of the tool you are applying.

The project stems from a specific example involving COWI and SBi. Daylight simulations made in two different programs gave very different results. Therefore, collaboration was initiated enlightening the reasons for these differing results. Focus of the collaboration was daylight simulations in practice and entailed knowledge of program-related limitations as well as knowledge of model-specific conditions The work was launched through a workshop with participants from the building industry and research institutions, who all had experience of daylight simulations and measurements in rooms and buildings. A core group was formed at the workshop, and this core group made further work based on the experience gained at the workshop. The core group made the calculations for this report.´

Aim

The aim of the project was to obtain a better understanding of what daylight simulations show and also to gain knowledge of how the different daylight simulation programs perform compared with each other. Furthermore, the aim was to provide knowledge of how to build the 3D models that were to be daylight-analysed.

It is an overall objective to enhance the quality of consultancy within the field of daylighting with a greater knowledge of the available daylight simulation programs and the accuracy of the simulated,.

The project is divided into three phases:

Part 1 - Identification
Conducting the workshop. Identification of the problem. Choosing room types and calculation programs

Part 2 – Calculation and analysis
Analysis of the simulation results from the first part of the work. Description of the different daylight simulation programs

Part 3 - Conclusion
Evaluation of the different programs
Conclusion

Part 1 - Identification **Part 2 – Calculation and analysis** **Part 3 - Conclusion**

Figure 1: The three phases of the project

Workshop

In order to highlight and clarify the projects, a workshop was held that included engineers, architects, program developers and others with experience of simulation and measurement of daylight in buildings. At the workshop, the participants were given typical examples of daylight simulations as well as presentations about the calculated and experienced light. With basis in this common denominator, the participants were divided into smaller groups where they discussed the daylight challenges they experienced in everyday life.

Content

The workshop was divided into two parts; 1) a morning with presentations and 2) an afternoon with discussions in groups. Nanet Krogsbæk Mathiasen from the School of Architecture gave a presentation about the experienced light and Francesco Anselmo fom ARUP London gave a presentation about the simulated light. There were three 'real life' cases where problems with daylight simulations had had a consequence on the layout of a building. The cases were presented by Glenn Elmbæk from Arkitema, Steffen Petersen from Alectia/AU-ASE and Mette Hvass from COWI.

Participants

SBi and COWI organised the workshop and arranged it in collaboration with VELUX. Other participants in the workshop were: ARUP London, School of Architecture Copenhagen, Rambøll, Grontmij, Esbensen, DTU, Niras, Alectia, Danske Ark, CCO Architects, Schmidt Hammer Lassen architects, Aarhus University, VKR Holding and the Danish Centre for Light.

Some of the key points from the presentations were:

- Daylight quality, What is good daylight quality?
- The effect of daylight on our physical and mental well-being
- Developer's and architects should present their wishes to daylight in a building in writing
- Choice of building details, materials and surfaces and their influence on daylight
- The experienced and calculated light, a holistic approach to daylight calculations
- How do we communicate daylight as well as the experienced light and the simulation results?
- At what stage in the design process do we employ daylight simulations?
- The influence of the parameters used in the daylight simulation programs
- What does the different daylight simulation results tell us about the daylight condition within the room; daylight factor, maximum, minimum and average values, glare, uniformity, light on vertical surfaces

The work of the core group

The core group was formed at the workshop and consisted of participants from universities, engineering, and architectural firms and program developers.

The core group selected room types for daylight simulations and simulation programs. The group performed the daylight simulations and documented the results in this report. The simulations were based on consistent input parameters as described in this report.

The working process of the core group included joint meetings and continuous communication to consider the results.

The core group consisted of:
Kjeld Johnsen
Anne Iversen
Mette Hvass
Michael Jørgensen
Nicolas Roy
Jens Christoffersen
Glenn Elmbæk
Werner Osterhaus
Steffen Petersen
Christian Anker Hviid

The simulations were made by:
Nicolas Roy: Radiance, Daysim, Velux Daylight Visualizer
Anne Iversen: DIALux
Michael Jørgensen: Ecotect, Ecotect/Radiance, IESVE
Steffen Petersen: LightCalc
Werner Osterhaus: Relux

Daylight demands

Daylight simulations are applied to demonstrate that the requirements or recommendation on the daylight factor given by the Danish Building Regulations is maintained. The following text contains the legal requirements stipulated in the Building Regulations from 2010; the recommendations given by the Danish Working Environment Authority; and a definition of the daylight factor.

Danish Building Regulations 2010

The quoted sections are from the English version of the Danish Building Regulations, from December 2010 (Danish Building Act, 2010). The additional text is from the updated Danish Building Regulations from January 2013.

6.5.2 Daylight (1)
"Workrooms, occupiable rooms in institutions, teaching rooms, dining areas, hereinafter called "workrooms etc.", and habitable rooms and kitchen must have sufficient daylight for the rooms to be well lit. Windows must be made, located and, where appropriate, screened such that sunlight through them does not cause overheating in the rooms, and such that nuisance from direct solar heat gain is avoided."

Guideline: (6.5.2 (1))
In workrooms etc., habitable rooms and kitchen "the daylight can usually be taken to be sufficient if the glazed area of side lights corresponds to a minimum of 10% of the room floor area or, in the case of rooflights, no less than 7% of the room floor area, assuming that the light transmittance of the glazing is no less than 0.75. The 10% and 7% are guidelines assuming a normal location of the building and a normal layout and fitting out of the rooms. If the type of window is not known at the time of design, the frame clear area can be converted to the glazed area by multiplying the clear frame area by a factor of 0.7. The glazed area must be increased in proportion to any reduction in light transmittance (for example solar control glazing) or reduced light ingress to the windows (for example nearby buildings)."

Daylight may similarly be deemed to be adequate in habitable rooms and kitchen when calculation can demonstrate that there is a daylight factor of 2% in half of the room area.
In workrooms, daylight may also be deemed to be adequate when calculation can demonstrate that there is a daylight factor of 2% in the work zone. This can be calculated by means of a calculation grid that covers the room or the work zone. The grid has an off set of 0.5m from the walls and contains evenly distributed grid points with a maximum distance of 0.5m.

"Daylight may similarly be deemed to be adequate when calculation or measurements can demonstrate that there is a daylight factor of 2% at the workplaces. When determining the daylight factor, account must be taken of actual conditions, including the design of the windows, the light transmittance of the pane and the nature of the room and of the surroundings. See By og Byg (SBi) Guidelines 203, "Beregning af dagslys i bygninger" [Calcula-

tion of daylight in buildings] and SBi Guidelines 219, “Dagslys i rum og bygninger” [Daylight in rooms and buildings].”

Danish Working Environment Authority

In their guideline A1.11, the Danish Working Environment Authority outline requirements to daylight in workrooms and permanent workplaces (June 2007):

Daylight levels in workrooms should be adequate. Daylight can usually be taken to be sufficient if the glazed area of side lights corresponds to a minimum of 10% of the room floor area or, in the case of roof lights, no less than 7% of the room floor area.

Another configuration may similarly be deemed to be adequate. The 10% and 7% is a guideline that will usually give adequate daylight with a normal layout of the rooms. However, situations may occur, where daylight access is not adequate. Daylight may similarly be deemed to be adequate when calculation or measurements can demonstrate that there is a daylight factor of 2% at the workplaces

Definition of daylight factor

As a simple means to describe the amount of daylight in a specific point in a room, the term daylight factor can be used.
A daylight factor (DF) is the ratio of the internal light level to the external light level and is defined as follows, see Figure 2. The daylight factor is normally given in per cent:

$$DF = \frac{\mathrm{E_{indoor}}}{\mathrm{E_{outdoor}}} \cdot 100\ \%$$

$\mathrm{E_{indoor}}$ is the illuminance due to daylight at a point on a given plane indoors (lux)
$\mathrm{E_{outdoor}}$ is the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky (lux)

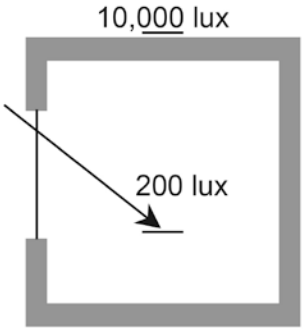


Figure 2: Definition of the daylight factor (DF) when the unobstructed outdoor illuminance level is 10,000 lux and the daylight level is 200 lux indoors, the daylight factor is 2%. The guideline to the Building Regulations 6.5.2 (1) states that in workrooms, the daylight can be seen as adequate when there is a daylight factor of 2% at the workspaces. The figure is taken from SBi Guidelines 219 (Johnsen & Christoffersen 2008)

For a given point in a room, the daylight factor is a permanent factor, which occurs on days with overcast skies. The daylight factor is calculated under a standard overcast sky, which means that the calculation is per definition independent of window orientation and does not express anything about how

much light there will be in the point under real sky conditions for a given orientation.

A topical profile for the daylight factor through the room is seen in Figure 3. The daylight factor is the factor closest to the window and the ratio between the highest and lowest daylight factors will typically be 20:1 and most often 50:1.

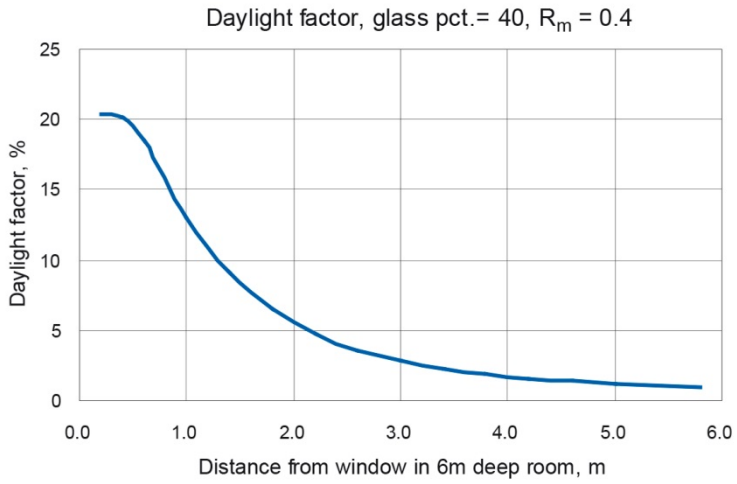


Figure 3: Typical daylight factor through a room with a glazing area of the facade of 40% and a mean room reflectance of 0.4. The figure is taken from SBi Guidelines 219 (Johnsen & Christoffersen 2008).

Methods for analysing the daylight factor

The daylight factor (DF) can be assessed in different ways. It can be measured at a specific point in the room to ensure DF levels for specific functions, e.g. at work places, and it can be measured on a working plane or floor area, dependent on the function of the room. If the area approach is applied, it is recommended to make use of a measurement grid (EN 12464-1:2011).

DFmean
The DFmean describes the average daylight factor for the investigated grid.

DFmedian
The DFmedian is the middle daylight factor when the calculated daylight factors are sorted in an ordered list. The median is thereby a term less dependent on high and low daylight factors in the room, e.g. very high daylight factors close to the window and very low daylight factors farthest away from the window.

Uniformity
The uniformity of the daylight factors on a work plane can be defined in two ways:

1) Ratio between DFmin / DFmean and
2) Ratio between DFmin / DFmax

According to the assessment method for sustainable buildings BREEAM 2.08 the ratio between DFmin / DFmean should at least be 0.4 or the minimum point daylight factor should be at least 0.8%.

Daylight zone
A daylight zone in a room can be defined as the distance from the facade where the recommended daylight factor is achieved.

Measurement grid

Grid systems should be created to indicate the points at which the illuminance values are calculated and verified for the task area(s), immediate surrounding area(s) and background area(s). The following description is in accordance with the description given in EN 12464-1:2011 and it is recommended to follow this instruction.

"Grid cells approximating to a square are preferred, the ratio of length to width of a grid cell shall be kept between 0.5 and 2 (EN 12193:2007 and EN 12464-2:2007). The maximum grid size shall be:

$$p = 0.2\ x\ 5^{log_{10}(d)} \quad (1)$$

Where
p is the maximum grid cell size (m) $\leq$ 10 m

d is the longer dimension of the calculation area (m),. However, if the ratio of the longer to the shorter side is 2 or more, then *d* becomes the shorter dimension of the area

The number of points in the relevant dimension is given by the nearest whole number of *d/p*.
The resulting spacing between the grid points is used to calculate the nearest whole number of grid points in the other dimension. This will give a ratio of length to width of a grid cell close to 1.
A border of 0.5 m from the walls is excluded from the calculation area except when a task area is in or extends into this border area.
An appropriate grid size shall be applied to walls and ceiling and a border of 0.5 m may be applied also.

NOTE 1 The grid point spacing should not coincide with the luminaire spacing.

NOTE 2 Formula (1) (coming from CIE x005-1992) has been derived under the assumption that *p* is proportional to log (*d)*, where:

p = 0.2 m for *d* = 1 m;
p = 1 m for *d* = 10 m;
p = *5* m for *d* = 100 m.

NOTE 3 Typical values of grid point spacing are given in Table 4."

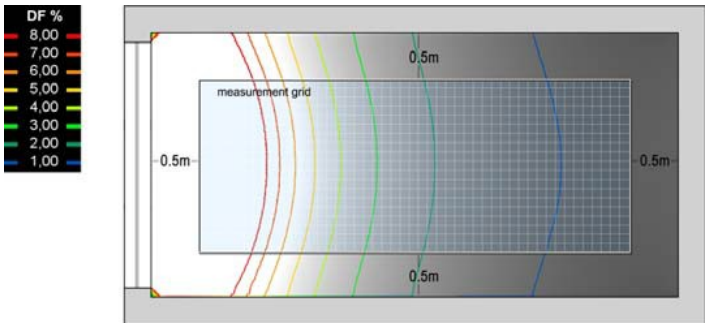
Table 4: Recommended number of grid points

Length of the area (d) [m]	Maximum distance between grid point (p) [m]	Minimum number of grid points
0.4	0.15	3
0.6	0.20	3
1.0	0.20	5
2.0	0.30	6
5.0	0.60	8
10.0	1.00	10
25.0	2.00	12
50.0	3.00	17
100.0	5.00	30

Example

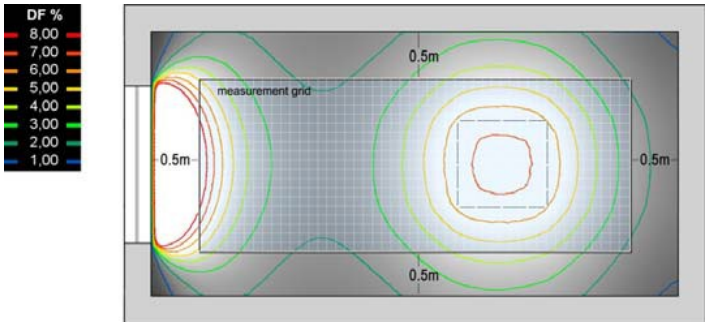
The examples below show DF measurements over a work plane in two rooms with identical dimensions (3m x 6m x 2.5m) and material properties (floor 0.2, wall 0.5, ceiling 0.8), but different window placement and glazing

area. Room 1 is solely illuminated by one large façade window with 5.9 m^2 glazing area, and Room 2 is illuminated by a combination of façade and roof window with 2.4m^2 glazing area. It's possible to observe that the DFmedian is a more sensitive metric than the DFmean in the room evaluation.



Room 1 (5.9 m^2 glazing area)	
DFmean	4.0%
DFmedian	2.3%
Uniformity (min/mean)	0.19
Uniformity (min/max)	0.04
Share of room with DF above 2%	54%

Figure 4: DF results in the example room with a window in the facade



Room 2 (2.4 m^2 glazing area)	
DFmean	4.2%
DFmedian	3.9%
Uniformity (min/mean)	0.41
Uniformity (min/max)	0.7
Share of room with DF above 2%	98%

Figure 5: DF results in a room with two different window configurations, facade window and roof window

From the figures it can be seen that the DFmean is of similar magnitude; 4.0 % and 4.2% within the two rooms. Looking at the room area with a daylight factor above 2%, a difference between 54% and 98% is observed in spite of the average daylight factor being almost equal. Comparing DFmean and DFmedian shows higher difference for the room with large contrasts (Room 1) compared with Room 2. This example demonstrates that the DFmedian and the area of the room with a daylight factor above 2% are more sensitive ways of assessing than the DFmean for assessing the daylight performance of the rooms.

