SAVINGS BY DAYLIGHT SOURCES

Steven Ipsen, 2010

CONTENTS

ABSTRACT

A study in the heating demand for a poorly insulated single family house showed that less window area is needed to acheive a certain daylight factor by using roof windows compared to using facade windows. While keeping the daylight factor constant and changing the percentage of roof window area compared to the total window area, the heating demand remained more or less unchanged. Furthermore the study showed that for highly insulated buildings it can even be beneficial regarding heating demand to use roof windows instead of facade windows when the daylight factor is fixed.

OBJECTIVE

The main purpose of this report is to analyse and conclude on relations between heating demands generated by the use of different window combinations and certain daylight conditions that are to be achieved inside a one-storey single family house.

METHODS / SETTINGS

In the analysis three different setpoints for the daylight conditions were to be achieved by the use of either facade windows, roof windows or a combination of both.

The daylight factors (DF) that were to be achieved in the room are:

- DF = 2%
- DF = 4%
- DF = 6%

VELUX Daylight Visualizer was used to assess the DF for different window combinations. The combinations that satisfied the demanded DF given above were then modelled in VELUX EIC Visualizer for calculation of the heating demands.

The following devision with regards to facade window orientation was sought; though it was not possible to obtain the exact values due to fixed window sizes and the best fit was chosen (roof windows were oriented equally towards north and south. When the number was uneven the majority were oriented towards south):

- 41.0 % windows to the south
- 16.5 % windows to the east
- 16.5 % windows to the west
- 26.0 % to the north

Model settings:

Location: Berlin

Internal dimensions: 8 m · 18 m · 2.5 m (width, length and height of wall).

Roof: pitch = 25°, overhang 300 mm in 2.5 m above floor. Open ceiling.

Table 1 Window properties. (S06) and (S10) are indicators for corresponding standard sizes of VELUX windows

Location	Pane	Width [mm]	Height [mm]		g [-]	U [W/m²K]
			DF = 2%	DF = [4 % ..6 %]		
Facade	59: Low energy	1200	1200	1500	0.77	
Roof	59: Low energy	1140	1178 (S06)	1600 (S10)	0.77	

The calculations were carried out for both a low insulated building and a highly insulated building.

Table 2 Construction properties

Building	U [W/m²K]			Leakiness
	Wall	Roof	Floor	
Standard	0.390	0.390	0.26	Average building from 1980
Low energy	0.097	0.086	0.68	Passive house standard

Heating and cooling:

- Number of people: 4 people – Always present
- Heating setpoint: 26°C (district heating)
- Electrical equipments: 3.5 W/m^2 – Always on
- Cooling and shading: Not active

Light and ventilation:

- Natural ventilation (all): Off
- Mechanical ventilation: ACH = 0.5 h^{-1}, with heat recovery of 85 %. Always used
- Electrical lighting: Standard settings in EIC Visualizer

Surface properties are listed in APPENDIX B: SURFACE PROPERTIES OF THE ROOM.

RESULTS

Daylight simulations

The daylight analysis proved that by using roof windows less window area is needed to achieve certain daylight factor than if facade windows were to meet the same daylight factor. The results are listed in APPENDIX A: DAYLIGHT FACTORS AND HEAT DEMAND RESULTS.

Heating needed for the standard building

For the standard building with a setpoint of DF = 2 the heating demand was in the range 68 kWh/(m^2·year) to 69 kWh/(m^2·year) seeming to be comparatively stable (Figure 1).

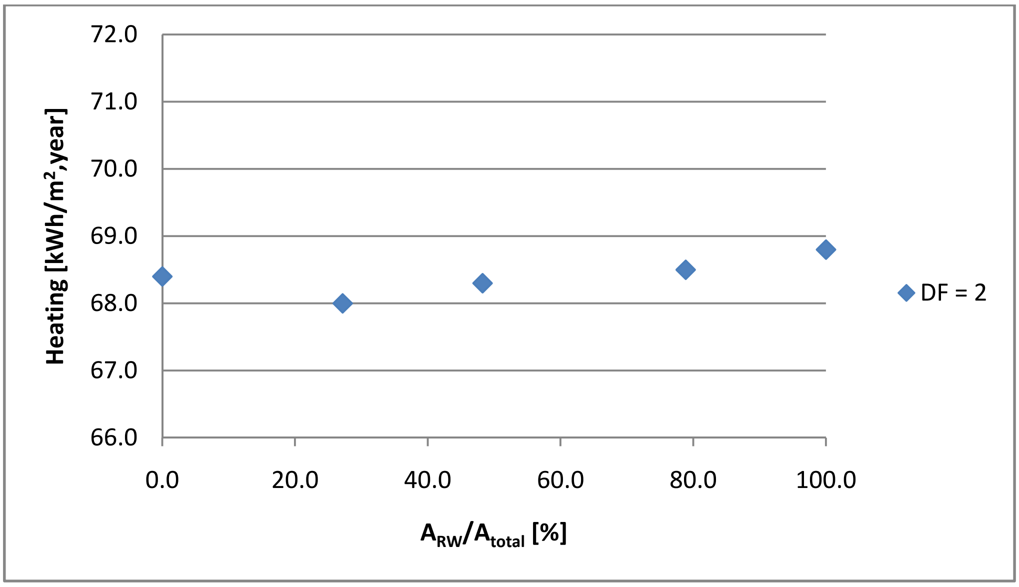

Figure 1 Heating demand when DF=2 is setpoint. A_{RW} is the roof window area and A_{total} is the total window area

When the setpoint DF = 4 the heating demand again appears to be fairly stable in the range 67.5 kWh/(m^2·year) to 69 kWh/(m^2·year). See Figure 2.

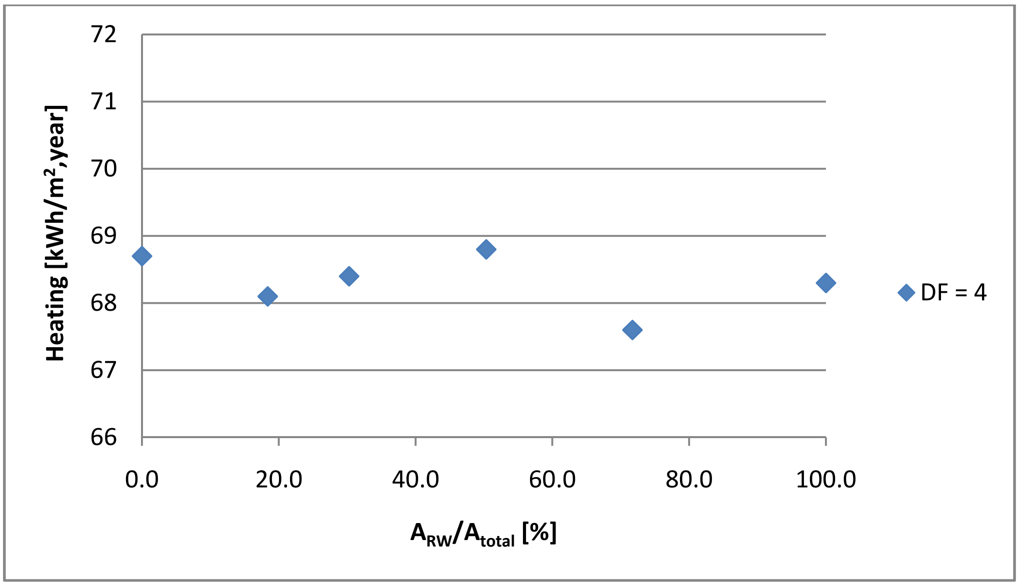

Figure 2 Heating demand for DF=4 as setpoint. ARW is the roof window area and Atotal is the total window area

The heating demand for setpoint DF = 6 is slightly higher than for DF = 2 and DF = 4, ranging from 69 kWh/(m^2·year) to 70.5 kWh/(m^2·year), (Figure 3).

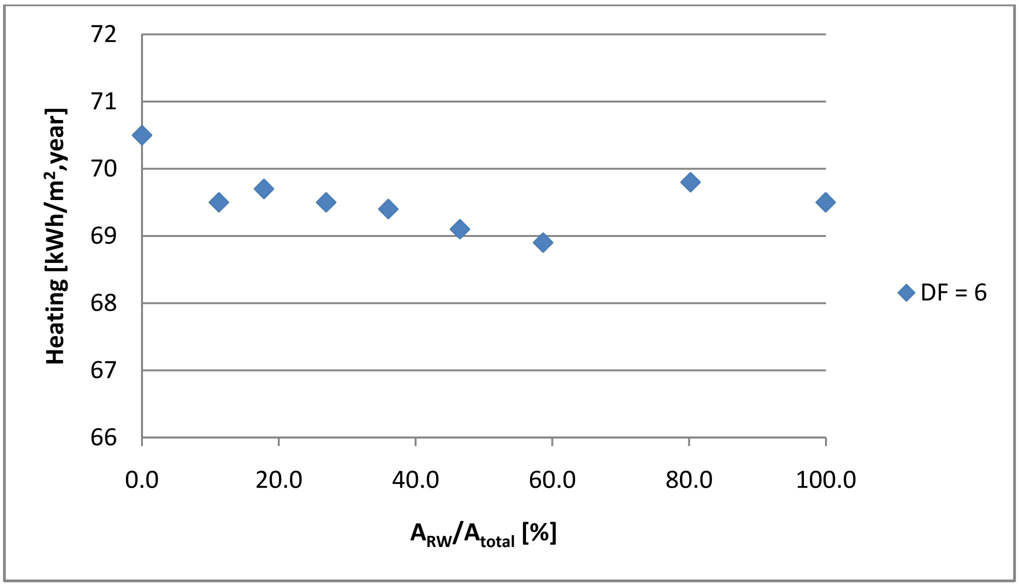

Figure 3 Heating demand when DF=6 is setpoint. A_{RW} is the roof window area and A_{total} is the total window area

An overview of the heating demands for the different DF setpoints is given in (Figure 4).