Calculation methods

Accuracy of daylight calculation

Lighting simulation software has experienced rapid growth in recent years. This is both due to requirements stipulated in the Danish Building Regulations and guidelines given by the Danish Working Environment Authority and to a wish from developers and architects to document the lighting qualities of the building. The daylighting software is capable of estimating daylight levels in a room. However, it it is important not to forget that the quality and accuracy of simulations can be influenced by a number of different factors including:

- calculation method
- sky model
- building model
- surface properties
- user expertise

Studies comparing real-life daylight measurements with daylight simulations show deviations around 10% (Mardaljevic 1995; Reinhart & Walkenhorst 2001; Reinhart & Andersen 2006; Reinhart 2010).

Split flux formula

The split flux formula is a simple algorithm derived from a manual calculation method established by BRE (The English Building Research Establishment). This method is based on the principle that the global illumination at a certain point in a room is the result of three distinctive components of daylight:

1. the direct sky component (SC)
2. the reflections from exterior surfaces (ERC) and
3. the reflections from internal surfaces (IRC).

Each component is calculated separately and then added up to obtain the global illumination in each sensor point. The internally reflected component is determined by an equation using the average reflectance of interior surfaces, the total glazing area and a correction factor for the external obstruction. Given these approximations, this method is likely to overestimate or underestimate the amount of daylight. It is only recommended to use this method for spaces in which the window openings are parallel to the walls.

The simulation program Ecotect applies this method as default in its calculations.

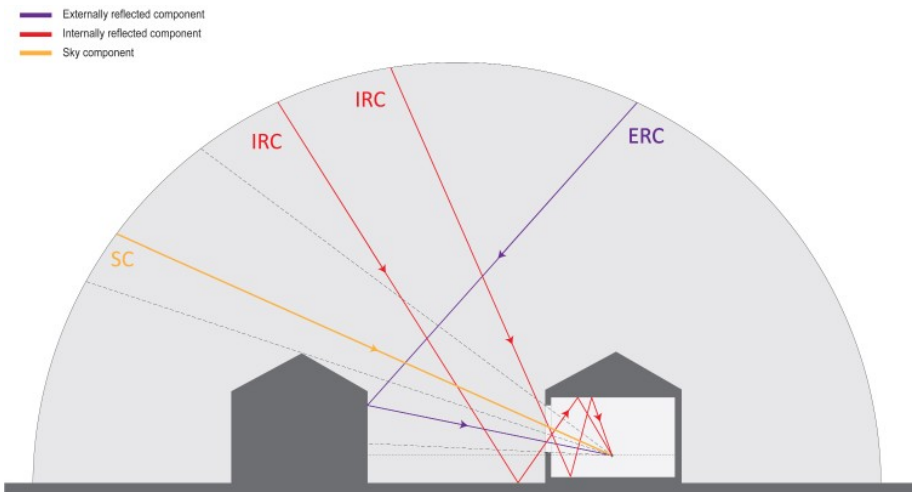


Figure 6: Components of the split flux formula

Radiosity

Radiosity is an algorithm capable of rendering realistic scenes with shadows and diffuse light (Watt 2000). It is an application of the finite element method to solve the rendering equation for scenes with purely diffuse surfaces, a method initially developed to study thermal transfer. This method requires the surfaces of the scene to be subdivided into a mesh of smaller patches. View factors between each pair of patches are computed, and the illumination of a patch is determined by adding the contribution of all visible surrounding patches and light sources. This method has constraints that limit its use for daylighting simulations (diffuse surface, complex description of the sky) and it should only be used to evaluate a relatively simple space.

The simulation programs Relux, DIALux and LightCalc apply radiosity as their simulation engine.

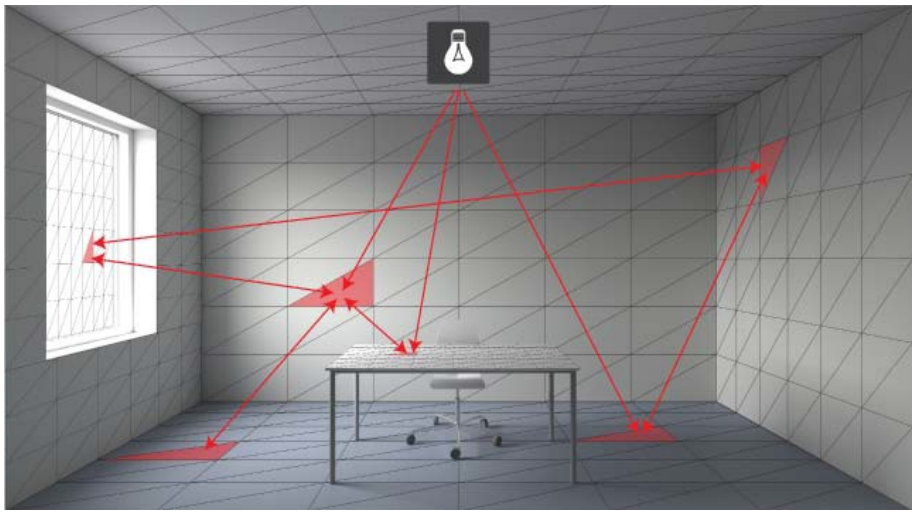


Figure 7: Illustration of the radiosity calculation method.

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) (Larson & Shakespeare 1998). 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, light pipe. Ray tracing algorithms support reflection, transmission and refraction properties of surfaces, which permits the use of complex materials in simulations (Watt 2000).

The simulation program Radiance applies ray tracing in its calculation engine.

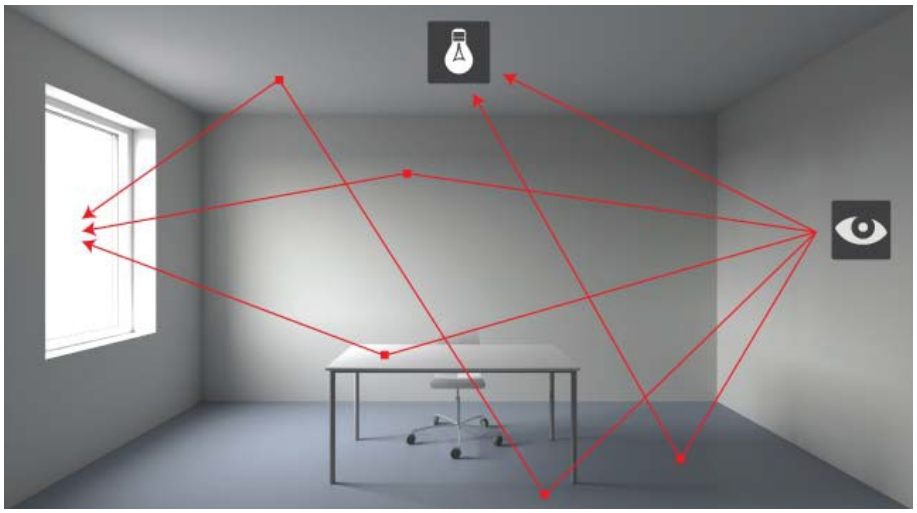


Figure 8: Illustration of the backward ray tracing calculation method

Photon mapping

Photon mapping is a rendering technique that uses bi-directional ray tracing. A first pass combines forward ray tracing and photon mapping to distribute the light in the room and cache the luminous flux on surfaces. A second pass consisting of backward ray tracing from the view point is then used to compute the final image. This optimised technique permits the simulation of more complex lighting scenes with accuracy, i.e. light pipe, and is faster than the traditional backward ray tracing.

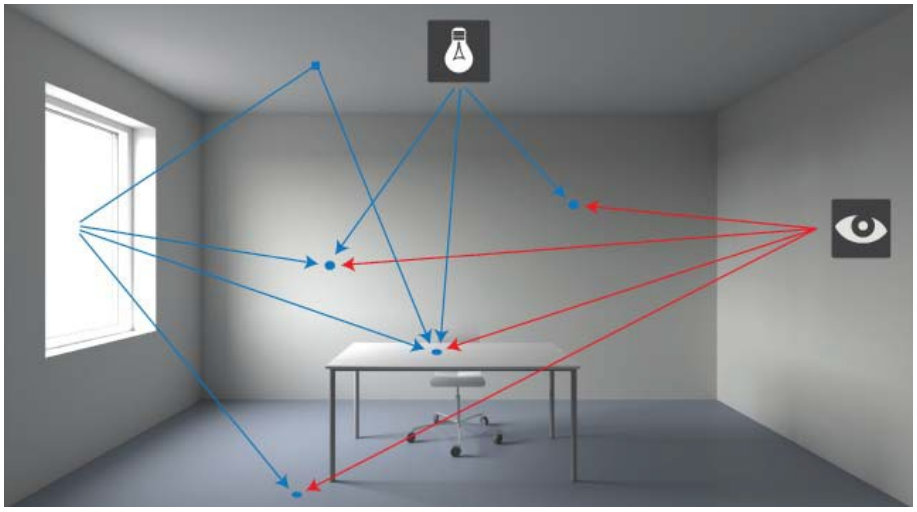


Figure 9: Illustration of the photon mapping calculation method

VELUX Daylight Visualizer applies photon mapping as its calculation engine.

Sky types

The nature of daylight is extremely varied and yields a wide range of occurring sky conditions. To this effect, CIE (Commission international de l'éclairage) has defined 15 normalised skies for use in lighting simulation (CIE 2003). In addition to these 15 skies, some older sky models remain such as the "Traditional Overcast Sky" which is now referred to as sky type 16.

The figure below shows the relative difference in luminance levels at different angular distance between a sky element and the zenith for sky types 1 and 16. The comparison shows a relative difference above 25% for the sky

luminance of the sky element located close to the horizon (80 degrees), which means that sky type 16 will be brighter, or more luminous, closer to the horizon.

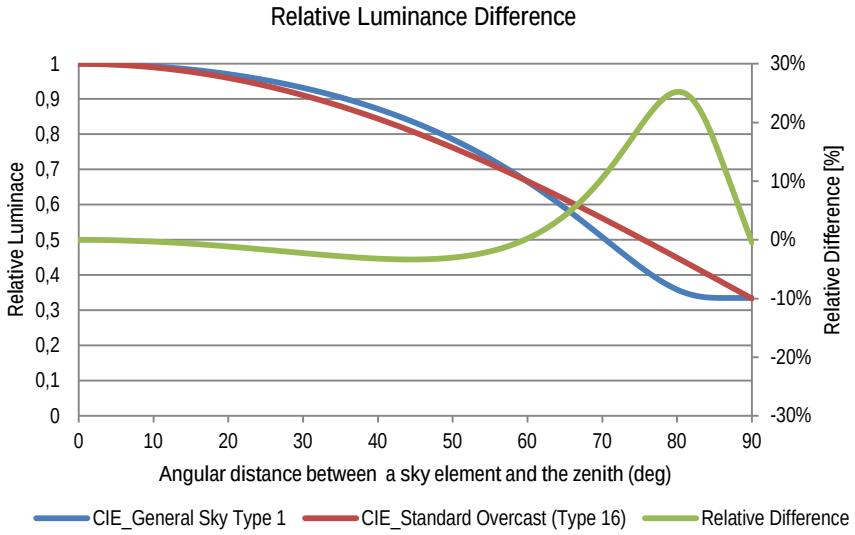


Figure 10: Relative difference between the luminance of overcast skies types 1 and 16

This is important to consider when comparing the calculations of different simulation programs, as it can explain some of the differences obtained between programs. For example, when we compare the results obtained between VELUX Daylight Visualizer and Radiance, we can see slightly higher results in Radiance for rooms 1, 2, 3 and 4, whereas the results are slightly higher in VELUX Daylight Visualizer for room 5. This can be explained by the fact that Radiance uses sky type 16 and VELUX Daylight Visualizer uses sky type 1, and the fact that only room 5 had a roof opening (all other rooms were lit solely by facade openings) and thus it was the room that would encounter the largest effect of different sky luminances at zenith.

The model

The quality of the building model used in simulation can significantly influence the quality and accuracy of daylighting simulations.

Geometry

It is important to ensure that the geometry of rooms and daylight openings is correctly modelled and that the correct simulation parameters are used. For example, in most programs when you model window glass you should make sure that you only have one layer of polygon to represent the glass, since that polygon's material is assigned with the correct transmittance properties of the window pane.

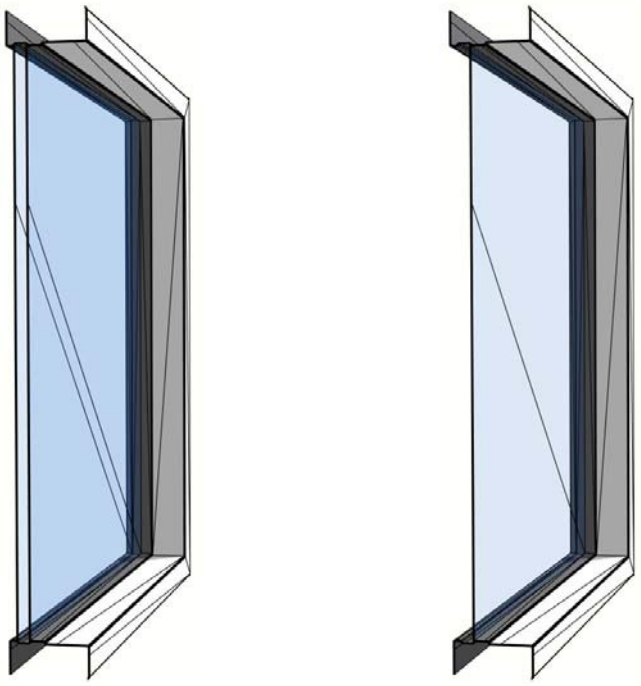


Figure 11: Illustration of a window model with 2 layers of polygon to model the glass (left) and one layer (right).

External obstruction

It is important to properly represent elements influencing daylight on the site, such as external obstruction from surrounding buildings, landscape and vegetation. The effect of external obstruction can be shown by comparing results for the simple room (without obstruction), and the room with obstruction.

Surface properties

Surface properties such as the material type, reflectance and transmittance values will influence the way daylight is distributed in the rooms. It is important to ensure that realistic values are used for the floor, wall and ceiling surfaces, as well as any other surfaces included in the model. It is also important to ensure that the glass transmittance is properly defined, and differentiated between openings using different type of glazing.

Example

In the example below, a scene with realistic surface properties (floor 0.2, wall 0.5, ceiling 0.7) is compared with a scene with unrealistic surface properties (floor 0.9, wall 0.9, ceiling 0.9). The results show a difference of 22% between the average DF values obtained.

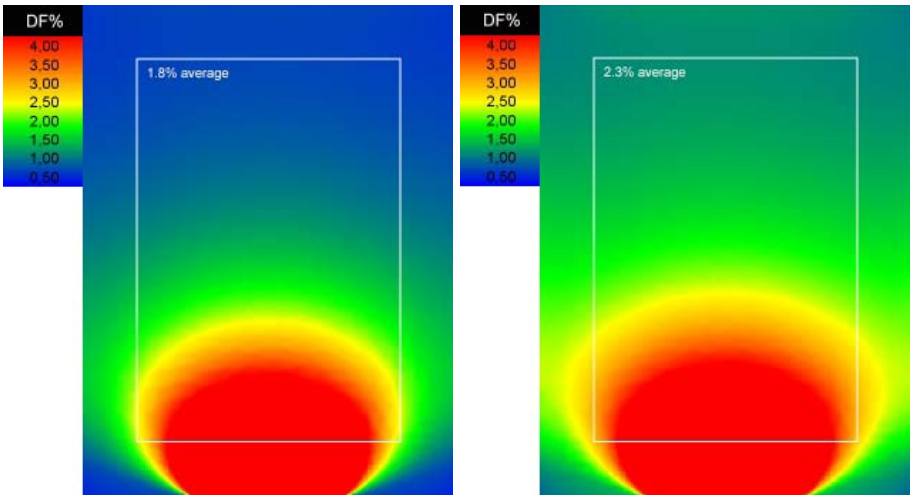


Figure 12: Daylight factor results for the rooms with realistic surface properties (left) and unrealistic surface properties (right).

User expertise

In order to ensure valid simulations, it is important for users to have a good control of the interface and data entry of the simulation software. It is also important to know the capabilities and limitations of the tools, and to select an appropriate method based on the complexity of the scene to be evaluated.

A study from 2009 made by researchers at Havard University investigated how correctly daylight simulations were performed by student/new users (Ibarra & Reinhart 2009). The study showed that typical sources of errors were geometrical errors, such as omitting the thickness of the wall from the model or that the material properties were wrong.

Description of simulation programs

This section gives a short description of the nine daylight simulation programs applied for this report. The description is based on information available on the respective homepages and information given by the software developers. For each simulation program, links are provided indicating where to find further reading.