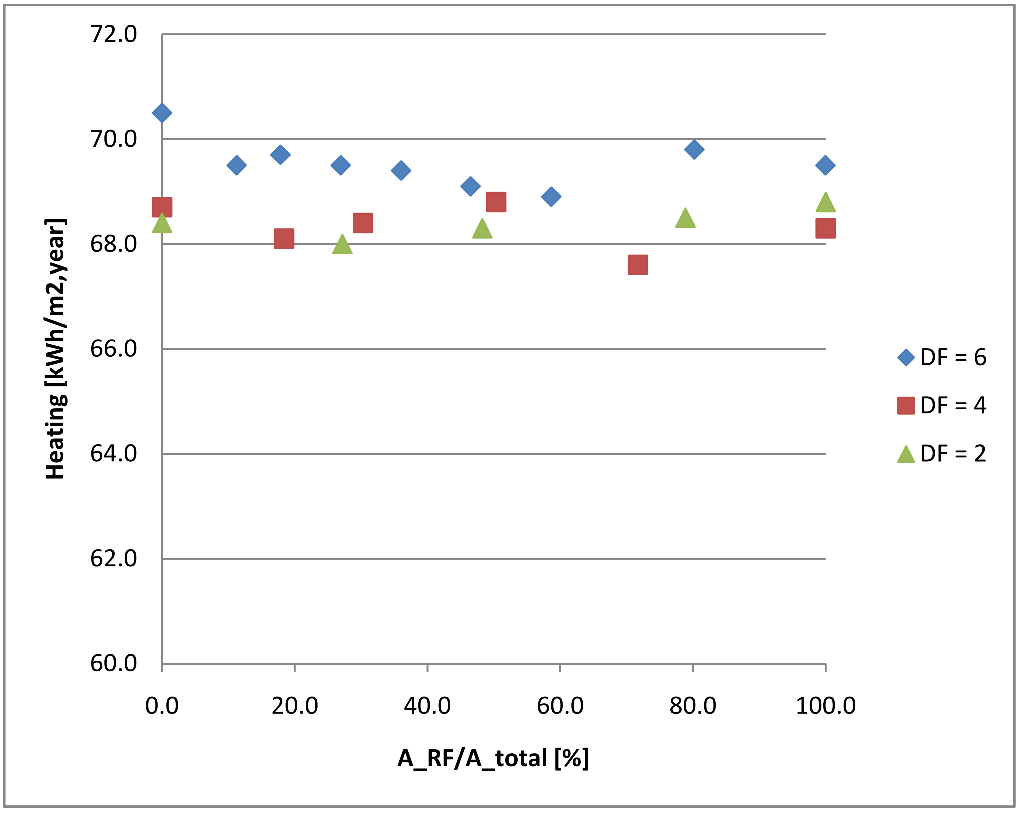

Figure 4 Total overview of heating demands for the standard building with regards to DF and roof window fraction

Heating needed for the low energy building

The heat demand for a DF = 2 in the low energy building ranges from 4.4 kWh/(m^2·year) to 5.5 kWh/(m^2·year) being fairly stable with the highest heating need when no roof windows were used.

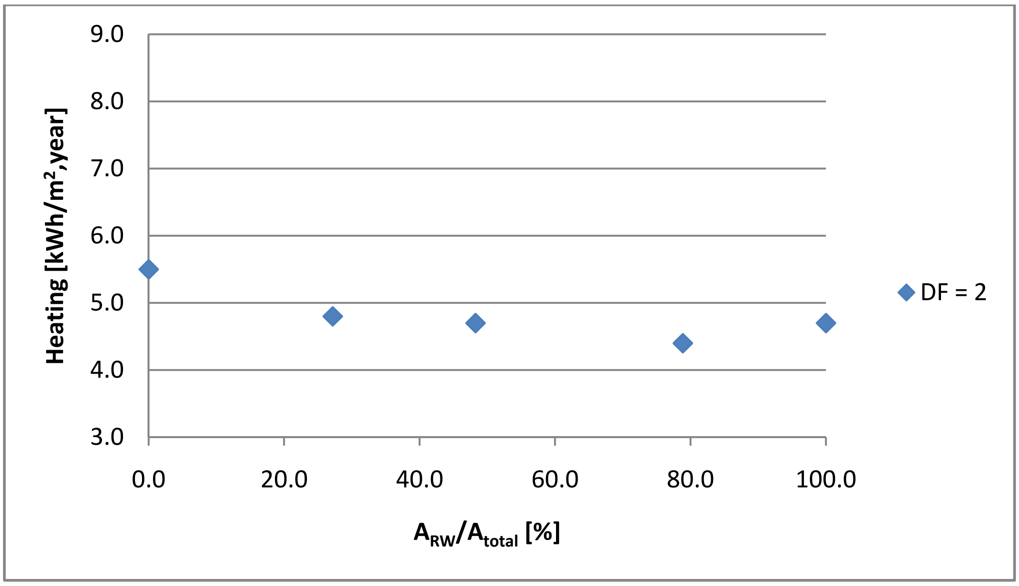

Figure 5 Heating demand when DF=2 is setpoint. A_{RW} is the roof window area and A_{total} is the total window area

A more distinct change in heating demand is found for the the low energy building when the setpoint DF = 4, ranging from 6.3 kWh/(m^2·year) to 9.1 kWh/(m^2·year). The heating demand is highest when no roof windows are used, and drops steadily untill roof windows account for about 70 % of the total window area. See Figure 6.

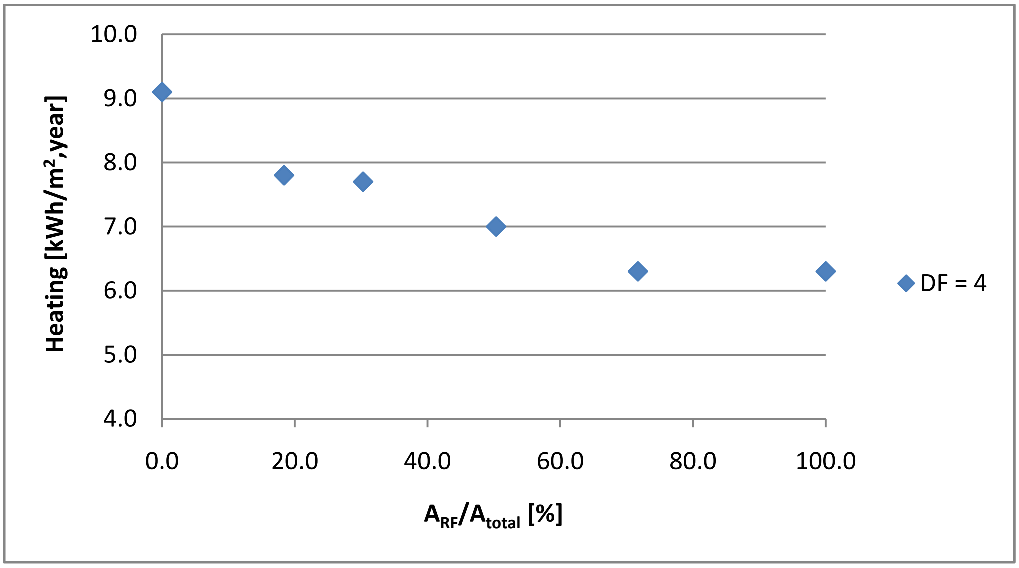

Figure 6 Heating demand for DF=4 as setpoint. A_{RW} is the roof window area and A_{total} is the total window area

When the setpoint DF = 6 the heating demand showed to be highest when no roof windows were included in the design. The heat demand decreased with an increasing roof window to total window area ratio (Figure 7).

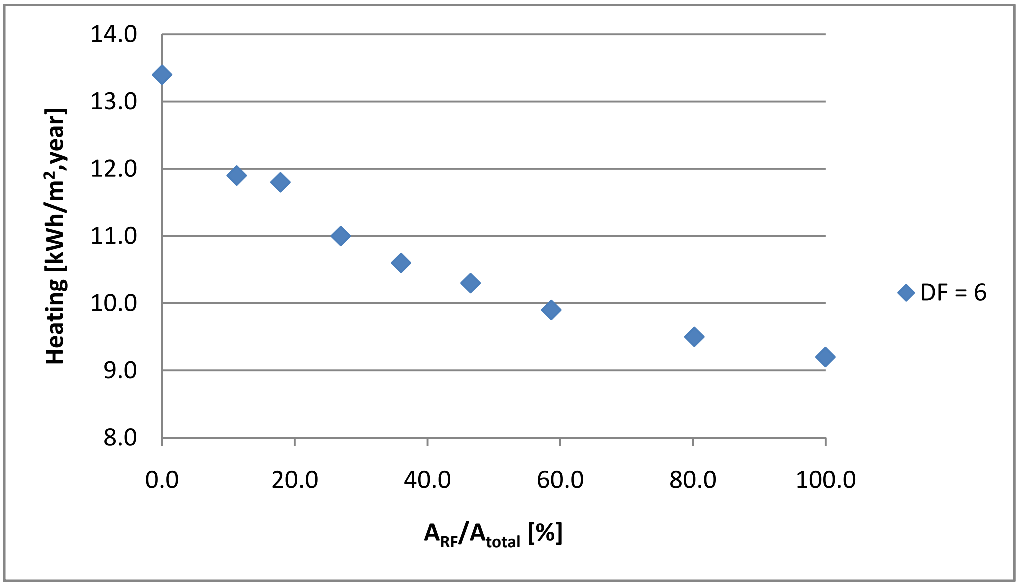

Figure 7 Heating demand when DF=6 is setpoint. A_{RW} is the roof window area and A_{total} is the total window area

In the overview it is apparent that the energy needed for heating increased with the window area.

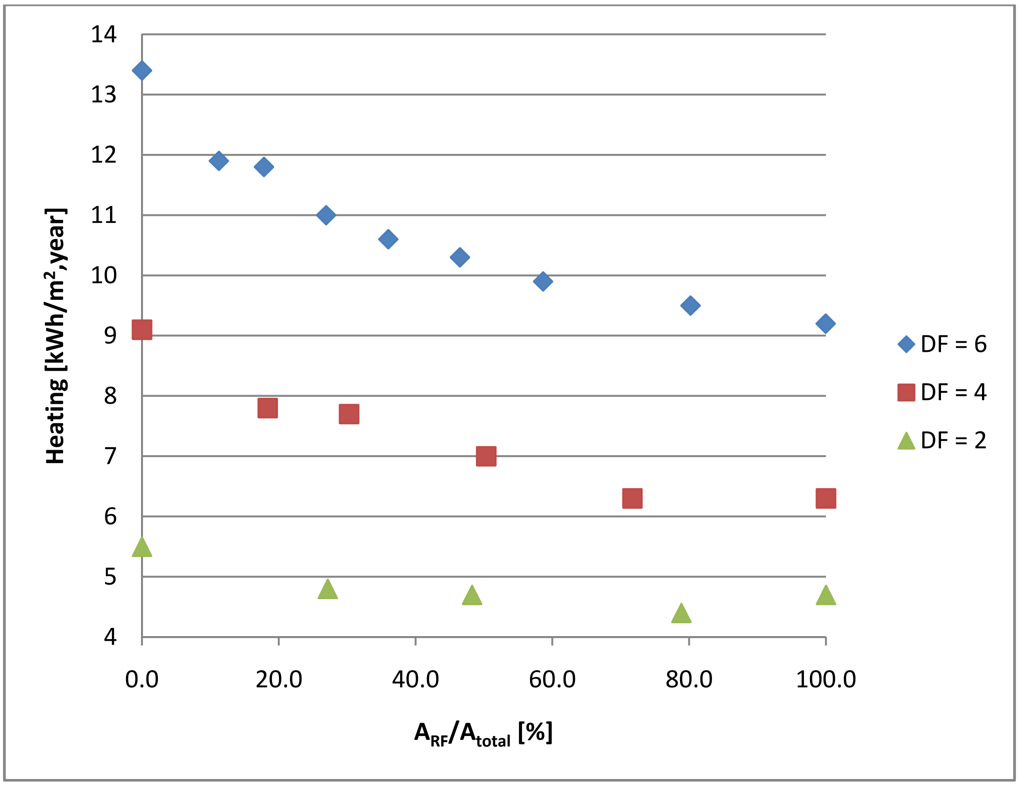

Figure 8 Total overview of heating demands for the low energy building with regards to DF and roof window fraction

DISCUSSION

From the results it is evident that for a standard building with little thermal insulation there is no significant difference in heating demand using facade windows or roof windows. Furthermore less window area is needed to achieve a certain daylight factor when using roof windows instead of facade windows. With this in mind initial costs can be lowered by choosing roof windows if more daylight is needed in the building. The results also showed that increasing the window area to gain higher daylight factors will not result in significant increase in heating demand.

For the highly insulated building the results clearly showed that replacing façade windows with roof windows to achieve a fixed daylight factor the heat demand dropped. The higher DF set point the more distinct the difference became. However, increasing the DF set point and keeping the ratio roof window area to total window area constant the heat demand increased. This may be due to an increase of total window area that means less building envelope with high insulation levels. If the heat balance of the windows performs worse than the insulation it substitutes it will influence the heating demand. However it is noted that the heating demand for DF = 4 with no roof windows was almost equal to the situation where DF = 6 achieved by using only roof windows, thus a higher daylight factor can be achieved at the same heat demand by using roof windows.

CONCLUSION

Low energy buildings benefit more from rooflight than standard insulated buildings and receives a reduced heating need.

Positive sides of using roof windows

- Initial cost: Less windows are needed to achieve certain daylight levels
- Lower need for heating when used in well insulated buildings with good air tightness
- In poorly insulated buildings it is possible to improve the daylight conditions without any significant change in heating demand

Negative sides of using roof windows:

- No view to the outdoor environment if only roof windows are used

APPENDIX A: DAYLIGHT FACTORS AND HEAT DEMAND RESULTS

Following tables contain results regarding the daylight simulations and heating demands. Reference names refer to the file names of Daylight Visualizer files and EIC Visualizer files. A_{RW}/A_{total} is the ratio of roof window area to the total window area.

Standard building results:

Table 3 Window setup and heat demand results when the aim is DF = 2

Reference name	Facade windows	Roof windows	Window area [m²]	DF	A_{RW}/A_{total} [%]	Heating [kWh/m²·year]
2.2_DF2	0	5	6.71	2.2	100.0	68.8
2.3_DF2	1	4	6.81	2.0	78.9	68.5
2.4_DF2	3	3	8.35	2.1	48.3	68.3
2.5_DF2	5	2	9.89	2.2	27.2	68.0
2.1_DF2	9	0	12.96	2.2	0.0	68.4

Reference name	Facade windows	Roof windows	Window area [m²]	DF	A_{RW}/A_{total} [%]	Heating [kWh/m²·year]
4.2_DF4	0	6	10.94	4.0	*100.0*	68.3
4.3_DF4	2	5	12.72	4.0	*71.7*	67.6
4.4_DF4	4	4	14.50	4.0	*50.3*	68.8
4.5_DF4	7	3	18.07	4.1	*30.3*	68.4
4.6_DF4	9	2	19.85	4.0	*18.4*	68.1
4.1_DF4	14	0	25.20	4.1	*0.0*	68.7

Reference name	Facade windows	Roof windows	Window area [m²]	DF	A_{RW}/A_{total} [%]	Heating [kWh/m²·year]
6.10_DF6	**0**	**9**	16.42	6.0	*100.0*	69.5
6.8_DF6	**2**	**8**	18.19	6.0	*80.2*	69.8
6.8b_DF6	**5**	**7**	21.77	6.1	*58.7*	68.9
6.9_DF6	**7**	**6**	23.54	6.1	*46.5*	69.1
6.11_DF6	**9**	**5**	25.32	6.1	*36.0*	69.4
6.12_DF6	**11**	**4**	27.10	6.0	*26.9*	69.5
6.13_DF6	**14**	**3**	30.67	6.1	*17.8*	69.7
6.14_DF6	**16**	**2**	32.45	6.1	*11.2*	69.5
6.1_DF6	21	0	37.80	6.0	*0.0*	70.5

Low energy building results:

Reference name	Facade windows	Roof windows	Window area [m^2]	DF	A_{RW}/A_{total} [%]	Heating [$kWh/m^2 \cdot year$]
2.2 Low-E	0	5	6.71	2.2	*100.0*	4.7
2.3 Low-E	1	4	6.81	2.0	*78.9*	4.4
2.4 Low-E	3	3	8.35	2.1	*48.3*	4.7
2.5 Low-E	5	2	9.89	2.2	*27.2*	4.8
2.1 Low-E	9	0	12.96	2.2	*0.0*	5.5

Reference name	Facade windows	Roof windows	Window area [m^2]	DF	A_{RW}/A_{total} [%]	Heating [$kWh/m^2 \cdot year$]
4.2 Low-E	0	6	10.94	4.0	*100.0*	6.3
4.3 Low-E	2	5	12.72	4.0	*71.7*	6.3
4.4 Low-E	4	4	14.50	4.0	*50.3*	7.0
4.5 Low-E	7	3	18.07	4.1	*30.3*	7.7
4.6 Low-E	9	2	19.85	4.0	*18.4*	7.8
4.1 Low-E	14	0	25.20	4.1	*0.0*	9.1

Reference name	Facade windows	Roof windows	Window area [m^2]	DF	A_{RW}/A_{total} [%]	Heating [$kWh/m^2 \cdot year$]
6.10 Low-E	**0**	**9**	16.42	6.0	*100.0*	9.2
6.8 Low-E	**2**	**8**	18.19	6.0	*80.2*	9.5
6.8b Low-E	**5**	**7**	21.77	6.1	*58.7*	9.9
6.9 Low-E	**7**	**6**	23.54	6.1	*46.5*	10.3
6.11 Low-E	**9**	**5**	25.32	6.1	*36.0*	10.6
6.12 Low-E	**11**	**4**	27.10	6.0	*26.9*	11
6.13 Low-E	**14**	**3**	30.67	6.1	*17.8*	11.8
6.14 Low-E	**16**	**2**	32.45	6.1	*11.2*	11.9
6.1 Low-E	21	0	37.80	6.0	*0.0*	13.4

APPENDIX B: SURFACE PROPERTIES OF THE ROOM

Location

Berlin

Area

Floor area 144.00 m²
Glass area 6.71 m²

Surface	(R, G, B)	Roughness	Specularity	Reflectance
Floor	(0.94, 0.82, 0.67)	0.03	0.15	0.84
Ceiling	(0.90, 0.90, 0.90)	0.03	0.00	0.90
Wall	(0.90, 0.90, 0.90)	0.03	0.00	0.90
Roof window frame	(0.92, 0.92, 0.92)	0.01	0.10	0.92
Roof window lining	(0.90, 0.90, 0.90)	0.03	0.00	0.90
Roof window pane	(0.77, 0.77, 0.77)	Transmittance: 0.77		
Facade window frame	(0.92, 0.92, 0.92)	0.01	0.10	0.92
Facade window lining	(0.90, 0.90, 0.90)	0.03	0.00	0.90
Facade window pane	(0.77, 0.77, 0.77)	Transmittance: 0.77		
Facade door frame	(0.92, 0.92, 0.92)	0.01	0.10	0.92
Facade door lining	(0.90, 0.90, 0.90)	0.03	0.00	0.90
Facade door pane	(0.78, 0.78, 0.78)	Transmittance: 0.78		

Products

5 x Standard roof window (1140mm x 1178mm)

Proposal for Energy Rating System of windows in EU

Department of Civil Engineering
Report 2008

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Proposal for energy rating system of windows in EU

The European Commission has proposed to expand the labelling directive to include energy saving products like windows. This report presents a proposal for such an energy rating system of windows in EU. The energy rating system includes vertical façade windows and sloped roof windows. The rating system is based on the net energy gain for windows used in reference houses in three zones in EU.

Conclusion:

The study in this report shows that

- it should be possible to develop an European scheme for windows where Europe is divided into zones as the performances of windows for the heating season do not differ significantly in the zones; therefore the evaluation of windows can be decided on the basis of the energy performance proposed in this report

- as the solar radiation becomes high in the summer period, it is necessary to include summer conditions for windows in a labelling scheme where dynamic solutions for summer conditions could be used also

- the energy performance of sloped windows differs from vertical windows, where the passive solar radiation for sloped windows is much higher than for vertical windows and thereby the energy performance of sloped windows is better than for vertical windows

- the best performing façade window for replacement in the northern part is low energy window with U-values between 0.8 and 1.2 however the difference between the 3 best windows is below 10 kWh/m² in northern climate. The best performing façade window on an overall evaluation will be a window with a U-value of approximately 1.2 W/m²K and a g-value of approximately 0.48 for the whole window

- the performance of best sloped windows for replacement is the same for all Europe, with a U-value of 1.2 W/m²K and a g-value of 0.48 for the whole window

- by replacing the windows in the existing building stock an energy saving in Europe can be up to 134,749 GWh/year if existing old windows are replaced with new windows with a U-value of 1.2 W/m²K and a g-value of 0.5 for the whole window

- further detailed studies for the individual zones are recommended in order to define the exact values for the energy performance for the heating season.

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1. Introduction

In 2008, VELUX asked The Technical University of Denmark, Department of Civil Engineering (DTU Byg) to perform a study with the objective of providing a proposal for an energy rating system of windows in EU and also to estimate the energy saving potential for EU by changing old windows to new improved windows. This report is composed after this application from VELUX A/S and is also financed by VELUX A/S /1/.

1.1 Background

Windows have a large influence on the energy demand and indoor climate in buildings. Apart from the heat loss through windows they also provide a solar gain to the building that in some periods can be exploited for space heating. In other periods the solar gain can result in over heating problems leading to a need for cooling, and therefore it is also important to create a labelling for summer conditions.

In order to stimulate and encourage the use of windows with improved energy performance, there is a need for developing an energy rating system that makes it easier to select the best windows for the actual climate.

1.2 Purpose

The purpose of this project is to develop a proposal of a simple energy rating system of windows in EU based on the net energy gain for a reference building. The aim is to make it as simple and general as possible and also applicable for sloped windows (roof windows).

2. Method

The energy performance of a window is very dependent on the climate and the dwelling/house. Therefore a reference house is needed to make an evaluation of a specific window. A general reference dwelling/house is almost impossible to lay down for the entire Europe, though. The climate in EU also differs both regarding solar radiation and degree hours, which also makes it difficult to establish one simple equation valid for all countries in EU.

As windows both provide heat losses and solar gains, the description of windows must be based on both the thermal transmittance and the solar energy transmittance. To evaluate the energy performance of a window, the net energy gain is therefore very suitable as the net energy gain takes into account both the solar gains and heat losses. The method used takes into account that the solar gain in the heating season reduces the heating consumption and in the cooling season increases the cooling consumption.