Radiance

"Radiance is a suite of programs for the analysis and visualisation of lighting in design. Input files specify the scene geometry, materials, luminaires, time, date and sky conditions. Calculated values include spectral radiance (ie. luminance + colour), irradiance (illuminance + colour) and glare indices. Simulation results may be displayed as colour images, numerical values and contour plots. The primary advantage of Radiance over simpler lighting calculation and rendering tools is that there are no limitations on the geometry or the materials that may be simulated. Radiance is used by architects and engineers to predict illumination, visual quality and appearance of innovative design spaces, and by researchers to evaluate new lighting and daylighting technologies."
The program is continuously being updated.

Useful links:
Alex Jacobs has written tutorials that can help you get started on Radiance:
http://www.jaloxa.eu/resources/radiance/documentation/index.shtml

The official link to the Radiance homepage is provided below. At this homepage, there is access to a Radiance mailing list and a possibility to look through Radiance-related questions asked. It is also from this homepage that the program can be downloaded for free.
http://www.radiance-online.org/

Furthermore, versions of Radiance that can be run on both UNIX and PC systems can be downloaded for free from this link:
https://openstudio.nrel.gov/getting-started-developer/getting-started-radiance

Daysim

"DAYSIM is a validated, RADIANCE-based daylighting analysis software that models the annual amount of daylight in and around buildings. DAYSIM allows users to model dynamic facades systems ranging from standard venetian blinds to state-of-the-art light redirecting elements, switchable glazings and combinations thereof. Users may further specify complex electric lighting systems and controls including manual light switches, occupancy sensors and photocell controlled dimming.

Simulation outputs range from climate-based daylighting metrics such as daylight autonomy and useful daylight illuminance to annual glare and electric lighting energy use. DAYSIM also generates hourly schedules for occupancy, electric lighting loads and shading device status which can be directly coupled with thermal simulation engines such as EnergyPlus, eQuest and TRNSYS." Daysim is free.

Useful link:

http://www.daysim.com/

Desktop Radiance

"Desktop Radiance is a Windows 95/98/NT software package that integrates the Radiance Synthetic Imaging System with AutoCAD Release 14. Desktop Radiance includes libraries of materials, glazings, luminaires and furnishings so you can quickly create realistic lighting models. The goal is to provide a design tool integrated with popular CAD packages to facilitate the consideration of energy efficient lighting and daylighting strategies in building design." The development of Desktop Radiance stopped in 2002. Desktop Radiance is included in this report since reference is made to Desktop Radiance for the users of Autodesk Ecotect. It is recommended to download the newest version of Radiance to Windows, as the calculation engine is updated and will be updated continuously.

Useful link:
http://radsite.lbl.gov/deskrad/

IESve

In IESve, it is possible to build a geometric model and simulate daylight conditions within this model.

"IES have been using Radiance over a wide range of commercial projects for many years and to facilitate this work IES have integrated Radiance into the <Virtual Environment>. The latest version of this integration RadianceIES provides users with even greater ease of use through its customised Graphical User Interface (known as the <Virtual Environment> Framework), which integrates with all the IES software packages (SunCast, Apache, etc.)."

Useful link:
http://www.iesve.com/

DIALux

DIALux can calculate electric light, daylight and the energy performance of electric light. The program is oriented towards the European market, and is widely used for calculation of indoor and outdoor electric lighting systems. It follows different national standard lighting calculations, and can import photometric databases directly from manufacturers. The daylight calculation capabilities within DIALux make use of German standard DIN 5043 and CIE Publication 110. Geometric input is limited to certain shapes. Sky choices are somewhat limited but acceptable for diverse ranges of weather conditions. There is an external radiosity and ray-tracing model, POV-Ray (Persistence of Vision 2010). It is used to produce images from calculation results and for presentation renderings. DIALux is available free of charge but is not open source.

Useful link:
http://dial.de/

Relux

Relux is oriented towards the European market and the program can calculate electric light, daylight, and the energy performance of electric light. The program can import photometrical databases from manufacturers.
Relux applies both radiosity and ray tracing in its simulation engine. It is up to the user to decide what calculation engine to apply for simulation.
Relux is free of charge but not open source.

Useful link:
http://www.relux.biz/

Ecotect

"Autodesk® Ecotect® Analysis sustainable design analysis software is a comprehensive concept-to-detail sustainable building design tool. Ecotect Analysis offers a wide range of simulation and building energy analysis functionality that can improve performance of existing buildings and new building designs." These simulations and analysis include energy performance of buildings, thermal simulations, solar radiation, daylight levels and shadow diagrams.

Useful link:
http://usa.autodesk.com/ecotect-analysis/

VELUX Daylight Visualizer

VELUX Daylight Visualizer is a simple, validated (Labayrade *et al.* 2009) daylight simulation and visualisation tool for daylighting design and analysis in buildings. "It is intended to promote the use of daylight in buildings and to aid professionals by predicting and documenting daylight levels and appearance of a space prior to realization of the building design.

The Daylight Visualizer intuitive modelling tool permits quick generation of 3D models in which roof and facade windows are freely inserted. The program also permits users to import 3D models generated by CAD programs in order to facilitate a good workflow and provide flexibility to the model geometry".

Daylight Visualizer can be used to calculate luminance, illuminance and daylight factors for all 15 sky types defined in CIE Standard General Sky. Outputs from Daylight Visualizer are image based and post-processed in a GUI, where pseudo colours are applied and pixel values can be exported for further analysis in other software. VELUX Daylight Visualizer has an efficient workflow and intuitive design, which makes it accessible and easy to use.

The program is freely available and can be accessed from the link below.

Useful link:
http://viz.velux.com

LightCalc

LightCalc is a freely available open-source tool for electric and artificial light simulations. LightCalc has its own calculation engine, based on forward ray tracing and radiosity. The light from the sky and other light sources are included in the simulations through forward ray tracing. Radiosity is applied to calculate the internal inter-reflected contribution.

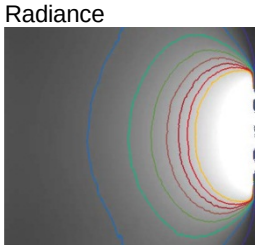
The program relies on input from the user and has a short calculation time. Through iDBuild, it is possible to couple light simulations from LightCalc directly to hourly thermal calculations. LightCalc is limited to calculation of one single room.

Useful link: *http://idbuild.dk/*

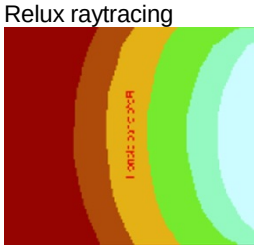
Graphical presentation of the results

The graphical output from the various simulation programs varies in their expression. Figure 13 shows examples of the graphical presentation of daylight factor levels in the simple room. In the following sections, the results are post-processed in Excel in order to be able to present them in a comparable graphical way.

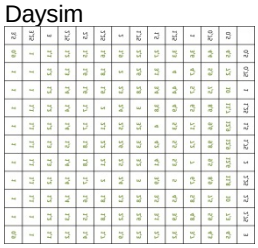
Radiance



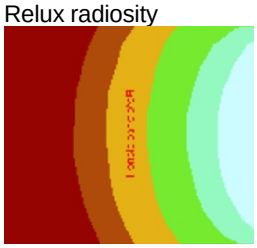
Relux raytracing



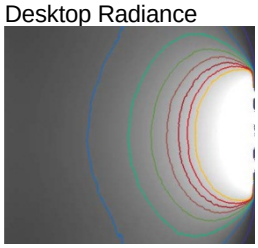
Daysim



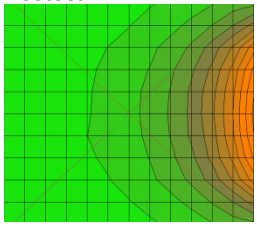
Relux radiosity



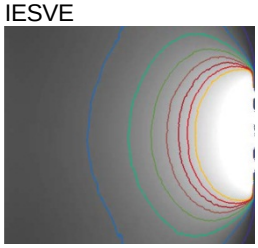
Desktop Radiance



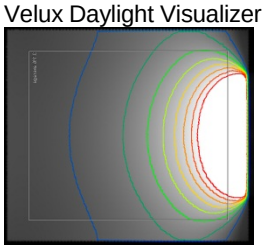
Ecotect



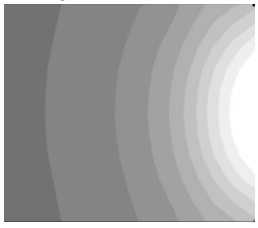
IESVE



Velux Daylight Visualizer



DIALux



LightCalc

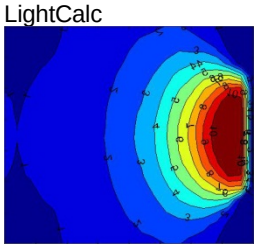


Figure 13: Simulation results (DF) on the working plane 0.85 m above floor level for the different simulation programs

Simulations and analysis

Room types

For this investigation, the room types are chosen based on a wish to compare simulations in rooms with a simple geometry with rooms with a slightly more complex geometry. Some of the chosen simulation programs are capable of calculating all room types whereas others can calculate only the simpler room types. The following room types were chosen for this investigation:

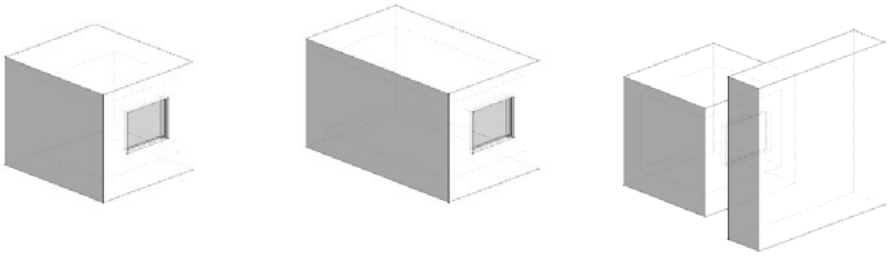
Room 1 – Simple room
A simple room with one window. Light entering the space is reflected both from the side walls and the end walls. The room dimensions are: Width of 3.5 m, height of 2.8 m, depth of 4 m. The thickness of the wall is 0.4 m and the thickness of the window frame is 0.06 m. The dimensions of the window opening in the facade are; 2 m in width and 1.5 m in height. The height of the spandrel is 0.9 m.

Room 2 – Deep room
The room depth is increased from 4 m to 7 m. Otherwise, the room and the window is the same size as the simple room. The light will not be reflected from the end walls.

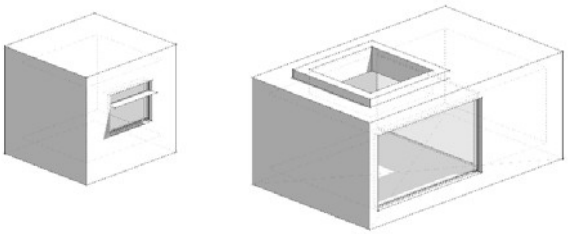
Room 3 – Room with obstruction
The dimensions of the room and the window are the same as those of the simple room. An obstruction is placed outside the window. In the simulation results, the effect of external obstructions on the daylight levels can be seen.

Room 4 – Room with light shelf
The geometry of this room is similar to that of the simple room, with the only exception that a light shelf is included in the window. The room type is included in these investigations in order to be able to calculate a detail in the facade/window.

Room 5 – Room with borrowed light
Daylight will pass through two windows before it enters the room that requires daylight. Window openings are placed in the facade and as a sky light. The light has to pass through these openings and then through an internal window before it enters the calculated room.



Simple room ***Deep room*** ***Room with obstruction***



Room with light shelf ***Room with borrowed light***

Figure 14: Chosen room types

Simulation parameters

The simulation parameters for the rooms are similar. Surface reflectances applied correspond to the ones shown in the figure below.

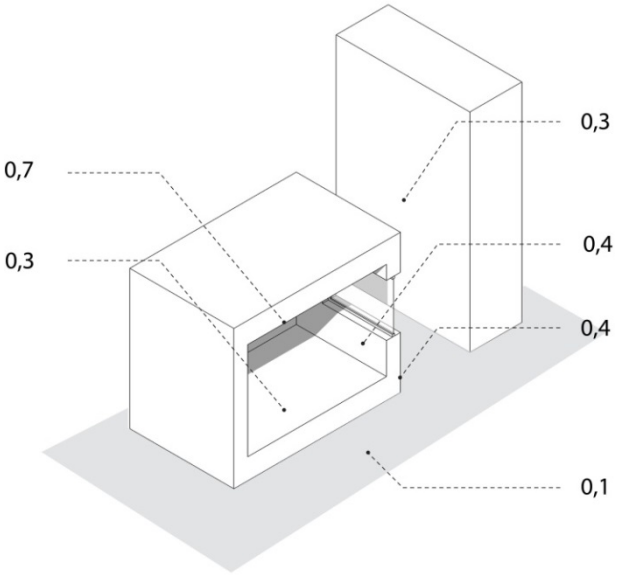


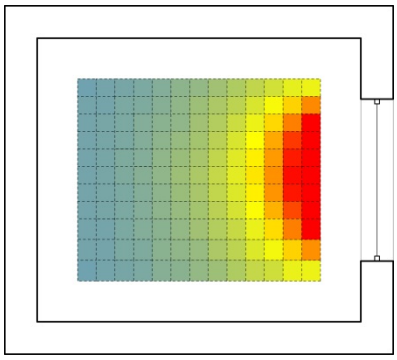
Table 5: Reflectances

	Reflectance (r)
Ground plane	0.1
External walls and obstruction	0.3
Floor	0.1
Wall	0.4
Ceiling	0.7
Window frame	0.8
Side of window opening, internal	0.7
Side of window opening, external	0.3
Light shelf	0.5

Table 6: Light transmittance

	Light transmit-tance(LT)
Window in facade and sky light	0.76
Internal glass	0.85

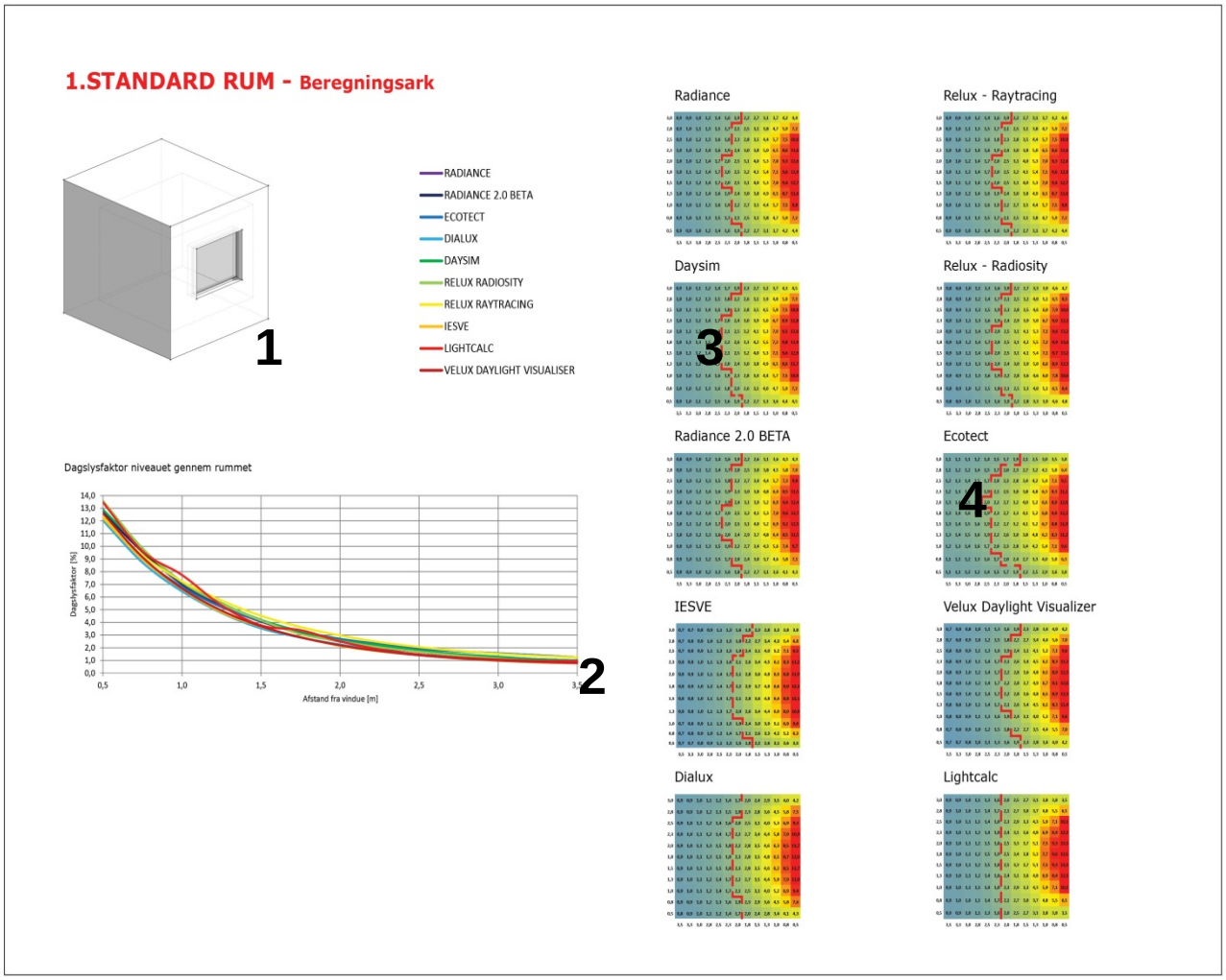
Table 7: Calculation points, calculation height and ground plane

Height of work plane	0.85m
Work zone	Distance from wall to calculated area is 0.5m
Grid	0.25 m horizontal and vertical 
Calculation level	High Quality
Ground plane	Rooms are located in the middle of ground plane of dimensions 50x50 m

Guidance to result sheet simulations

The following pages will show the simulation results of the different room types. A result sheet as shown below is presented for each room. The result sheet for the simulations includes:

1) Illustration of room type,
2) Figure that shows the daylight factor in the centre line of the room as a function of the room depth. The results for this case are post-processed in Excel in order to obtain the same graphical expression for all the simulation programs.
3) Caption explaining the figure.
4) Simulation results shown for a calculation grid in working plane height.

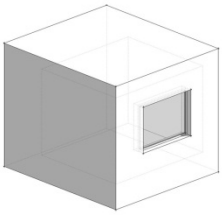


Guidance to result sheet analysis

The following pages will show the analysis results of the different room types. A result sheet as shown below is presented for each room. The result sheet for the analysis includes:

1) Illustration of room type
2) Explanation of figures
3) Figure showing the daylight factor of the different programs given as the DFmean, DFmedian, DFmin and DFmax, as well as the uniformity: DFmin/DFmean and DFmin/DFmax
4) Figure showing the distribution of the daylight factor simulations in a box plot. DFmax is the highest value, followed by the 75% percentile, DFmean, the 25% percentile and DFmin. Percentiles of 75% and 25% describe the daylight factor for 75% and 25% of the calculation points
5) Figure showing the distance from the facade with a daylight factor of 2% for the different simulation programs

1.STANDARD RUM - Analyseark



Figur 8 - Tabel med dagslysfaktorværdier

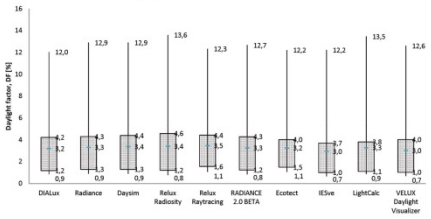
	DIALux	Radiance	Daysim	Relux Radiosity	Relux Raytracing	RADIANCE 2.0 BETA	Ecotect	IESve	LightCalc	VELUX Daylight Visualizer
	DF [%]									
Average	3,2	3,3	3,4	3,4	3,5	3,3	3,2	3,0	3,3	3,0
Median	2,1	2,2	2,3	2,2	2,6	2,2	2,2	1,9	2,3	1,9
Min	0,9	0,9	0,9	0,8	1,1	0,8	1,1	0,7	0,9	0,7
Max	12,0	12,9	12,9	13,6	12,3	12,7	12,2	12,2	13,5	12,6
Uniformity										
Dmin/Davg	0,3	0,3	0,3	0,2	0,3	0,3	0,3	0,2	0,3	0,2
Dmin/Dmax	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

Figur 8 viser dagslysfaktorværdier i tal i det simulerede rum.

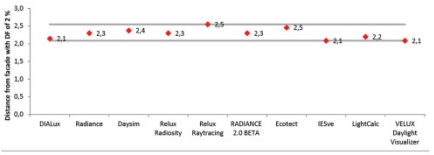
Figur 9 viser, at spredningen i den gennemsnitlige dagslysfaktor for de 10 beregningsprogrammer ligger mellem 3,0% (Visualizer og IESve) til 3,5% (Relux raytracing). Dette betyder, at der er en afvigelse på 15% mellem de største og mindste værdi i simuleret gennemsnitlige dagslysfaktor for de 10 programmer. Endvidere er standardafvigelsen beregnet. Standardafvigelsen er 0,17, hvilket svarer til en standardafvigelse på ± 5,1% mellem de forskellige programmer. Denne type rum repræsenterer en standard scene uden spektakulære dagslysparametre. Det forventes derfor, at denne simulering vil give den laveste forskel mellem de forskellige simuleringsprogrammer.

Figur 10 viser at afstanden fra facade med en dagslysfaktor på 2% varierer fra 2,1 m til 2,5 m. Det fører til forskelle på 18% i dagslys indtrængningsdybde mellem den maksimale og minimale afstand. Standardafvigelsen er 0,15 m, hvilket giver standardafvigelse på ± 6,4% for de forskellige simuleringsprogrammer. Alle simuleringsprogrammer er i stand til at simulere standard rummet. Det kunne ikke fastslås, at simuleringsprogrammer der anvender den samme simulering algoritme, giver de samme resultater. Dette tyder på, at et program er lige så godt som et andet til at simulere standard rummet. Standardfejlen mellem de forskellige simuleringsprogrammer var ± 5,5%. Og forskellen i gennemsnitlig dagslysfaktor mellem største- og mindsteværdier var 15%. Når man ser på dagslys indtrængningsdybde, var standardfejlen ± 6,4% mellem de forskellige simuleringsprogrammer, og forskellen mellem den største og mindste dagslys indtrængningsdybde var 18%.

Figur 9 - Boxplot diagram med dagslysfaktorværdier



Figur 10 - Afstanden fra facaden, hvor en dagslysfaktor på 2% er opnået



ROOM 1 – SIMPEL ROOM – Simulation sheet

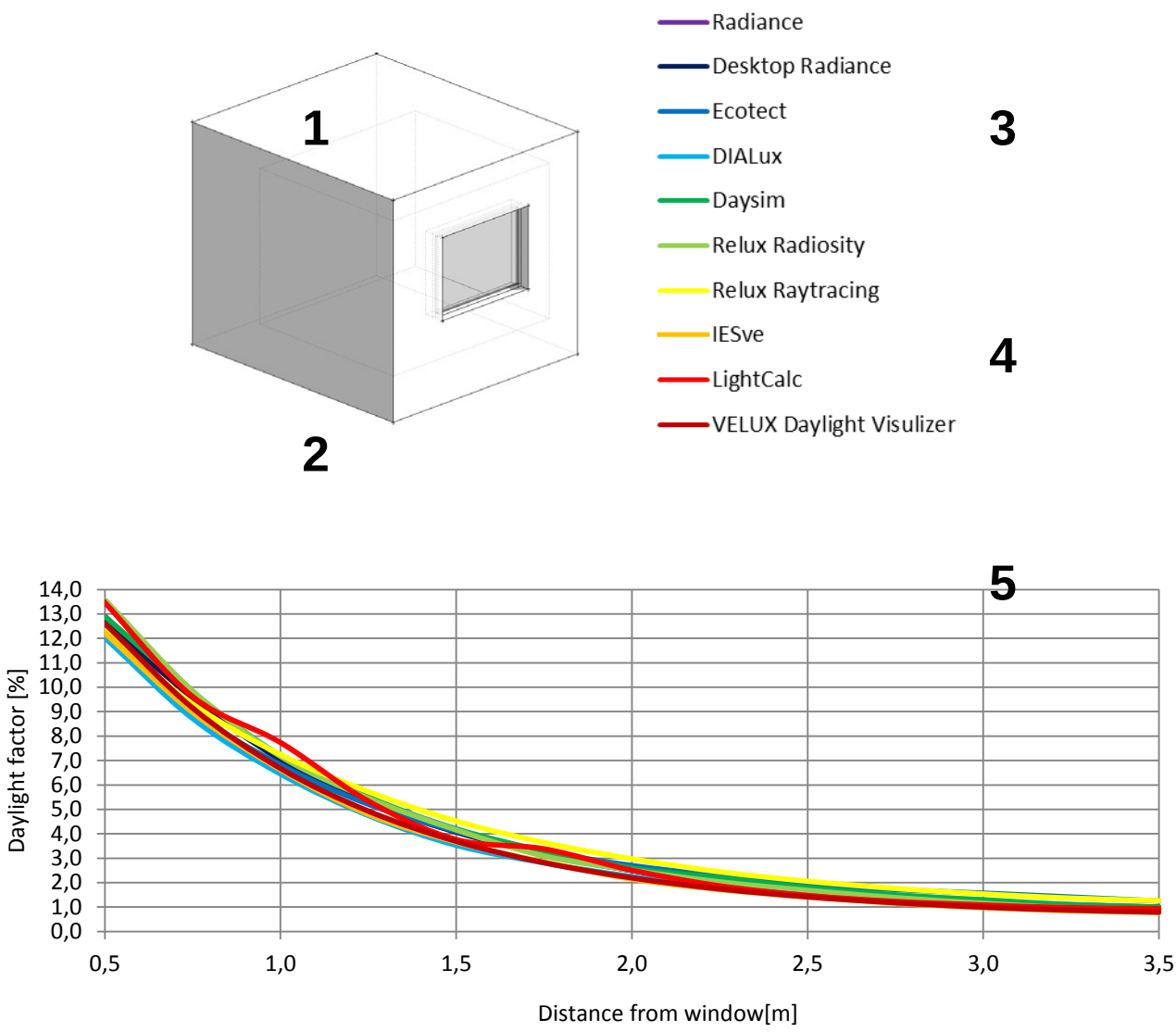
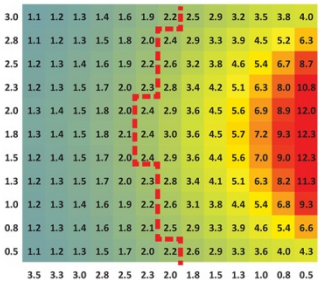
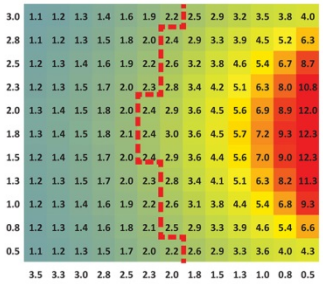


Figure 15: Daylight factor levels through the room

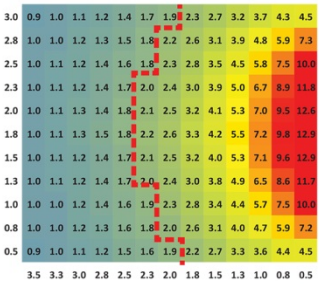
Radiance



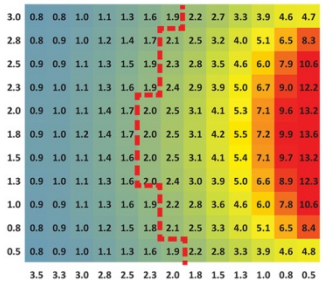
Relux - Raytracing



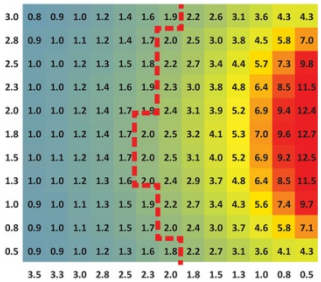
Daysim



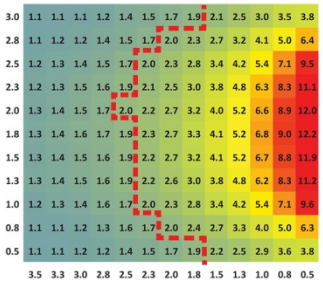
Relux - Radiosity



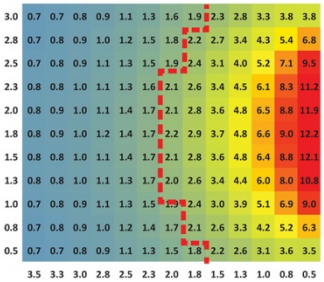
Desktop Radiance



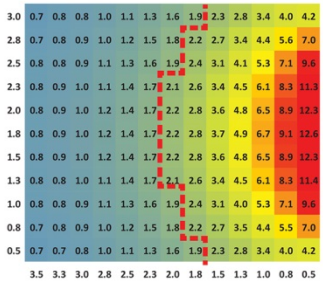
Ecotect



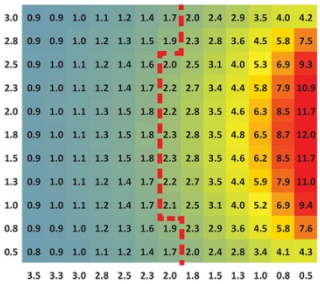
IESve



VELUX Daylight Visualizer



DIAlux



LightCalc

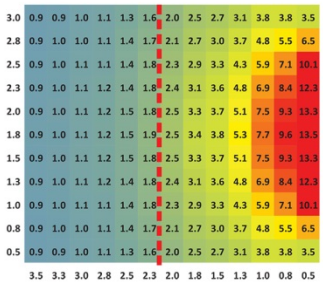


Figure 16: Simulation sheet

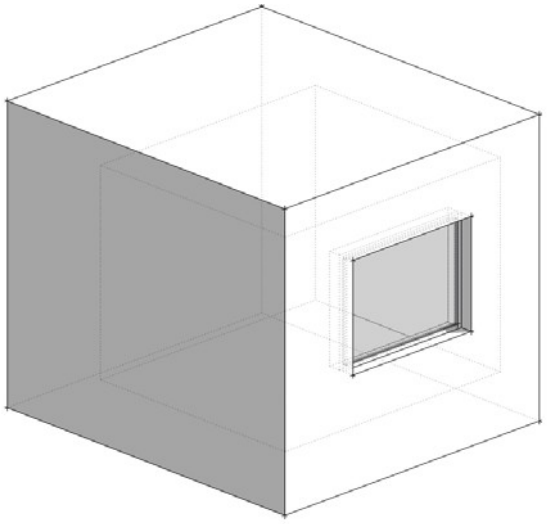


Table 8 lists the daylight factors for the simulated simple room given as DFmean, DFmedian, DFmin and DFmax. Similar results are visualised in Figure 17 as box plots.

The figure and the table show that the spread of the average daylight factor for the 10 calculation programs ranges between 3.0% (Visualizer and IESve) and 3.5% (Relux Raytracing). This means that there is a deviation of 15% between the maximum and the minimum values of the simulated average daylight factor for the 10 programs. Furthermore, the standard deviation has been calculated. The standard deviation is 0.17 which corresponds to a difference of ±5.1% between the different programs.

Figure 18 shows the distance from the façade where a daylight factor of 2% is achieved. The distance from the facade with a DF of 2% varies from 2.1m to 2.5m leading to differences of 18% in daylight penetration depth between the maximum and the minimum distances. The standard deviation is 0.15m, which gives a variation of ±6.4% for the different simulation programs.

This type of room represents a standard scene with no spectacular daylighting parameters. It is therefore expected that this simulation will give the lowest difference between the different simulation programs.

All simulation programs are capable of simulating the standard room. This suggests that one program is just as good as another for simulating a standard room. The standard deviation resulted in differences between the different simulation programs of ±5.5%. And the difference in the average daylight factor between the maximum and the minimum values was 15%. When looking at the daylight penetration depth, the standard deviation resulted in a difference of ±6.4% between the different simulation programs, and the difference between the maximum and minimum daylight penetration depth was 18%.