The method suggested in this proposal for an energy labelling system of window assumes:

- On the basis of the climate in Europe, Europe is divided into three climate zones following country borders
- Two reference houses are used to calculate the length of the heating and cooling season
- The performance of the a window is evaluated in the cooling and heating season separately using the net energy gain which is defined as the solar gain minus the heat loss

The method also takes into account the influence of solar shading devices on the energy performance of a window.

2.1 The climate data

The climatic data used in this analysis is taken from:
http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm

Hourly data for the calculations are:

➢ Dry Bulb Temperature	[°C]
➢ Global Horizontal Radiation	[W/m²]
➢ Direct Normal Radiation	[W/m²]
➢ Diffuse Horizontal Radiation	[W/m²]

Based on the weather data for different cities in Europe the global solar radiation and the degree hours on different locations in EU are shown in Figure 1 and Figure 2

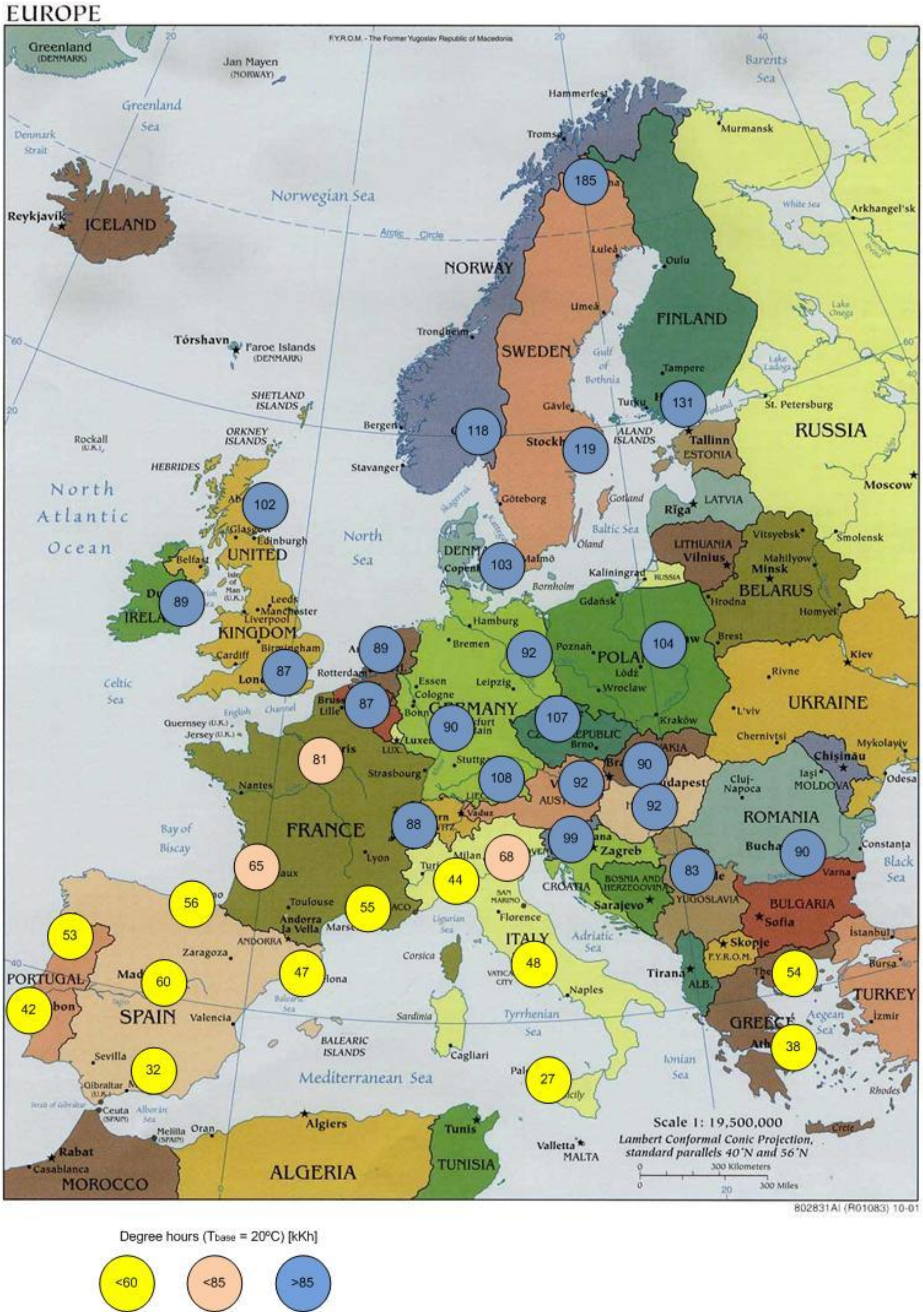

Figure 1 Degree hours on different locations in Europe, based on indoor temperature of 20 ℃

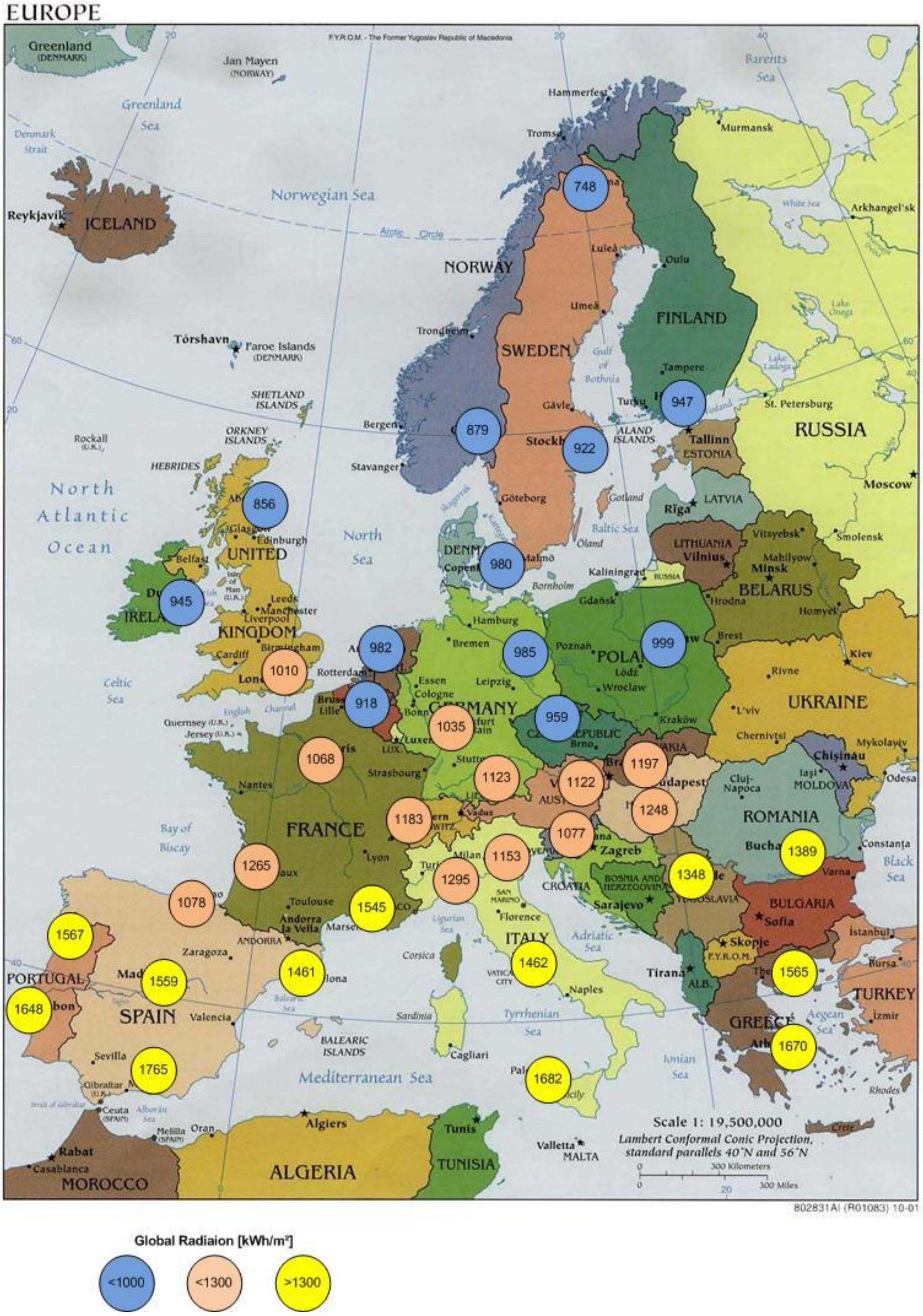

Figure 2 Annual solar radiation on different locations in Europe. (Radiation on horizontal plane)

2.2 The climate zones

Based on analysis of the weather data of EU shown in Figure 1 and Figure 2 it is proposed to divide the EU in three zones following country borders as shown in Figure 3. The zones are found by comparing weather data (solar radiation and degree hours) in 10 suitable cities in EU. Although there can be variations in the climate within each country it is chosen to draw the zone borders along the national country borders. This simplification is justified by the fact that, in most cases, the energy performance ranking of different windows is maintained for every part of a specific country regardless of the variations in climate. Furthermore, following the country borders will simplify the administration of the rating system.