Table 8: Daylight factor values given as mean, median, min and max values, as well as the uniformity given as DFmin/DFmean og DFmin/DFmax

	DIALux	Radiance	Daysim	Relux Radiosity	Relux Raytracing	Desktop Radiance	Ecotect	IESve	LightCalc	VELUX Daylight Visualizer
	DF [%]									
DFmean	3.2	3.3	3.4	3.4	3.5	3.3	3.2	3.0	3.3	3.0
DFmedian	2.1	2.2	2.3	2.2	2.6	2.2	2.2	1.9	2.3	1.9
DFmin	0.9	0.9	0.9	0.8	1.1	0.8	1.1	0.7	0.9	0.7
DFmax	12.0	12.9	12.9	13.6	12.3	12.7	12.2	12.2	13.5	12.6
Uniformity										
DFmin/DFmean	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.2	0.3	0.2
DFmin/DFmax	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

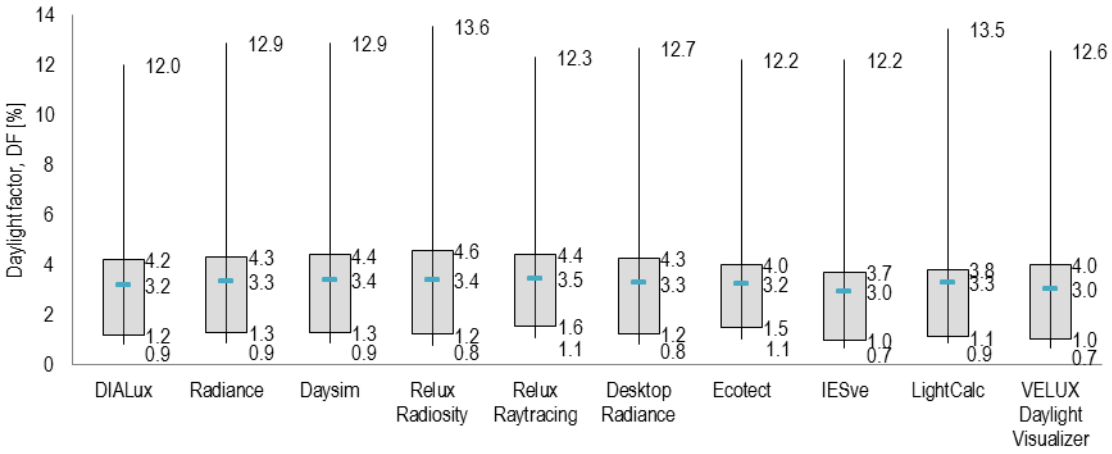


Figure 17: Box plot of the daylight factor for the simple room simulated using the different simulation programs.

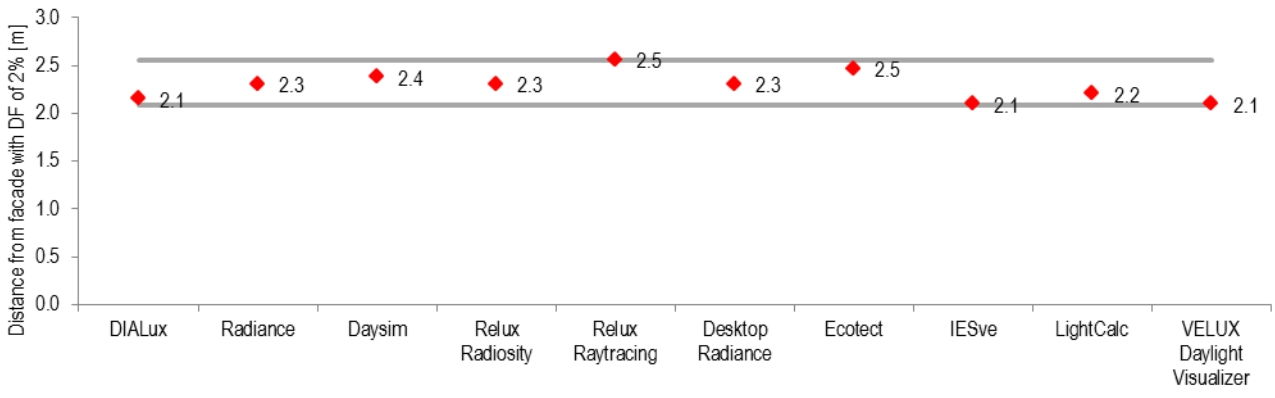
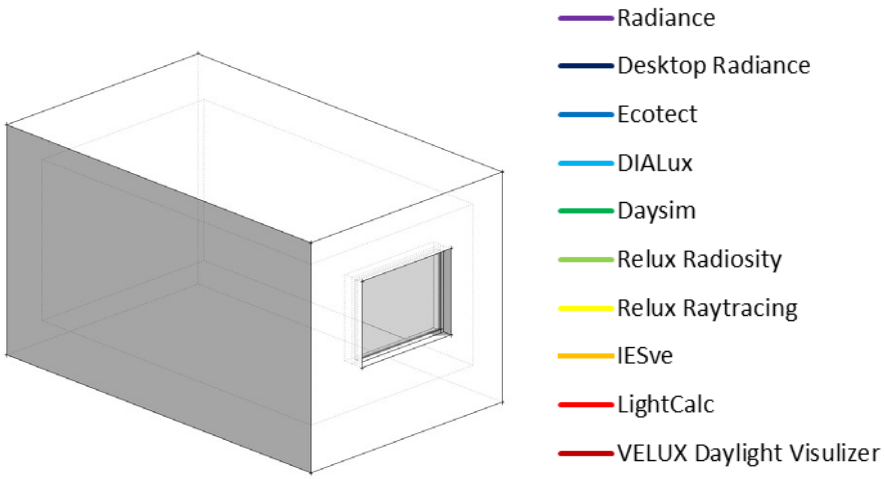


Figure 18: Distance from the facade with a daylight factor of 2%, simulated using the different simulation programs.

ROOM 2 – DEEP ROOM – Simulation sheet



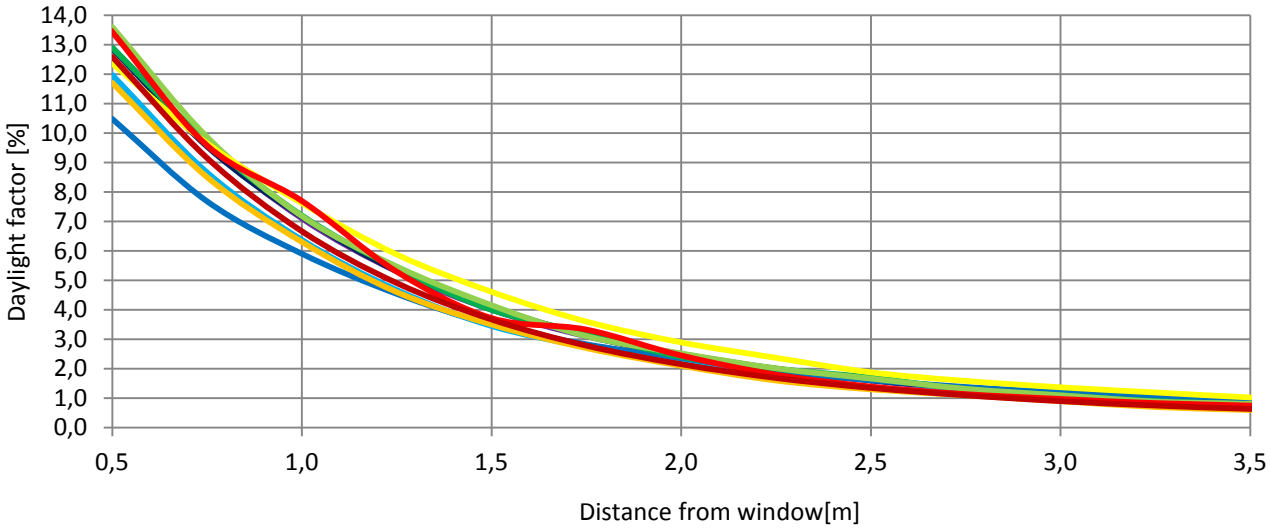
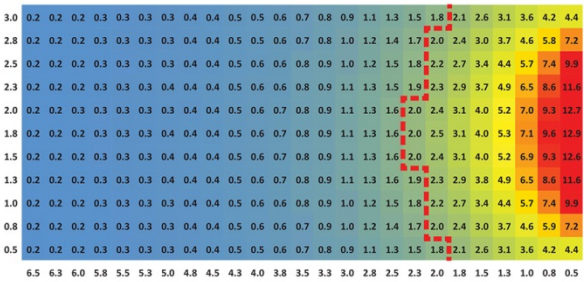
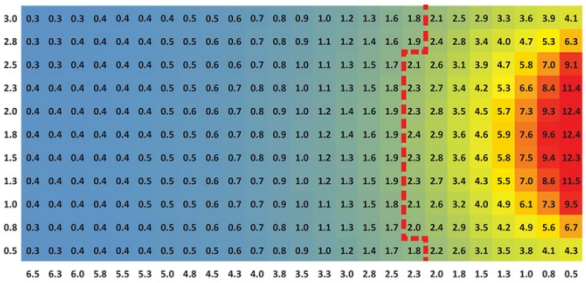


Figure 19: Daylight factor level throughout the room

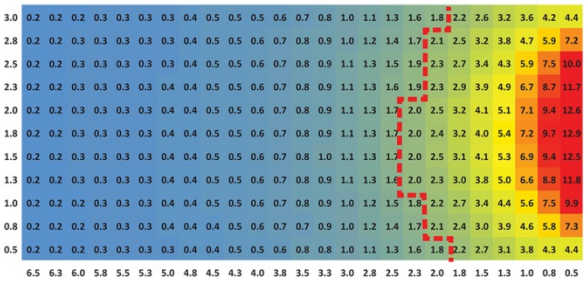
Radiance



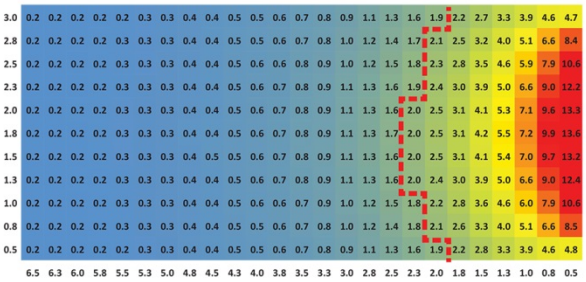
Relux - Raytracing



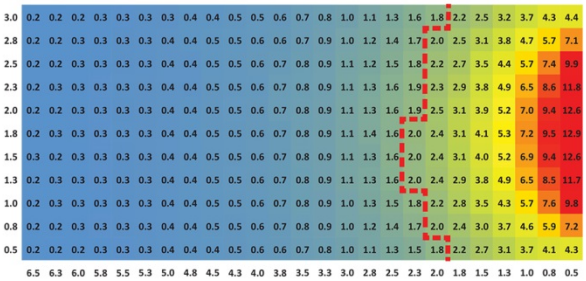
Daysim



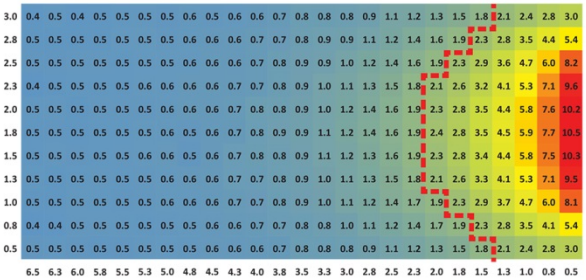
Relux - Radiosity



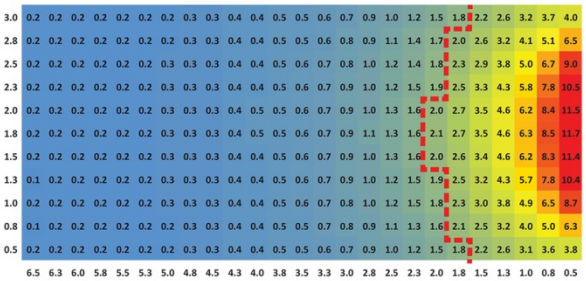
Desktop Radiance



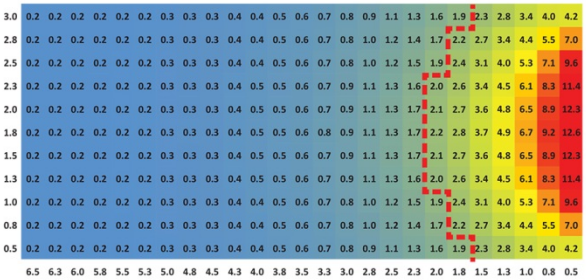
Ecotect



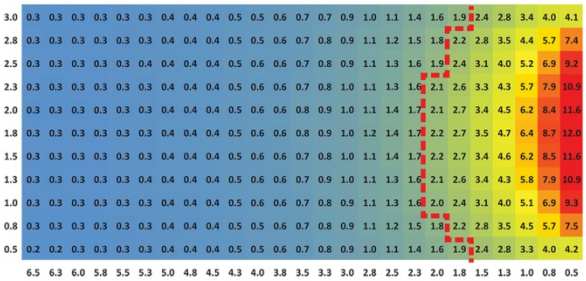
IESve



VELUX Daylight Visualizer



DIAlux



LightCalc

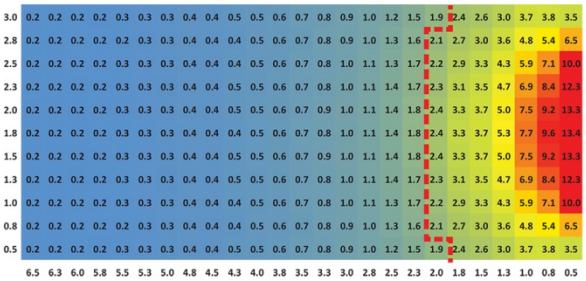


Figure 20: Deep room simulation sheet

ROOM 2 – DEEP ROOM – Analysis sheet

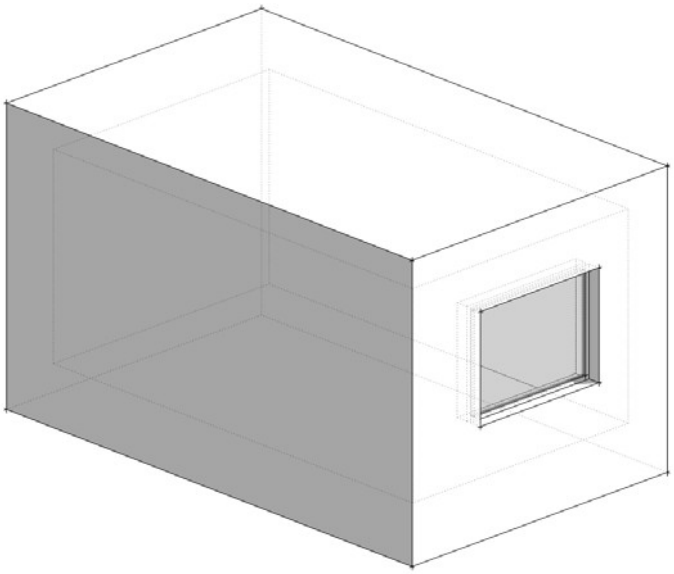


Table 9 and Figure 21 show daylight factor values of the simulated deep room. For the average daylight factor the maximum value is 2.1% (Relux Raytracing), and the minimum value is 1.6% (IESve). The difference is 23% between the maximum and the minimum values of the simulated average DF, and the standard deviation is 0.13 resulting in differences of ±7.4%.

Figure 22 shows the distance from the façade with a daylight factor of 2%. The simulated maximum distance from a facade with a DF of 2% is 2.4m (Relux Raytracing) and the simulated minimum distance from the facade is 2.1m (DIALux, IESve and VELUX Daylight Visualizer). This is a difference of 0.3m, or 16%. The standard deviation is 0.11m which corresponds to differences between the different simulation programs of ±4.9%. The daylight penetration depth is slightly shorter in the deep room than in the simple room 1. This is due to the reflected, bouncing off from the back wall, contributing to an increment in DF in the standard room, whereas this is not the case for the deep room.

All simulation programs are capable of simulating the standard room.

Table 9: Daylight factor values given as mean, median, min and max values, as well as the uniformity given as DFmin/DFmean and DFmin/DFmax

	DIALux	Radiance	Daysim	Relux Radiosity	Relux Raytracing	Desktop Radiance	Ecotect	IESve	LightCalc	VELUX Daylight Visualizer
	DF [%]									
DFmean	1.7	1.9	1.9	1.9	2.1	1.9	1.7	1.6	1.8	1.7
DFmedian	0.7	0.8	0.8	0.8	1.0	0.8	0.8	0.6	0.7	0.6
DFmin	0.2	0.2	0.2	0.2	0.3	0.2	0.4	0.1	0.2	0.2
DFmax	12.0	12.9	12.9	13.6	12.4	12.9	10.5	11.7	13.4	12.6
Uniformity										
DFmin/DFmean	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.1	0.1	0.1
DFmin/DFmax	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

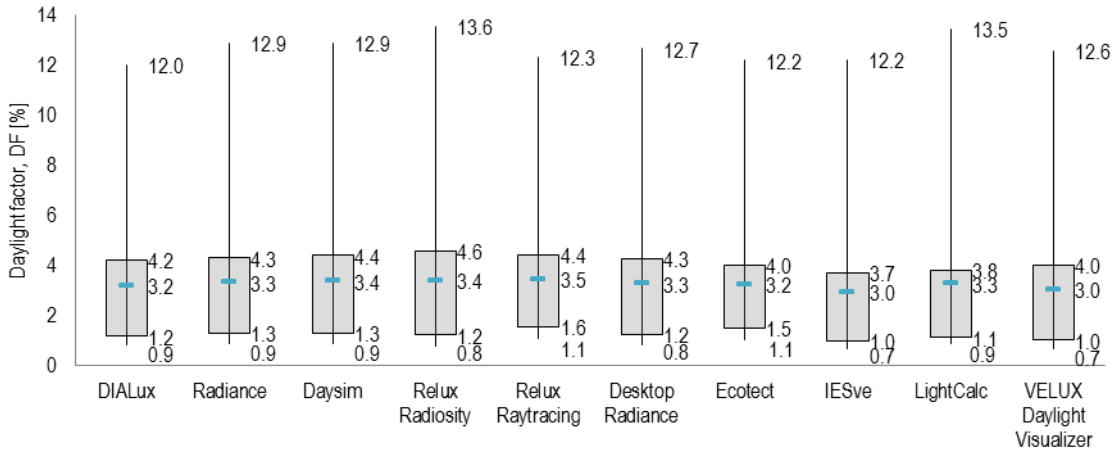


Figure 21: Box plot of daylight factor levels in the deep room simulated using the different simulation programs

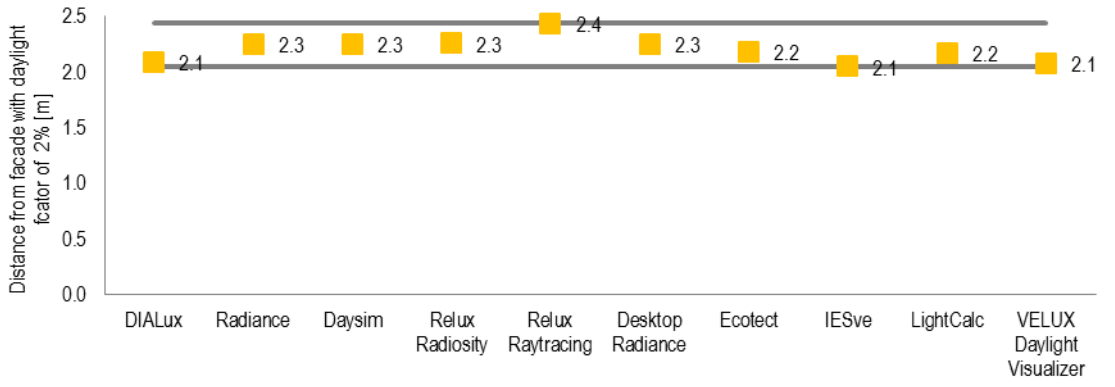


Figure 22: Distance from the facade with a daylight factor of 2%

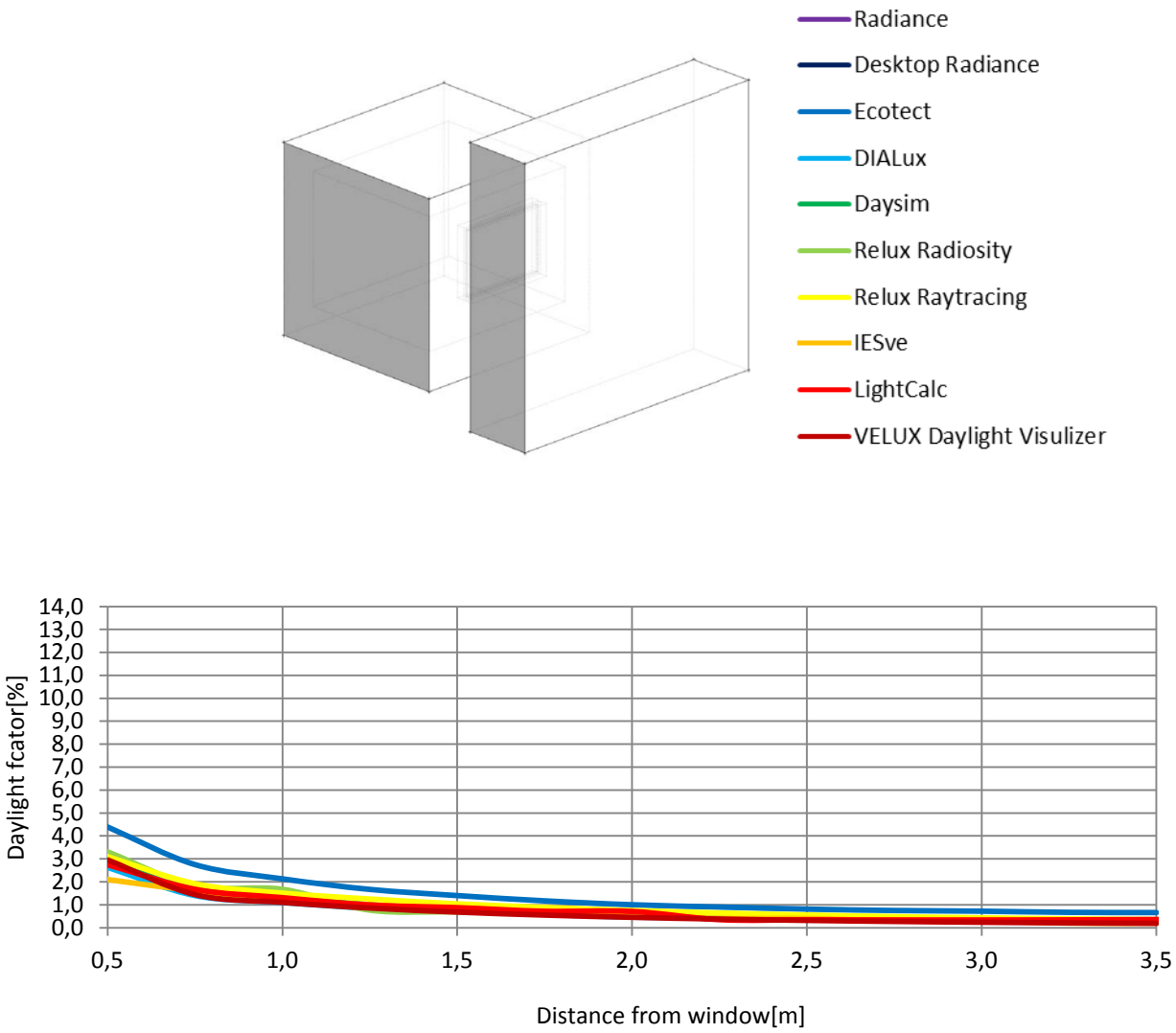
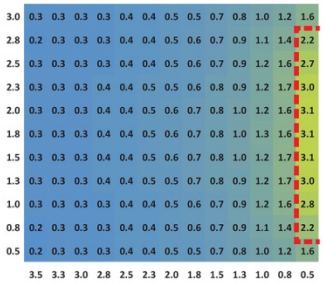
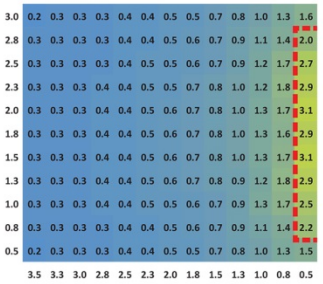


Figure 23: Daylight factor level throughout the room

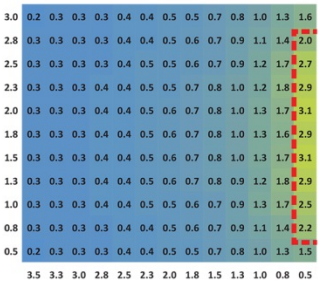
Radiance



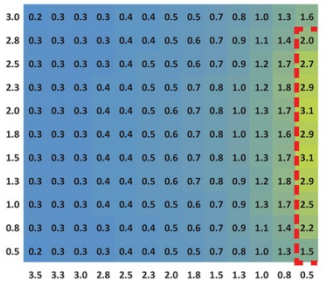
Relux - Raytracing



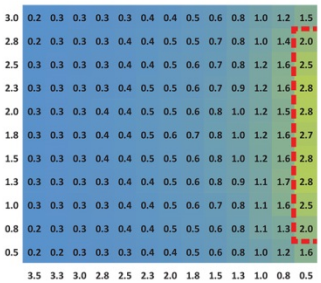
Daysim



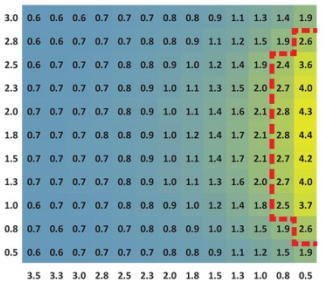
Relux - Radiosity



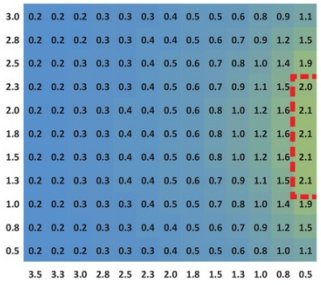
Desktop Radiance



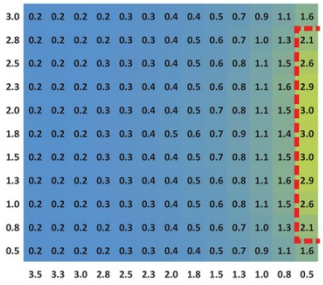
Ecotect



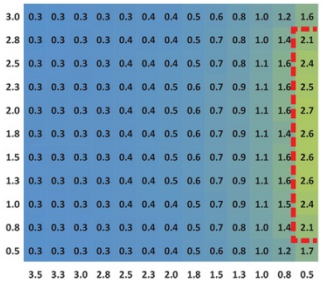
IESve



VELUX Daylight Visualizer



DIAlux



LightCalc

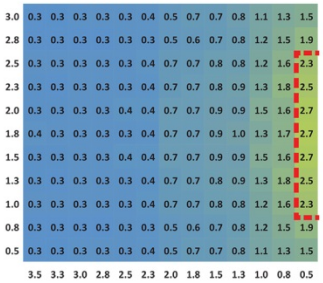


Figure 24: Simulation sheet – Room with obstruction

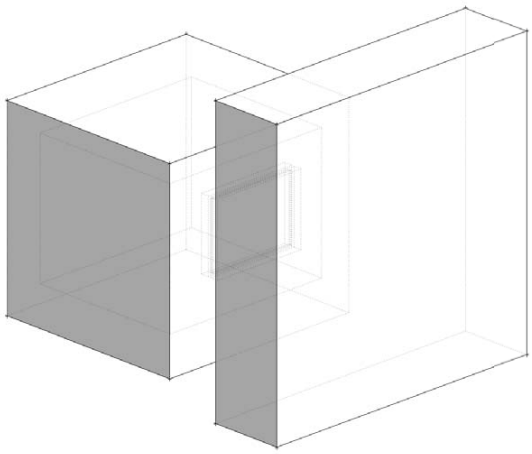


Table 10 and Figure 25 show daylight factor values for the simulated room with obstruction.

From the table and figure it can be seen that the maximum average daylight factor is 1.2% (Ecotect), and the minimum average daylight factor is 0.7% (VELUX Daylight Visualizer, Desktop Radiance, DIAlux). However, it shows clearly that the Ecotect results differ greatly from the other results with generally higher simulation results. If the Ecotect results are excluded, the maximum average daylight factor is 0.9%. This means that the range between the maximum and the minimum average daylight factor is 25%. The standard deviation for the average daylight factor in Room 3 is a DF of 0.08% corresponding to simulated differences of ±10.4%.

It is furthermore worth noting the IESve simulation results. The maximum value for this simulation program is noticeably lower than those of the other simulation programs. The difference might be due to the physical composition of the model in the simulation program, or that the default simulation parameters when running 'highest accuracy' in IESve are not set high enough to consider obstructions correctly. In Radiance, you have a simulation setting called ambient bounces. This setting tells you the number of inter-reflections applied in the simulations. For the Daysim simulations and Radiance simulations, the ambient bounces were set to 7, whereas the default IESve setting was 3.

When a practitioner applies IESve and uses the highest accuracy for his/her simulation, he/she would of course expect that the program produces reliable results. However, when dealing with obstructions, this does not seem to be the case.

Figure 26 shows the distance from the façade with a daylight factor of 2%. From the figure it can be seen that Ecotect is an outlier. Ecotect has therefore been excluded from the analysis. The IESve program results in the lowest daylight penetration depth (0.55m); the maximum daylight penetration depth of 0.73m was obtained with the Relux Raytracing program. This results in a difference in daylight penetration depths of 25% between the maximum and the minimum distances. The standard deviation is 0.06m resulting in differences of ±8.7%.

Except for simulations with Ecotect, the investigated simulation programs were capable of including obstruction in its simulations. It should be noted that for the simulation program of IESve, there is a tendency that this pro-

gram underestimates the daylight availability, when you apply the highest accuracy in its simulation.

Ecotect is the only program that applies the BRE Split Flux method for its calculation. This calculation method is a simplified method and is limited in terms of considering multiple reflections, and this might be the reason why we see this high discrepancy between Ecotect and the other simulation programs.

Table 10: Daylight factor values given as mean, median, min and max values, as well as the uniformity given as DFmin/DFmean og DFmin/DFmax

	DIALux	Radiance	Daysim	Relux Radiosity	Relux Raytracing	Desktop Radiance	Ecotect	IESve	LightCalc	VELUX Daylight Visualizer
	DF [%]									
DFmean	0.7	0.8	0.8	0.9	0.9	0.7	1.2	0.6	0.8	0.7
DFmedian	0.4	0.5	0.5	0.6	0.7	0.5	0.9	0.5	0.6	0.4
DFmin	0.3	0.2	0.2	0.3	0.3	0.2	0.6	0.2	0.3	0.2
DFmax	2.7	3.1	3.1	3.4	3.1	2.8	4.4	2.1	2.7	3.0
Uniformity										
DFmin/DFmean	0.4	0.3	0.3	0.4	0.3	0.3	0.5	0.3	0.3	0.2
DFmin/DFmax	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

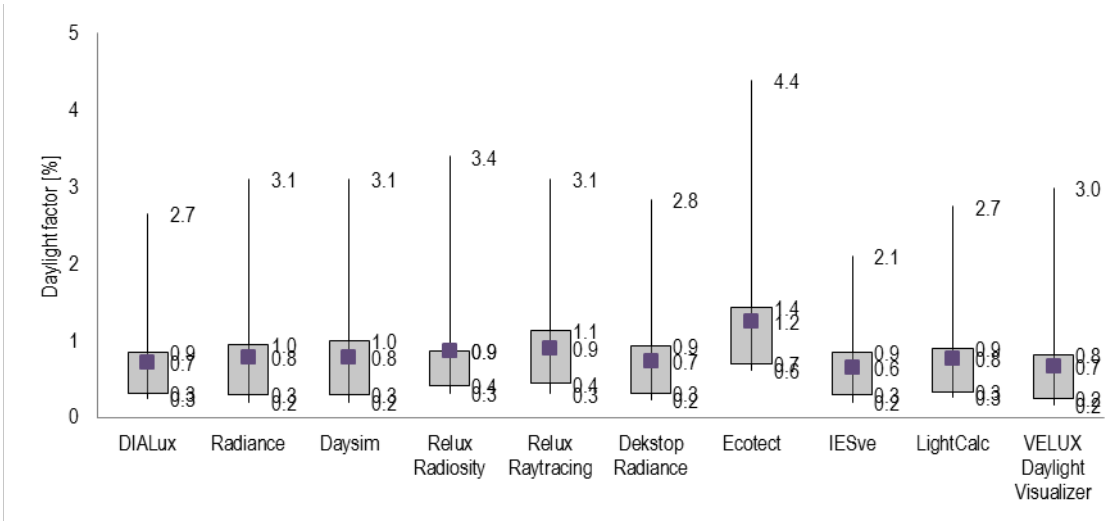


Figure 25: Box plot of daylight factor levels in the room with obstruction simulated using the different simulation programs