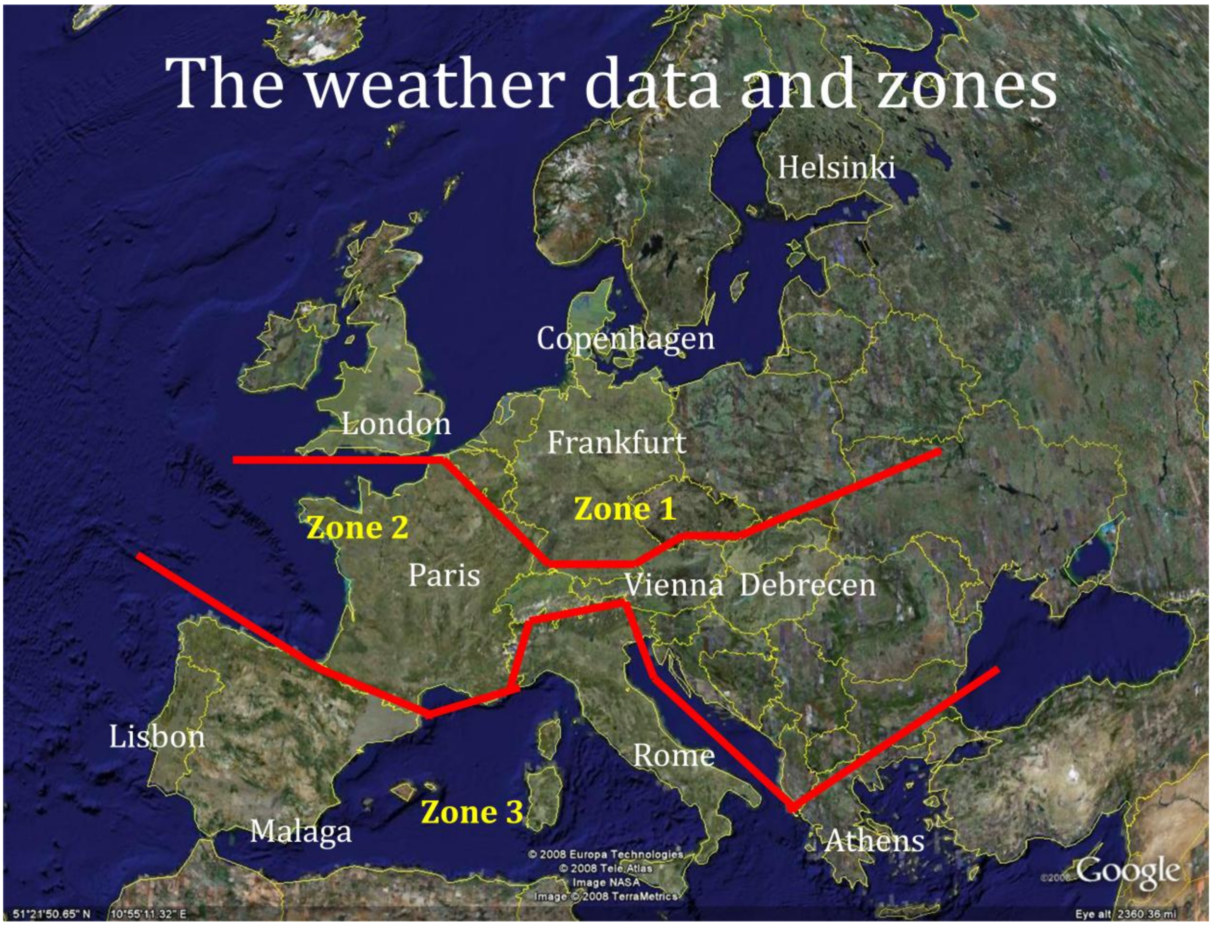

Figure 3 The suggested climate zone in EU with suitable selected cities.

Zone 1: Ireland, United Kingdom, Denmark, Sweden, Finland, The Netherlands, Belgium, Luxemburg, Germany, Poland, Estonia, Latvia and Lithuania.

Zone 2: France, Austria, Switzerland, Hungary, Slovenian, Czech Republic, Bulgaria, Romania and Slovakia.

Zone 3: Portugal, Spain, Italy, Malta, Greece and Cyprus.

2.3 The reference houses

The two reference houses are used to calculate the length of the heating and cooling season. The design of the reference houses are chosen so they represent common dwellings in northern and southern Europe, respectively.
The first reference house (type 1) is a 1½ storey house and the second (type 2) is a single storey house. The ground floor area of the two houses is 96 m² and 140 m², respectively.
The total window area of the reference houses is assumed to be 20% of the heated floor area. The distribution of the vertical windows is assumed to be 41 % south, 16.5% west, 16.5% east and 26% north, see Figure 4.

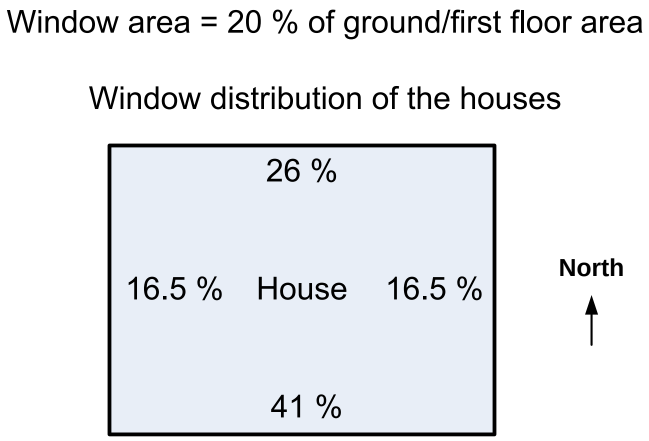

Figure 4 Distribution of the window area in the reference houses regarding the orientations. The total window area is calculated as 20 % of the floor area.

The area of roof windows is calculated assuming the same distribution as shown in Figure 4 and only for orientation to the north and south. The windows to the east and west are assumed to be vertical. For reference house type 1 the ground floor area is 96 m^2, resulting in 19 m^2 vertical façade windows, and a first floor area of 67 m^2, resulting in 4 m^2 vertical windows and 9 m^2 roof windows. For reference house type 2 the ground floor area is 140 m^2. The windows are distributed as 21 m^2 (15%) vertical façade windows and 7 m^2 (5%) roof windows.

The slope angle of the roof windows is assumed to be 45º in type 1 and 30º in type 2. The reference house types 1 and 2 are shown in Figure 5 and Figure 6 respectively.

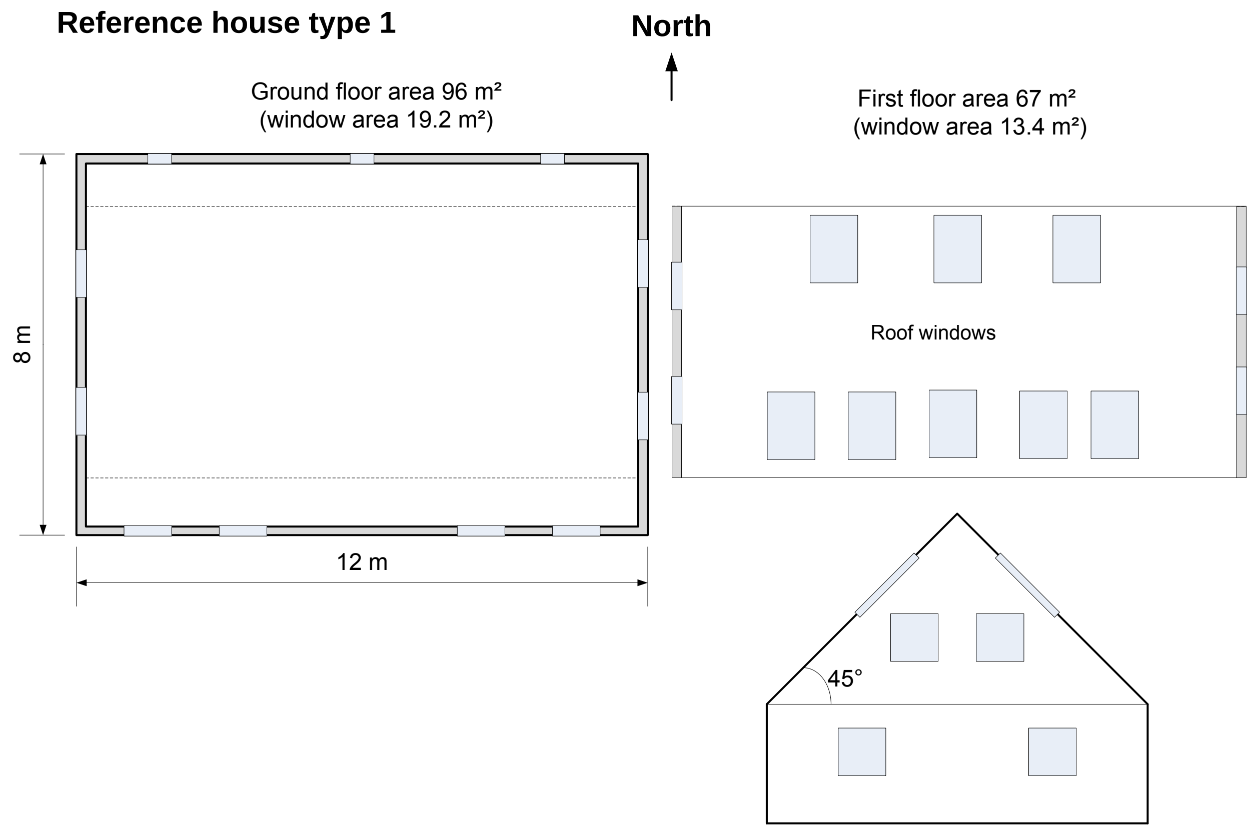

Figure 5 Outline of the reference house type 1 with 45º sloped roof construction

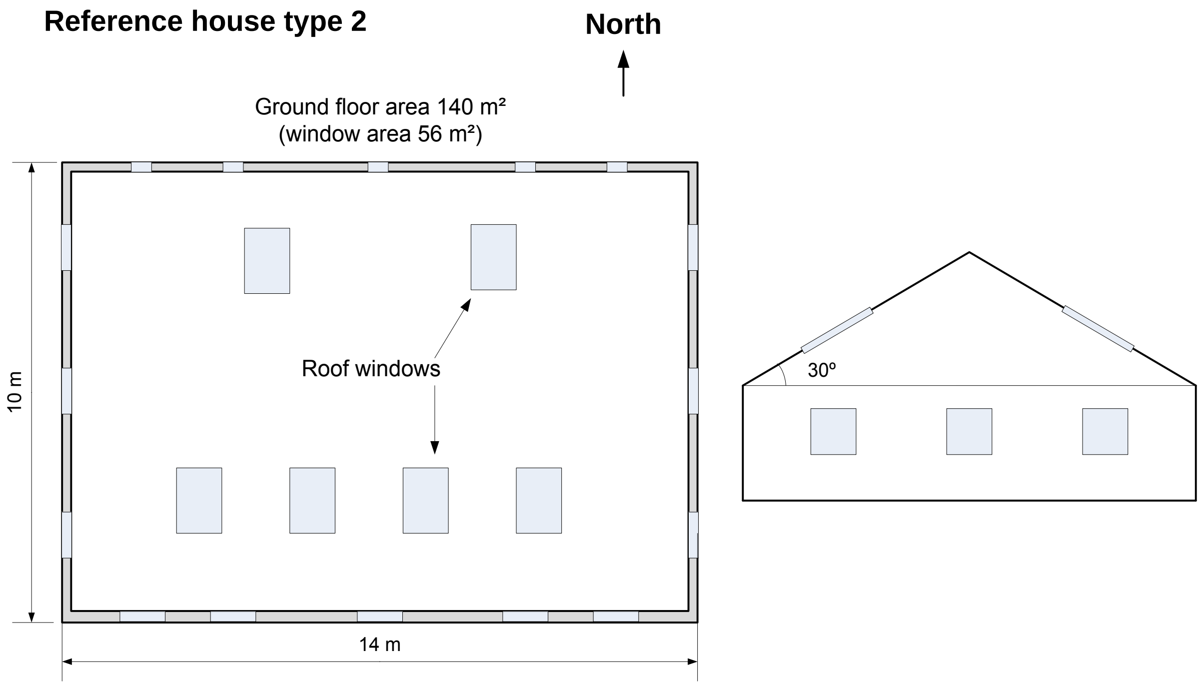

Figure 6 Outline of the reference house type 2 with 30º sloped roof construction

The thermal properties of the constructions of the building envelope of the two reference houses are shown in Table 1, Table 2 and Table 3. The data are taken from /2/.

Table 1 U-value for the building envelope of the reference houses

Construction	U-value [W/m²K] Zone 1 / 2/ 3
Roof	0.2/0.5/0.8
Wall	0.3/1.0/1.2
Floor	0.2/0.8/0.8

Table 2 Air change rate of the reference houses during winter and summer

Ventilation	Winter/Summer $[h^{-1}]$
Zone 1	0.5/1.5
Zone 2	0.5/2.0
Zone 3	0.5/2.5

Table 3 Data of the window in the reference houses

Window	U_w-value	g_w - value
Zone 1/2	2.0/3.5	0.50/0.58
Zone 2/3	3.5/4.2	0.58/0.58

Table 4 Heat capacity of the reference houses

Window	Category	C [J/Km2]
House type 1 Zone 1, 2 and 3	Medium	165.000
House type 2 Zone 1, 2 and 3	Heavy	260.000

2.4 The heating and cooling season in selected cities in EU

In order to determine the net energy gain, the length of the heating and cooling season must be known for the actual location and for the specific reference house. The length of the heating and cooling season is calculated in selected cities covering the EU according to method described in ISO 13790 /5/ and using the two reference houses types 1 and 2. According to the standard, the heating season includes all days for which the heat gains, calculated with a conventional utilization factor, do not balance the heat transfer and vice-versa for the cooling season. The program WinDesign /4/ that is based on ISO 13790 was used for the calculations. The method takes into account an utilisation factor for the heat gains and for the heat losses in the calculations of energy needs for heating and cooling. The calculated heating and cooling seasons are shown in Table 5.

Table 5 Calculated heating and cooling seasons for selected EU cities.

Reference house	Location	Heating	Cooling
Type 1	Helsinki	9.8 – 18.5	13.6 – 15.8
Type 1	Copenhagen	17.9 – 14.5	12.6 – 21.8
Type 1	Frankfurt	2.10 – 24.4	2.6 – 2.9
Type 1	London	24.9 – 10.5	21.6 – 22.8
Type 2	Helsinki	5.9 – 27.5	5.7 – 26.7
Type 2	Copenhagen	12.9 – 23.5	12.7 – 30.7
Type 2	Frankfurt	27.9 – 30.4	23.6 – 24.8
Type 2	London	16.9 – 25.5	10.7 – 29.7
Type 1	Paris	19.9 – 27.5	3.7 – 22.8
Type 1	Vienna	19.9 – 19.5	26.6 – 23.8
Type 1	Debrecen	23.9 – 8.5	5.6 – 27.8
Type 2	Paris	14.9 – 7.6	15.7 – 16.8
Type 2	Vienna	15.9 – 1.6	6.7 – 18.8
Type 2	Debrecen	18.9 – 15.5	13.6 – 22.8
Type 1	Lisbon	1.11 – 25.4	1.6 – 28.9
Type 1	Rome	25.10 – 27.4	30.5 – 24.9
Type 1	Athens	10.11 – 14.4	13.5 – 9.10
Type 2	Lisbon	29.10 – 2.5	17.6 – 20.9
Type 2	Rome	23.10 – 1.5	9.6 – 18.9
Type 2	Athens	7.11 – 17.4	21.5 – 3.10

The results in Table 5 show that the length of the heating season does not change much from zone 1 to zone 2, although there is a difference in climate. This is because the thermal properties of the reference houses in the two zones are different, i.e. the house in zone 2 is poorly insulated compared to the house in zone 1.

2.5 Degree hours

For the different locations the net degree hour, D, is calculated for each cooling and heating season as the sum of the difference between the indoor base temperature and the external temperature during the heating season on an hourly basis using equations (1) and (2):

$$D_{heating} = \sum_{i=\text{heating start}}^{\text{heating stop}} T_{base,heating} - T_{out} \quad \textit{for the heating season} \qquad (1)$$

$$D_{cooling} = \sum_{i=\text{cooling start}}^{\text{cooling stop}} T_{out} - T_{base,cooling} \quad \textit{for the cooling season} \qquad (2)$$

Where

T_{out}	is the dry bulb temperature outside	[ºC]
$T_{base, heating}$	is the base temperature for heating	[ºC]
$T_{base, cooling}$	is the base temperature for cooling	[ºC]

The calculations are based on the weather data for the specific location.

2.6 Solar radiation

Using a pc software as e.g. BuildingCalc /3/, the solar radiation is calculated on hourly basis on vertical (90º) and sloped (45° and 30º) surfaces orientated south, west, east and north.

The total solar irradiance on the windows is calculated assuming a distribution of the windows in the reference houses as: 41% south, 16.5% west, 16.5% east and 26% north.

$$I_{90º} = 0.26 \cdot I_{north,90º} + 0.165 \cdot I_{west,90º} + 0.165 \cdot I_{east,90º} + 0.41 \cdot I_{south,90º} \qquad (3)$$

$$I_{45º} = 0.26 \cdot I_{north,45º} + 0.165 \cdot I_{west,45º} + 0.165 \cdot I_{east,45º} + 0.41 \cdot I_{south,45º} \qquad (4)$$

$$I_{30º} = 0.26 \cdot I_{north,30º} + 0.165 \cdot I_{west,30º} + 0.165 \cdot I_{east,30º} + 0.41 \cdot I_{south,30º} \qquad (5)$$

For vertical windows the solar radiation usable for heating, $I_{heating}$ is calculated for the heating season using eq. (6)

$$I_{heating} = \sum_{i=\text{heating start}}^{\text{heating stop}} I_{90°} \quad , \textit{for the heating seseason} \qquad (6)$$

The solar radiation which needs to be cooled, $I_{cooling}$, is calculated for the cooling season using eq. (7). As not all the solar gains during the cooling season result in cooling demand, only the solar irradiance above 300 W/m^2 is included. This corresponds to ISO 13790, Annex G, which states "solar shading shall be taken as being switched on if the intensity of the solar radiation on the surface at the given hour exceeds 300 W/m^2." This criteria is though further extended so only solar radiation in hours where the outside temperature is above 23 ºC is included. See eq. (7).

$$I_{cooling} = \sum_{\text{i=cooling start}}^{\text{cooling stop}} I_{90°} \text{ for } I_{90°} > 300W \text{ and } T_{out} > 23\ ºC \qquad (7)$$

The solar radiation on sloped windows is calculated similar as eq. (6) and (7).

3. THE WINDOW ENERGY PERFORMANCE

The energy performance of the window is calculated as the difference between the transmitted solar energy and the thermal heat loss during the cooling and heating seasons.

$$E_{ref,cooling} = I_{cooling} \cdot F_s \cdot g_w - D_{cooling} \cdot U_w \qquad (8)$$

$$E_{ref,heating} = I_{heating} \cdot F_s \cdot g_w - D_{heating} \cdot U_w \qquad (9)$$

Where,

$E_{ref,\ cooling}$	is the energy performance of the window in the cooling season	[kWh/m²]
$E_{ref,\ heating}$	is the energy performance of the window in the heating season	[kWh/m²]
$I_{heating}$	is the solar radiation on the window in the heating season	[kWh/m²]
$I_{cooling^o}$	is the unusable solar radiation in the cooling season	[kWh/m²]
$D_{cooling}$	is the degree hour in the cooling season	[kKh]
$D_{heating}$	is the degree hour in the heating season	[kKh]
g_w	is the solar energy transmittance of the window (including solar shading)	[-]
F_s	is the shadow factor due to the horizon and build-in (overhang, side fins)	[-]
U_w	is the total heat transfer coefficient of the window	[W/m²K]

NOTE: there may be a difference in g_w between heating and cooling mode if the window is adaptive to the season (e.g. movable solar shading devices)

The shadow factor for the horizon and build-in, F_s, could be estimated in general to be 0.7 for horizontal windows (European standard EN 832, 1998). For roof windows $F_s = 0.9$ can be used.

4. Results

The heating and cooling seasons were calculated for both reference houses in the three climate zones. The three zones are represented by three to four cities each in order to evaluate the climate differences within the zones. The results are shown in Table 6.

Table 6 Calculated solar radiation on vertical and sloped windows and degree hours for the heating and cooling season for the two reference houses used on different locations in Europe.

			Heating season				Cooling season			
			Solar radiation (kWh/m^2)			Degree hours (kKh)	Solar radiation (kWh/m^2)			Degree hours (kKh)
	Location	Ref. House	I_90º	I_45º	I_30º	D	I_90º	I_45º	I_30º	D
Zone 1	**Helsinki**	Type 1	252	420	434	119	16	35	43	0
	Copenhagen	Type 1	203	335	343	88	12	27	34	0
	Frankfurt	Type 1	164	273	281	73	37	105	126	0
	London	Type 1	200	333	342	71	22	63	74	0
Zone 1	**Helsinki**	Type 2	230	382	394	118	14	30	38	0
	Copenhagen	Type 2	227	381	393	90	12	27	34	0
	Frankfurt	Type 2	183	308	317	76	37	104	125	0
	London	Type 2	234	398	413	75	11	32	38	0
Zone 2	**Paris**	Type 1	239	422	443	72	26	78	95	0
	Vienna	Type 1	241	424	445	83	41	130	156	0
	Debrecen	Type 1	235	409	426	83	58	184	219	1
Zone 2	**Paris**	Type 2	265	476	502	75	17	54	65	0
	Vienna	Type 2	269	483	510	85	29	88	106	0
	Debrecen	Type 2	256	449	471	84	48	158	188	1
Zone 3	**Lisbon**	Type 1	283	459	466	33	107	390	458	2
	Rome	Type 1	248	417	430	42	111	388	457	1
	Athens	Type 1	216	366	378	32	161	564	653	4
Zone 3	**Lisbon**	Type 2	302	500	510	34	87	323	379	2
	Rome	Type 2	253	428	442	43	98	340	401	1
	Athens	Type 2	226	383	396	33	157	547	634	4

In order to compare different window solutions, 10 different windows are calculated with the above values. The result is shown in appendix 2.

4.1 Zones

From the results in Table 6 it can be seen that there are variations in the solar radiation and the degree hours for both heating and cooling season within each zone and for one reference house as a result of the different climates. For instance the solar radiation and degree hours in Frankfurt are smaller than in Helsinki.

In spite of this, the values are in the same magnitude, and when used in the expression of the net energy gain for specific windows, the ranking will be the same meaning that a good window in Frankfurt will also be a good window in Helsinki. A simple study of 10 different windows shows that the classifications of the individual windows do not differ much within the zones. See appendix 2. Therefore, putting the countries together in the mentioned zones makes good sense.

4.2 Slope angle

The results show that solar radiation on the vertical windows is significantly lower than on the sloped windows. Therefore the vertical windows must also be treated separately from the sloped roof windows when evaluated in the net energy gain expression. On the other hand, looking at the sloped windows, the radiation only varies slightly between 30º and 45º.

4.3 Final proposal

In Table 7 the values of solar radiation and degree hours used in the proposed energy rating system are shown. The values in Table 7 are average values for the two building forms based on the detailed values in Table 6.