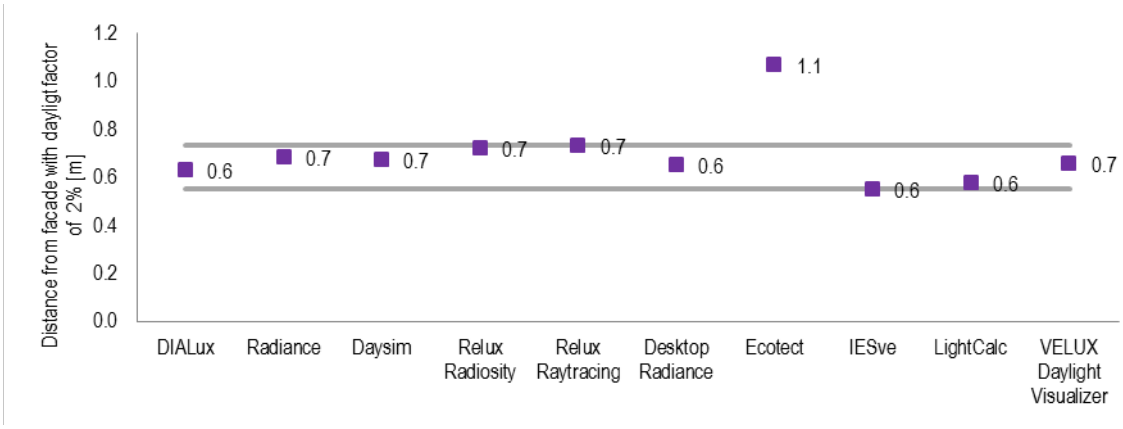


Figure 26: Distance from the facade with a daylight factor of 2% obtained using the different simulation programs

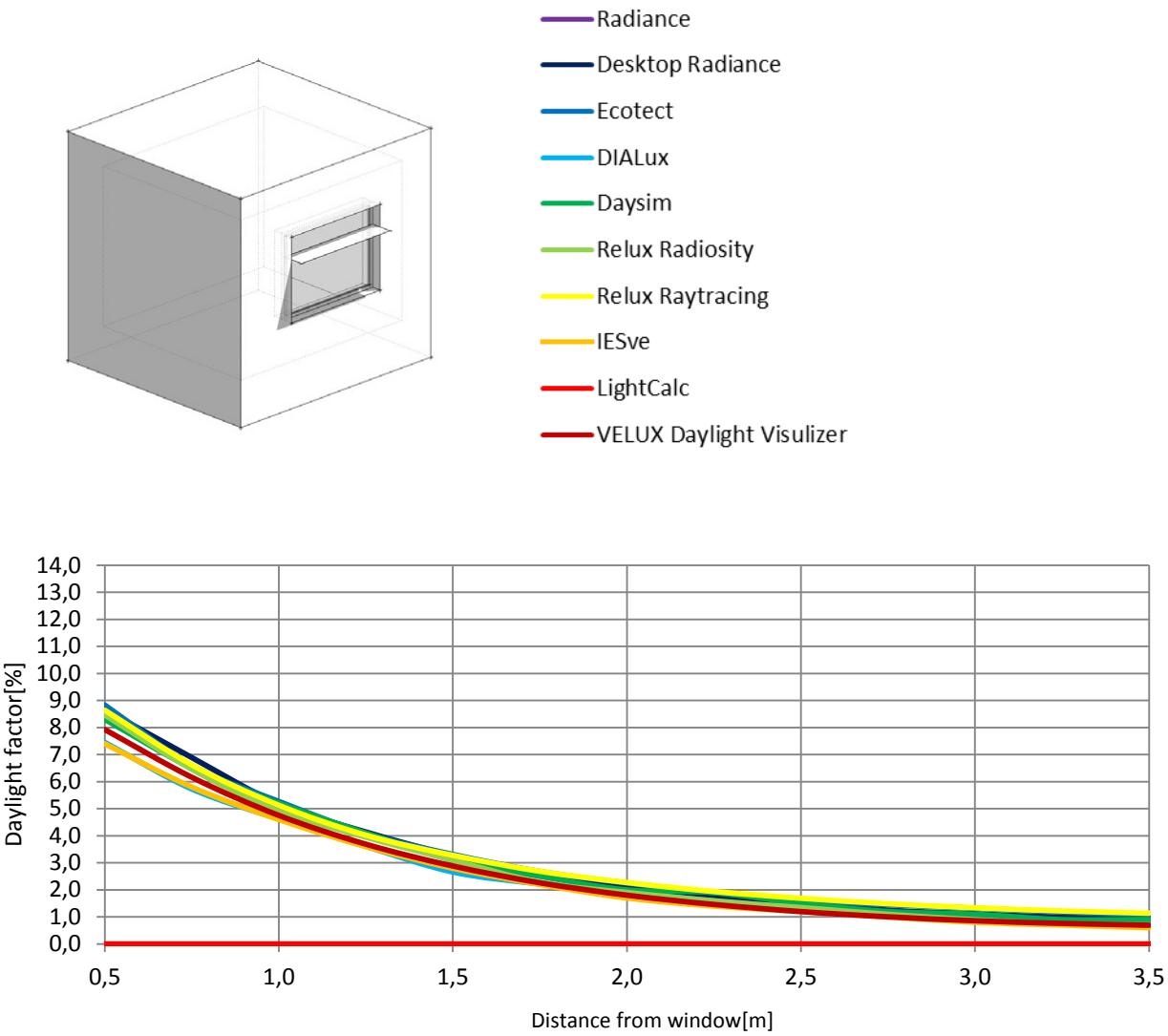


Figure 27: Daylight factor level through the room

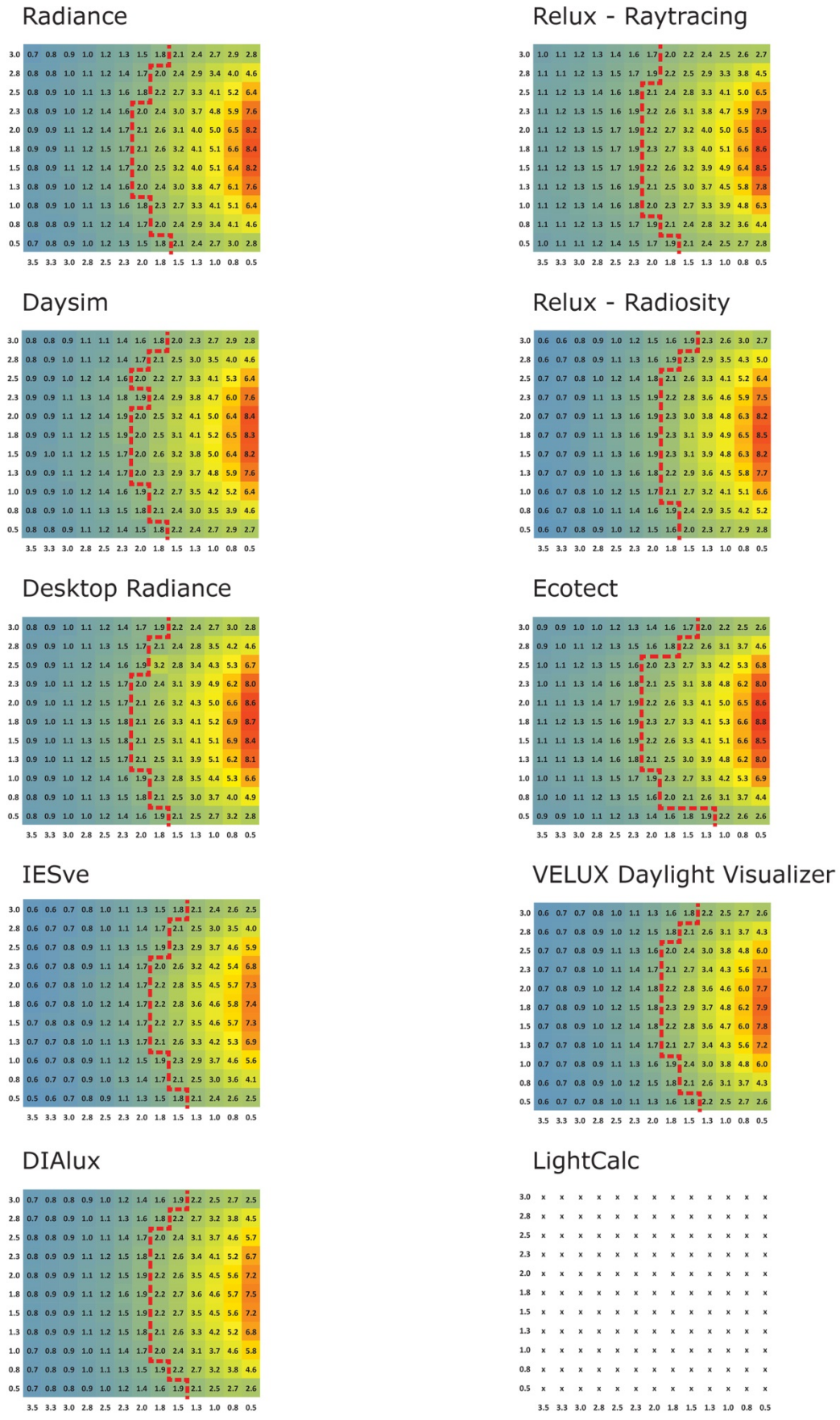


Figure 28: Simulation sheet – Room with light shelf

ROOM 4 – ROOM WITH LIGHT SHELF– Analysis sheet

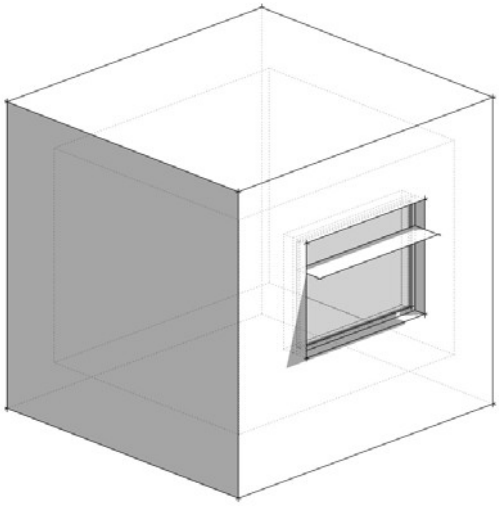


Table 11 and Figure 29 show the daylight factor levels for the simulated room with a shelf. The maximum average DF is 2.6% (Relux Raytracing and Radiance 2.0 BETA), and the minimum average DF is 2.1% (IESve). The relative difference in average DF between the program that results in the maximum average DF and the minimum DF is 18%; the standard deviation is ±6.6%.
Compared with the simple room (Room 1), the average DF for the room with light shelf is decreased due to less light entering the room, because the light shelf has the same effect as an overhang. The redirecting effect of light from a light shelf cannot be seen in the daylight factor simulations since this simulation is made under diffuse overcast skies and the reflections are ideal diffuse lambertian with an even distribution of the reflected light.

Figure 30 shows the distance from the façade where a daylight factor of 2% is obtained. Looking at the daylight penetration depth, the minimum daylight penetration depth obtained is 1.8 m from the façade (IESve) and the maximum daylight penetration depth is 2.2 m from the façade (Relux Raytracing and Ecotect). This means that there is a difference of 0.4m between the maximum and the minimum distances from the façade where 2% DF is reached for all the applied simulation programs. This corresponds to a difference between the maximum and the minimum daylight penetration depth of 21%. The standard deviation is 0.14m corresponding to a simulated difference of ±6.7%.

LightCalc was not capable of simulating the light shelf. However, the other programs were capable of simulating a light shelf as a shelf with a reflectance of 0.5.

Table 11: Daylight factor values given as mean, median, min and max values, as well as the uniformity given as DFmin/DFmean og DFmin/DFmax

	DIALux	Radiance	Daysim	Relux Radiosity	Relux Raytracing	Desktop Radiance	Ecotect	IESve	LightCalc	Velux Daylight Visual-izer
	DF [%]									
DFmean	2.2	2.5	2.5	2.4	2.6	2.6	2.5	2.1		2.2
DFmedian	1.6	1.8	1.9	1.6	2.0	1.9	1.8	1.5		1.6
DFmin	0.7	0.7	0.8	0.6	1.0	0.8	0.9	0.5		0.6
DFmax	7.5	8.4	8.4	8.5	8.6	8.7	8.8	7.4		7.9
Uniformity										
DFmin/DFmean	0.3	0.3	0.3	0.2	0.4	0.3	0.4	0.2		0.3
DFmin/DFmax	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1		0.1

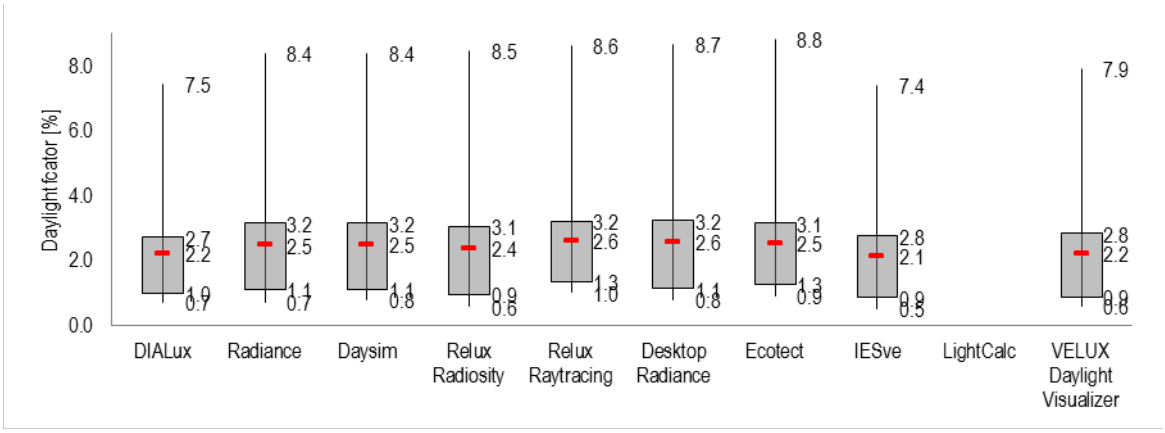


Figure 29: Box plot of daylight factor levels in the room with light shelf simulated with the different simulation programs

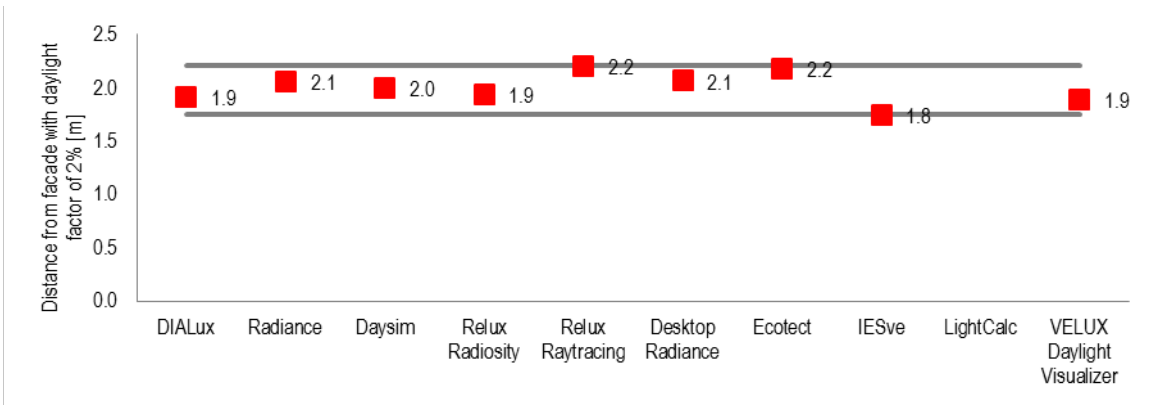
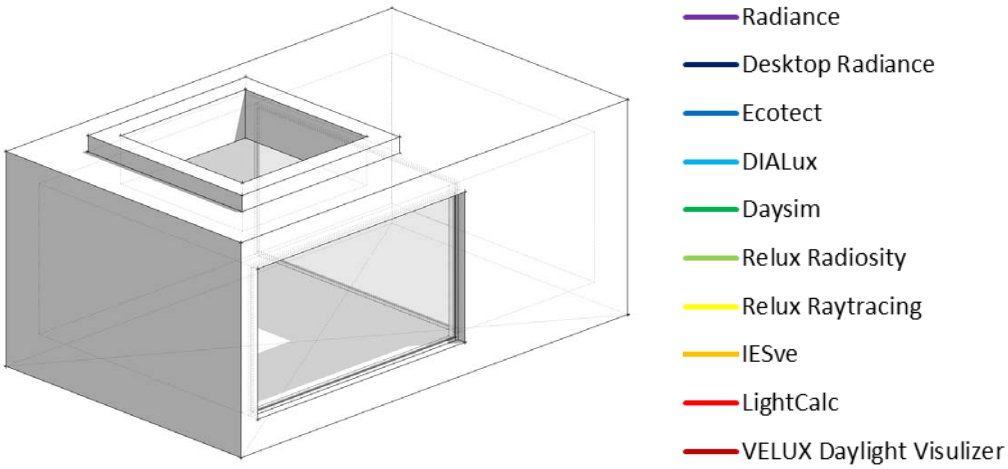