Table 7 Solar radiation on vertical and sloped windows and degree hours for the heating and cooling season for the two reference houses used in the three climate zones in Europe. Average values.

	Heating season				Cooling season			
	Solar radiation (kWh/m^2)			Degree hours (kKh)	Solar radiation (kWh/m^2)			Degree hours (kKh)
Location	I_90º	I_45º	I_30º	D	I_90º	I_45º	I_30º	D
Zone 1	212	354	365	89	20	53	64	0
Zone 2	251	444	466	80	36	116	138	1
Zone 3	254	426	437	36	120	425	497	2

For reference the above can be compared with existing national energy labelling schemes for windows.

The Danish Energy Label for vertical windows has a solar radiation of 196 kWh/m^2 and a degree hour of 90 kKh.

The BFRC /7/ label for vertical windows in UK has a solar radiation of 218.6 kWh/m² and a degree hour of 68.5 kKh, including the air permeability of the window.

The net energy gain equations

In Table 8 the specific equations of the net energy gain in the heating and cooling season are presented. The table also includes equations for sloped windows of 30º and 45º.

Table 8 Equations for determination of the net energy gain in the heating and cooling season in the three zones for window sloped angles of 90º, 45º and 30º.

Net energy gain [kWh/m²]	Slope angle	Heating	Cooling
Zone 1	90º	$E_{ref,heating} = 212 \cdot g_w - 89 \cdot U_w$	$E_{ref,cooling} = 20 \cdot g_w - 0 \cdot U_w$
	45º	$E_{ref,heating} = 354 \cdot g_w - 89 \cdot U_w$	$E_{ref,cooling} = 53 \cdot g_w - 0 \cdot U_w$
	30º	$E_{ref,heating} = 365 \cdot g_w - 89 \cdot U_w$	$E_{ref,cooling} = 64 \cdot g_w - 0 \cdot U_w$
Zone 2	90º	$E_{ref,heating} = 251 \cdot g_w - 80 \cdot U_w$	$E_{ref,cooling} = 36 \cdot g_w - 1 \cdot U_w$
	45º	$E_{ref,heating} = 444 \cdot g_w - 80 \cdot U_w$	$E_{ref,cooling} = 116 \cdot g_w - 1 \cdot U_w$
	30º	$E_{ref,heating} = 466 \cdot g_w - 80 \cdot U_w$	$E_{ref,cooling} = 138 \cdot g_w - 1 \cdot U_w$
Zone 3	90º	$E_{ref,heating} = 254 \cdot g_w - 36 \cdot U_w$	$E_{ref,cooling} = 120 \cdot g_w - 2 \cdot U_w$
	45º	$E_{ref,heating} = 426 \cdot g_w - 36 \cdot U_w$	$E_{ref,cooling} = 425 \cdot g_w - 2 \cdot U_w$
	30º	$E_{ref,heating} = 437 \cdot g_w - 36 \cdot U_w$	$E_{ref,cooling} = 497 \cdot g_w - 2 \cdot U_w$

Using the above equation, the input data should be

- the U-value calculated according to EN 10077(1-2) or EN 12567 (1-2)
- the U-value of the reference dimension 1230 mm x 1480 mm.
- the U-value for sloped windows must be given for the slope angle
- the g-value for the window, where the g-value for the pane is calculated from EN 610

5. Energy saving potential

The energy saving potential for EU by changing old windows to new improved windows which are found as the best average windows is determined based on the proposed expression (eq. 8 and 9) and the climate data given in Table 7.

The number of old windows in EU, U-values and g-values are assumed as presented in Table 9.

Table 9 Number of windows in EU, assumed U-value and g-value of the old windows /2/ and estimated U-value and g-value of new windows. The window area is estimate as being 15 % of the building area.

Energy saving potential in EU		Number of buildings (mill m²) dwellings	Window area (mill m²) (15 %)	Old windows U-value [W/m²K]	Old windows g-value	New windows U-value [W/m²K]	New windows g-value [-]
North	Before 1975	67	10	3.0	0.58	1.2	0.5
Zone 1	Before 1975, but renovated	266	40				
	1975-1990	102	15	2.0	0.50	1.2	0.5
	1991-2002	86	13	1.6	0.43	1.2	0.5
	2002-2006	43	6				
Baltic	Before 1975	68	10	3.0	0.58	1.2	0.5
Zone 1	Before 1975, but renovated	17	3				
	1975-1990	36	5	2.6	0.50	1.2	0.5
	1991-2002	7	1	2.1	0.50	1.2	0.5
	2002-2006	2	0				
Central Coast	Before 1975	911	137	4.0	0.58	1.2	0.5
Zone 2	Before 1975, but renovated	2125	319				
	1975-1990	840	126	3.5	0.58	1.2	0.5
	1991-2002	633	95	2.0	0.50	1.2	0.5
	2002-2006	187	28				
Central continent	Before 1975	521	78	4.0	0.58	1.2	0.5
Zone 2	Before 1975, but renovated	1216	182				
	1975-1990	480	72	3.5	0.58	1.2	0.5
	1991-2002	362	54	2.0	0.50	1.2	0.5
	2002-2006	107	16				
Poland	Before 1975	189	28	3.5	0.58	1.2	0.5
Zone 2	Before 1975, but renovated	47	7				
	1975-1990	121	18	2.6	0.50	1.2	0.5
	1991-2002	57	9	2.4	0.50	1.2	0.5
	2002-2006	17	3				
Central east	Before 1975	238	36	4.0	0.58	1.2	0.5
Zone 2	Before 1975, but renovated	60	9				
	1975-1990	132	20	3.4	0.58	1.2	0.5
	1991-2002	26	4	3.4	0.58	1.2	0.5
	2002-2006	8	1				
South	Before 1975	599	90	4.2	0.58	1.2	0.5
Zone 3	Before 1975, but renovated	599	90				
	1975-1990	748	112	4.2	0.58	1.2	0.5
	1991-2002	506	76	3.5	0.58	1.2	0.5
	2002-2006	102	15				

Calculating the difference in the net energy gain (both the cooling and heating seasons) shows an energy saving potential of 134,749 GWh per year. See appendix A for the savings in the different zones of EU.

6. SUGGESTION FOR A RATING SYSTEM OF WINDOWS

The aim of the rating system is to develop a scheme that helps consumers to choose the best performing windows for replacement in the different regions, taking into account both the energy performance during the heating period and the energy performance for the summer period.

In order to have simplified labelling, the same labelling must be used both for vertical and sloped windows, as well as the same labelling scheme must be used in all zones in Europe, however the calculation of the window depends on the zone and the formula described in table 8.

A labelling scheme can be developed as illustrated below. The classification for the heating season is equal to the BFRC label /7/ used for vertical windows in UK.

Label for heating period		**Label for cooling period**		
kWh/m^2		**Without shading**	**With shading**	**kWh/m^2**
> 0	**A**	**A**	**A**	**< 10**
0 to -10	**B**	**B**	**B**	**10 to <30**
> -10 to -20	**C**	**C**	**C**	**30 to <50**
> -20 to -30	**D**	**D**	**D**	**50 to <70**
> -30 to -50	**E**	**E**	**E**	**70 to <100**
> -50 to -70	**F**	**F**	**F**	**100 to <130**
> -70	**G**	**G**	**G**	**more than 130**

A window needs to be labelled both for the heating period as well as the cooling period. This will allow the consumer to do the correct evaluation for the best window, depending on the need.

For northern climate it is most important to focus on the heating period and to choose a high rated window for that performance, while for the southern climate it can be more important to focus on the cooling period and to choose a window with a high rating for that purpose.

As an example, a window in zone 1 with a U-value of 1.2 W/m^2K and a g-value for the whole window of 0.48 will

- for the heating season be classified as $212 \cdot 0.48 - 89 \cdot 1.2 = -5$ kWh/m^2 equal to a B label,
- for the cooling period be classified as $20 \cdot 0.48 = 9.6$ equal to an A label

The same window in zone 3 will

- for the heating season be classified as $254 \cdot 0.48 - 36 \cdot 1.2 = 79$ kWh/m^2 equal to an A label,
- for the cooling period be classified as $120 \cdot 0.48 - 2 \cdot 1.2 = 55$ kWh/m^2 equal to a D label

The above indicates that, for the Zone 1, better performances can be reached for the heating season, while for zone 3; better performances can be reached for the cooling season.

If the window in zone 3 is equipped with shadings, the g-value is reduced, and it should be possible to use the g-value with shadings. If external shading is installed on the window in zone 3, the g-value can for instance be reduced to 0.1, which then can move the window from a D classification to a $120 \cdot 0.1 - 2 \cdot 1.2 = 9.6$ kWh/m², equal to A label.

Daylight

The amount of daylight in buildings is very important for people's well being, and daylight is normally preferred rather than electric lighting. Furthermore, optimised exploitation of daylight can lead to large energy savings. Therefore it is recommended to include daylight properties, given by the light transmittance, τ, in the rating system, and with the daylight potential, as described in ISO/CD 18292 /6/.

The daylight potential (DP) is expressed as:

$$DP = t_{vis} \cdot (F_{g-s} + 0.2\ F_{g-g}) \cdot A_g/A_w \qquad (11)$$

Where,

t_{vis} is the visible transmittance of the glazing

F_{g-s} is the view factor from the glazing to the sky

F_{g-g} is the view factor from the glazing to the ground

0.2 is the albedo of the ground

A_g is the visible glazing area of the window [m²]

A_w is the area of the window [m²]

7. Conclusion

The study in this report shows that

- it should be possible to develop an European scheme for windows where Europe is divided into zones as the performances of windows for the heating season do not differ significantly in the zones; therefore the evaluation of windows can be decided on the basis of the energy performance proposed in this report

- as the solar radiation becomes high in the summer period, it is necessary to include summer conditions for windows in a labelling scheme where dynamic solutions for summer conditions could be used also

- the energy performance of sloped windows differs from vertical windows, where the passive solar radiation for sloped windows is much higher than for vertical windows and thereby the energy performance of sloped windows is better than for vertical windows

- the best performing façade window for replacement in the northern part is low energy window with U-values between 0.8 and 1.2 however the difference between the 3 best windows is below 10 kWh/m² in northern climate. The best performing façade window on an overall evaluation will be a window with a U-value of approximately 1.2 W/m²K and a g-value of approximately 0.48 for the whole window

- the performance of best sloped windows for replacement is the same for all Europe, with a U-value of 1.2 W/m²K and a g-value of 0.48 for the whole window

- by replacing the windows in the existing building stock an energy saving in Europe can be up to 134,749 GWh/year if existing old windows are replaced with new windows with a U-value of 1.2 W/m²K and a g-value of 0.5 for the whole window

- further detailed studies for the individual zones are recommended in order to define the exact values for the energy performance for the heating season.