Figure 30: Distance from the facade with a daylight factor of 2% obtained with the different simulation programs



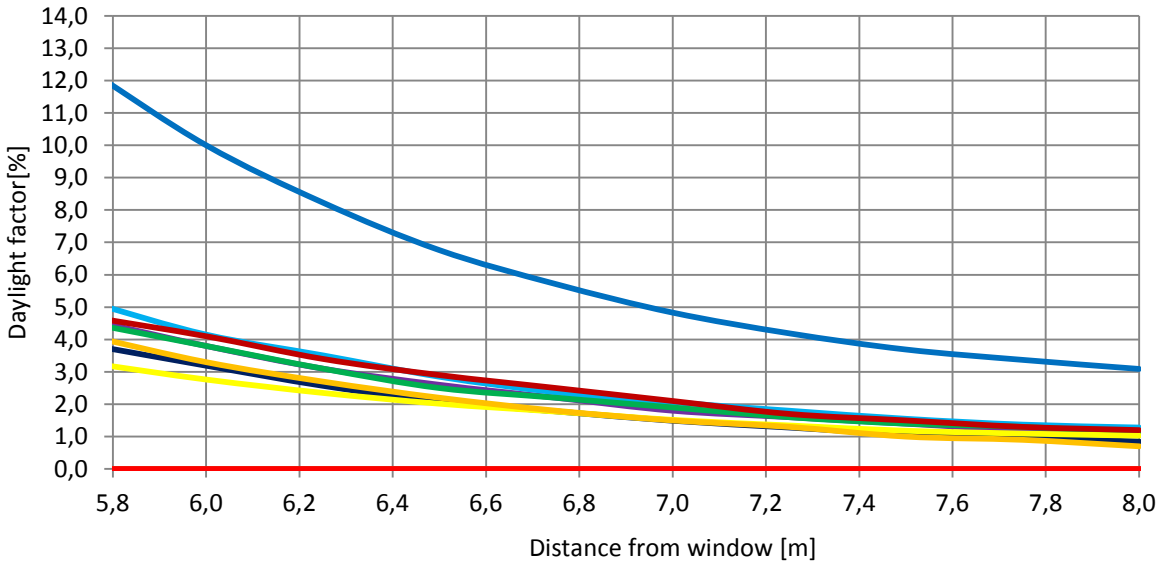
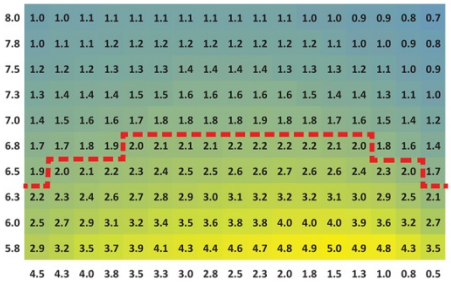
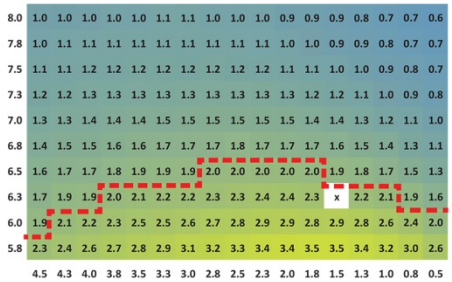


Figure 31: Daylight factor level throughout the room

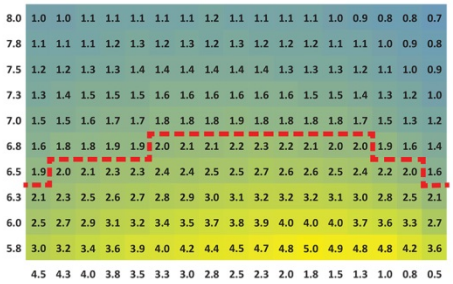
Radiance



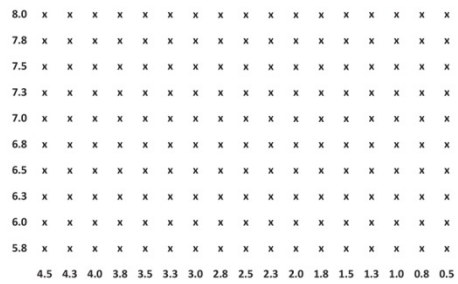
Relux - Raytracing



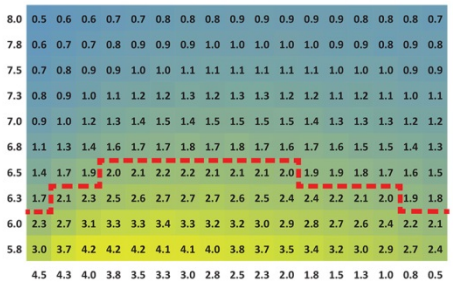
Daysim



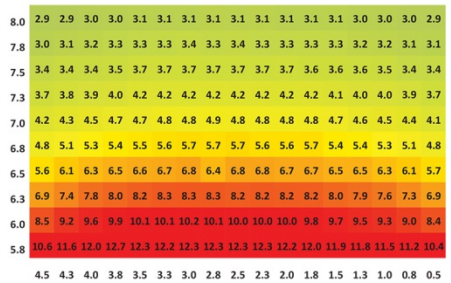
Relux - Radiosity



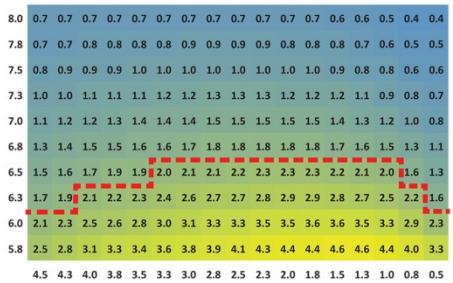
Desktop Radiance



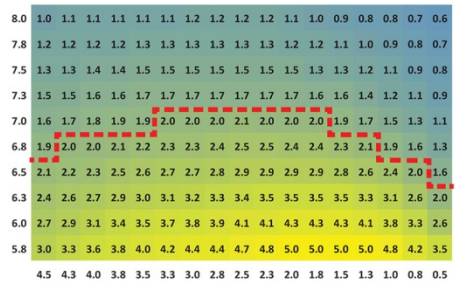
Ecotect



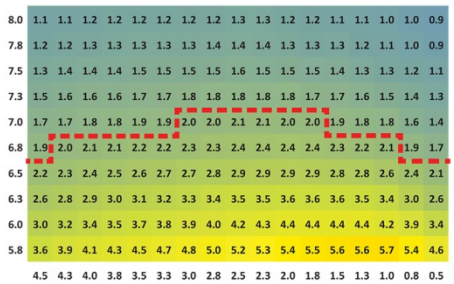
IESve



VELUX Daylight Visualizer



DIAlux



LightCalc

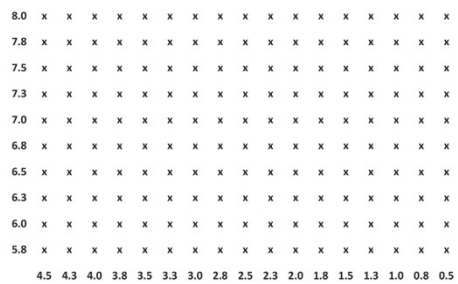


Figure 32: Simulation sheet – Room with borrowed light

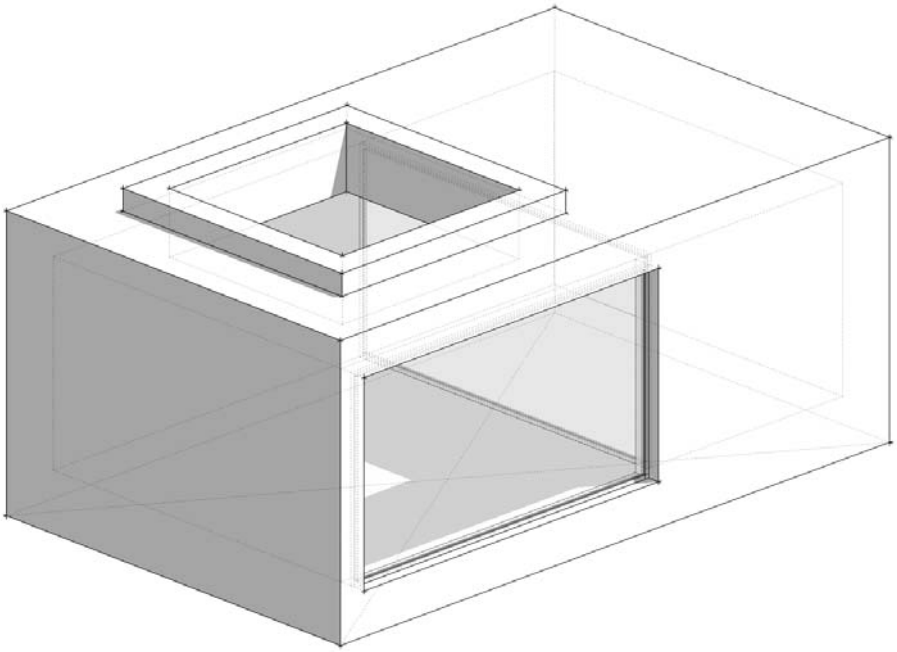


Table 12 and Figure 33 show the daylight factor values for the simulated room with borrowed light. It can clearly be seen that the results from Ecotect differ greatly from those of the other programs. With Ecotect, the DFmean is 6%, whereas the mean values for the other programs range from 1.7% to 2.4%. This large difference is caused by the limitations of the split flux method applied in Ecotect.

When excluding Ecotect from the results, the maximum average daylight factor is 2.4% (DIALux) and the minimum average daylight factor is 1.7% (Relux Raytracing, Desktop Radiance, IESve) and the difference between max and mean is 31%. The standard deviation in average daylight factor for this room is 0.24 corresponding to differences of ± 9.5%.

No analysis of the daylight penetration depth has been made in this room as it is an internal room with borrowed light.

Table 12: Daylight factor values given as mean, median, minimum and maximum values. As well as the uniformity given as DFmin/DFmean og DFmin/DFmax

	DIALux	Radiance	Daysim	Relux Radiosity	Relux Raytracing	Desktop Radiance	Ecotect	IESve	LightCalc	VELUX Daylight Visualizer
	DF [%]									
DFmean	2.4	2.1	2.1		1.7	1.7	6.0	1.7		2.2
DFmedian	2.0	1.8	1.8		1.5	1.4	4.8	1.5		2.0
DFmin	0.9	0.7	0.7		0.6	0.5	2.9	0.4		0.6
DFmax	5.7	5.0	5.0		3.5	4.2	12.7	4.6		5.0
Uniformity										
DFmin/DFmean	0.4	0.3	0.3		0.4	0.3	0.5	0.2		0.3
DFmin/DFmax	0.2	0.1	0.1		0.2	0.1	0.2	0.1		0.1

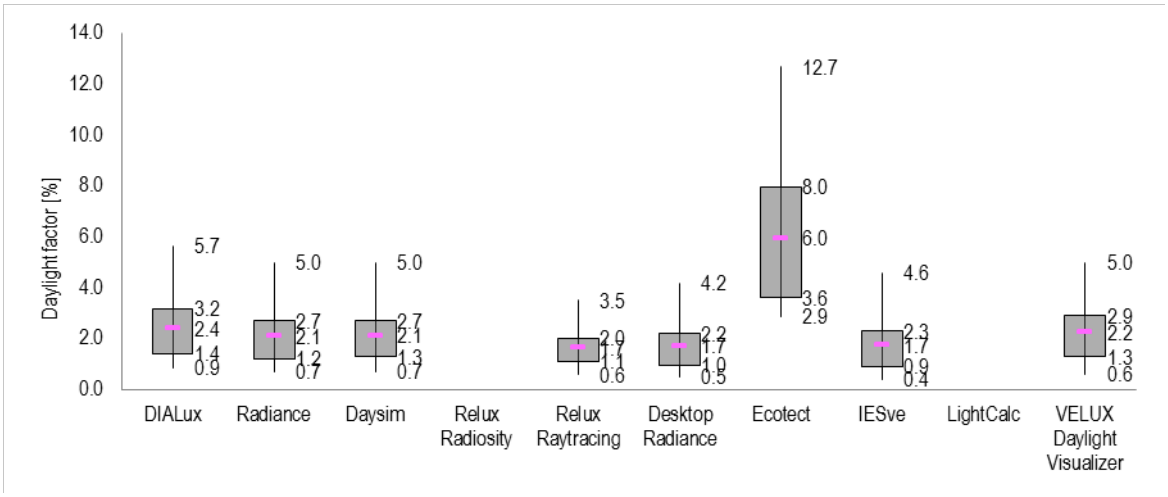


Figure 33: Box plot of daylight factor levels in the room with borrowed light simulated using the different simulation programs

Assessment of the nine daylight simulation programs

An overall assessment of the nine simulations programs based on their simulation engine, ability to perform calculations of the five room types, their output, their user friendliness and price is given in the table below.

	Radiance	**Desktop Radiance**	**Daysim**	**VELUX Daylight Visualizer**	**DIAlux**	**Ecotect**	**IESVE**	**Light-Calc**	**Relux***
Calculation method	Backward raytrac-ing	Backward raytracing	Back-ward ray-trac-ing	Bidirectional raytracing with photon map-ping and irradi-ance caching	Radiosity	BRE Split Flux	Back-ward ray-tracing	For-ward ray-trac-ing	Radi-osity og back-ward
The programs ability to calculate on the five room types									
1. Simple room	Yes	yes	Yes	Yes	yes	yes	Yes	yes	yes
2.Deep room	Yes	yes	yes	Yes	yes	yes	Yes	yes	yes
3. Room with obstruction	Yes	yes	yes	Yes	yes	no	Yes	yes	yes
4. Room with light shelf	Yes	yes	yes	Yes	yes	yes	Yes	no	yes
5. Room with borrowed light	Yes	yes	yes	Yes	yes	no	Yes	no	Yes/No**
Output									
Daylight factor and illuminance	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean daylight factor	Yes	yes	yes	Yes	no	yes	Yes	yes	yes
User friendlyness									
Generel interface	-2	-2	-1	2	1	2	1	0	1
Geometric model-ling facility within the program	-2	-2	Ikke muligt	2	0	1	0	2	0
Import of geometric model in the program	Yes	yes	yes	Yes	yes	yes	Yes	yes	yes
File types***	.obj .skp .disxml .dxf .mgf	.obj	.eco .skp .3ds .rad	.obj .skp .dwg .dxxf	.skp .sat .m3d .3ds	.obj .dwg .dxf	.skp .3ds .rvt	.skp	.skp .3ds .dxf .wrl
Graphical treatment of results	0	-1	-2	2	1	2	-1	-2	1
User license	No	No	No	No	No	Yes	Yes	No	No

* Relux applied two simulation approaches, radiosity and raytracing

**Yes: Relux Raytracing can simulate internal rooms. No: Relux Radiosity cannot simulate internal rooms.

***file types that the authors of this report have knowledge about that can be imported. Other file types might be imported as well.

-2 = very bad / very difficult. -1 = slightly good / slightly difficult. 0 = average.
1= easy. 2 = very easy

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Experience has shown that results for the same room, obtained from two daylight simulation programs can give different results. This can be due to restrictions in the program itself and/or be due to the skills of the persons setting up the models. This is crucial as daylight calculations are used to document that the demands and recommendations to daylight levels outlined by building authorities. The aim of the project was to obtain a better understanding of what daylight calculations show and also to gain knowledge of how the different daylight simulation programs perform compared with each other. Furthermore the aim was to provide knowledge of how to build up the 3D models that were to be daylight-analysed. It is an overall objective to enhance the quality of consultancy within the field of daylighting with a greater knowledge of the available daylight simulation programs and the accuracy of the simulated.
The programs investigated are: Radiance, Daysim, VELUX Daylight Visualizer, DIAlux, Ecotect, Ecotect/Radiance, IESve, LightCalc and Relux.

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