8. Reference

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/5/ ISO 13970. Energy performance of buildings — Calculation of energy use for space heating and cooling. 2008

/6/ ISO/WD 18292 – Thermal performance and energy use in the built environment Calculation methods

/7/ British Fenestration Rating Council, http://www.bfrc.org/ratings.aspx

9. Appendix 1 – Energy saving potential in EU

Energy saving potential in EU		Number of buildings (mill m2) dwellings	Window area (mill m2) 0.15	Old Windows Net Energy Gain		New Windows Net Energy Gain		Savings per m²		Energy saving potential		
				Heating [kWh/m²]	Cooling [kWh/m²]	Heating [kWh/m²]	Cooling [kWh/m²]	Heating [kWh/m²]	Cooling [kWh/m²]	Heating [GWh]	Cooling [GWh]	Total [GWh]
North	Before 1975	67	10	-145	12	-1	10	144	2	1,448	15	1,464
Zone 1	Before 1975, but renovated	266	40									
	1975-1990	102	15	-71	10	-1	10	70	0	1,076	1	1,078
	1991-2002	86	13	-51	9	-1	10	50	-1	645	-17	627
	2002-2006	43	6									
Baltic	Before 1975	68	10	-145	12	-1	10	144	2	1,470	16	1,486
Zone 1	Before 1975, but renovated	17	3									
	1975-1990	36	5	-125	10	-1	10	124	0	668	1	669
	1991-2002	7	1	-80	10	-1	10	79	0	83	0	83
	2002-2006	2	0									
Central Coast	Before 1975	911	137	-177	19	29	18	206	1	28,175	129	28,303
Zone 2	Before 1975, but renovated	2125	319									
	1975-1990	840	126	-137	19	29	18	166	1	20,914	150	21,064
	1991-2002	633	95	-34	17	29	18	63	-1	6,023	-64	5,959
	2002-2006	187	28									
Central continent	Before 1975	521	78	-177	19	29	18	206	1	16,113	74	16,187
Zone 2	Before 1975, but renovated	1216	182									
	1975-1990	480	72	-137	19	29	18	166	1	11,951	86	12,036
	1991-2002	362	54	-34	17	29	18	63	-1	3,444	-37	3,408
	2002-2006	107	16									
Poland	Before 1975	189	28	-137	19	29	18	166	1	4,706	34	4,739
Zone 2	Before 1975, but renovated	47	7									
	1975-1990	121	18	-83	17	29	18	112	-1	2,027	-18	2,009
	1991-2002	57	9	-67	17	29	18	96	-1	817	-7	810
	2002-2006	17	3									
Central east	Before 1975	238	36	-177	19	29	18	206	1	7,361	34	7,394
Zone 2	Before 1975, but renovated	60	9									
	1975-1990	132	20	-129	19	29	18	158	1	3,127	25	3,152
	1991-2002	26	4	-129	19	29	18	158	1	616	5	621
	2002-2006	8	1									
South	Before 1975	599	90	-5	61	84	58	89	3	7,987	247	8,234
Zone 3	Before 1975, but renovated	599	90									
	1975-1990	748	112	-5	61	84	58	89	3	9,974	308	10,282
	1991-2002	506	76	20	62	84	58	64	4	4,831	315	5,146
	2002-2006	102	15									
									Total [GWh]	**133,455**	**1,294**	**134,749**

10. Appendix 2 – Evaluation of 10 different windows

An evaluation of 10 different windows and their classification has been calculated in order to study their energy performance in different climates and in order to evaluate the classification.

The technical values are estimated for different panes which are available on the market.

Windows with U-values of 0.8 W/m²K are estimated to be triple glazed windows with special gas fillings (Krypton) that are not available as standard solutions for all windows produced in Europe, however they are included in the evaluation to show the performance.

Windows with U-values of 1.0 W/m²K are estimated to be triple glazed windows with standard gas fillings (Argon) and low e coatings.

Windows with U-values of 1.2 W/m²K and above are estimated to be double glazed windows with standard gas filling (Argon), with low e coatings and with different energy performances of sash and frame.

The glazed area of the windows is estimated to be 80% of the total window area.

Table 10 Technical values for the windows evaluated

Type	U_w [W/m²K] vertical window (90°)	U_w [W/m²K] roof window (45°)	U_w [W/m²K] roof window (30°)	g-value for the pane	g-value for the window
1	0.8	0.95	1.0	0.30	0.24
2	0.8	0.95	1.0	0.40	0.32
3	1.0	1.15	1.2	0.40	0.32
4	1.0	1.15	1.2	0.50	0.40
5	1.2	1.4	1.5	0.50	0.40
6	1.2	1.4	1.5	0.60	0.48
7	1.4	1.6	1.7	0.50	0.40
8	1.4	1.6	1.7	0.60	0.48
9	1.6	1.8	1.9	0.50	0.40
10	1.6	1.8	1.9	0.60	0.48

Table 11-13 shows the energy performance of the different windows in the heating season for the different locations in Europe. The calculation is based on the figures from table 6.

Table 11 Vertical windows

Window type	1	2	3	4	5	6	7	8	9	10
U-value - 90 degrees	0.8	0.8	1	1	1.2	1.2	1.4	1.4	1.6	1.6
g-value for the window	0.24	0.32	0.32	0.40	0.40	0.48	0.40	0.48	0.40	0.48
Location/Energy balance [kWh/m²]										
Helsinki	-35	-15	-38	-18	-42	-22	-66	-46	-90	-69
Copenhagen	-21	-5	-23	-6	-24	-8	-41	-25	-59	-43
Frankfurt	-19	-6	-20	-7	-22	-9	-36	-23	-51	-38
London	-8	8	-7	9	-5	11	-19	-3	-33	-17
Helsinki	-39	-21	-44	-26	-49	-31	-73	-54	-96	-78
Copenhagen	-18	0	-18	1	-18	1	-36	-17	-54	-36
Frankfurt	-17	-2	-17	-3	-18	-3	-33	-18	-48	-33
London	-4	15	0	19	4	23	-11	8	-26	-7
Paris	0	19	4	23	9	28	-6	14	-20	-1
Vienna	-9	10	-6	13	-4	16	-20	-1	-37	-18
Debrecen	-10	9	-7	11	-5	14	-22	-3	-38	-19
Paris	4	25	10	31	16	38	1	23	-13	8
Vienna	-4	18	1	22	5	27	-12	10	-29	-8
Debrecen	-6	15	-2	18	1	22	-16	5	-32	-12
Lisbon	42	64	58	80	74	96	67	90	60	83
Rome	26	46	37	57	49	69	41	60	32	52
Athens	26	43	37	54	48	65	41	58	35	52
Lisbon	45	70	63	87	80	104	73	98	67	91
Rome	27	47	39	59	50	71	42	62	33	54
Athens	28	46	39	57	51	69	44	62	37	55

Green	Best performing product
Cyan	2. best performing product
Yellow	3. best performing product
Light orange	4. best performing product
Red	Worth performing product

Table 12 Sloped windows in 45 degrees roof pitch

Window type	1	2	3	4	5	6	7	8	9	10
U-value - 45 degrees	0.95	0.95	1.15	1.15	1.4	1.4	1.6	1.6	1.8	1.8
g-value for the window	0.24	0.32	0.32	0.40	0.40	0.48	0.40	0.48	0.40	0.48
Location/Energy balance [kWh/m²]										
Helsinki	-12	21	-2	31	1	35	-22	11	-46	-13
Copenhagen	-3	24	6	33	11	38	-6	21	-24	3
Frankfurt	-4	18	4	25	7	29	-7	14	-22	0
London	13	39	25	52	34	61	20	47	6	33
Helsinki	-20	11	-13	18	-12	19	-35	-5	-59	-28
Copenhagen	6	36	18	49	26	56	8	38	-10	20
Frankfurt	2	27	11	36	17	42	2	27	-13	11
London	25	57	42	73	55	87	40	72	25	57
Paris	33	67	52	86	68	102	53	87	39	73
Vienna	23	56	40	74	53	87	36	70	20	53
Debrecen	20	52	36	68	48	80	31	64	15	47
Paris	43	81	66	105	86	124	71	109	56	94
Vienna	35	74	57	95	74	113	57	95	40	78
Debrecen	28	64	47	83	62	98	45	81	28	64
Lisbon	79	116	109	146	138	174	131	168	125	161
Rome	60	94	85	119	108	142	100	133	92	125
Athens	57	86	80	109	101	130	95	124	88	117
Lisbon	88	128	121	161	152	192	146	186	139	179
Rome	62	97	88	122	112	146	103	138	95	129
Athens	61	91	85	115	107	138	100	131	94	124

(green)	Best performing product
(cyan)	2. best performing product
(yellow)	3. best performing product
(light orange)	4. best performing product
(red)	Worth performing product

Table 13 Sloped windows in 30 degree roof pitch

Window type	1	2	3	4	5	6	7	8	9	10
U-value - 30 degrees	1	1	1.2	1.2	1.5	1.5	1.7	1.7	1.9	1.9
g-value for the window	0.24	0.32	0.32	0.40	0.40	0.48	0.40	0.48	0.40	0.48
Location/Energy balance [kWh/m²]										
Helsinki	-15	20	-4	31	-5	30	-29	6	-53	-18
Copenhagen	-5	22	5	32	6	33	-11	16	-29	-2
Frankfurt	-6	17	2	25	3	25	-12	11	-26	-4
London	11	39	25	52	31	58	17	44	2	30
Helsinki	-23	8	-15	16	-19	13	-43	-11	-66	-35
Copenhagen	4	36	17	49	22	53	4	35	-14	17
Frankfurt	0	26	11	36	13	39	-2	24	-17	9
London	24	57	42	75	53	86	38	71	23	56
Paris	34	70	55	91	69	104	55	90	40	76
Vienna	23	59	42	78	53	88	36	72	19	55
Debrecen	20	54	37	71	46	81	30	64	13	47
Paris	46	86	71	111	89	129	74	114	59	99
Vienna	37	78	61	102	76	117	59	100	42	83
Debrecen	29	66	50	87	62	100	45	83	28	66
Lisbon	79	116	110	147	137	174	130	168	124	161
Rome	61	96	87	122	109	143	101	135	92	127
Athens	58	89	82	112	103	133	96	126	90	120
Lisbon	89	129	123	163	153	194	146	187	140	180
Rome	64	99	90	126	113	148	104	140	96	131
Athens	62	94	87	119	109	140	102	134	96	127

	Best performing product
	2. best performing product
	3. best performing product
	4. best performing product
	Worth performing product

Notes

The European Commission has proposed to expand the labelling directive to include energy saving products like windows. This report shows that it should be possible to develop an European scheme for windows where Europe is divided into three zones. As the solar gain becomes high in the summer period, it is necessary to include summer conditions for windows in a labelling scheme where dynamic solutions for summer conditions could be used also.

Due to solar gain roof windows and façade windows have different performances and therefore different calculations methods are needed, however the same classification could be used. The best performing façade window on an overall evaluation will be a window with a U-value of approximately 1.2 W/m²K and a g-value of approximately 0.48 for the whole window.

The performance of best sloped windows for replacement is the same for all Europe, with a U-value of 1.2 W/m²K and a g-value of 0.48 for the whole window.

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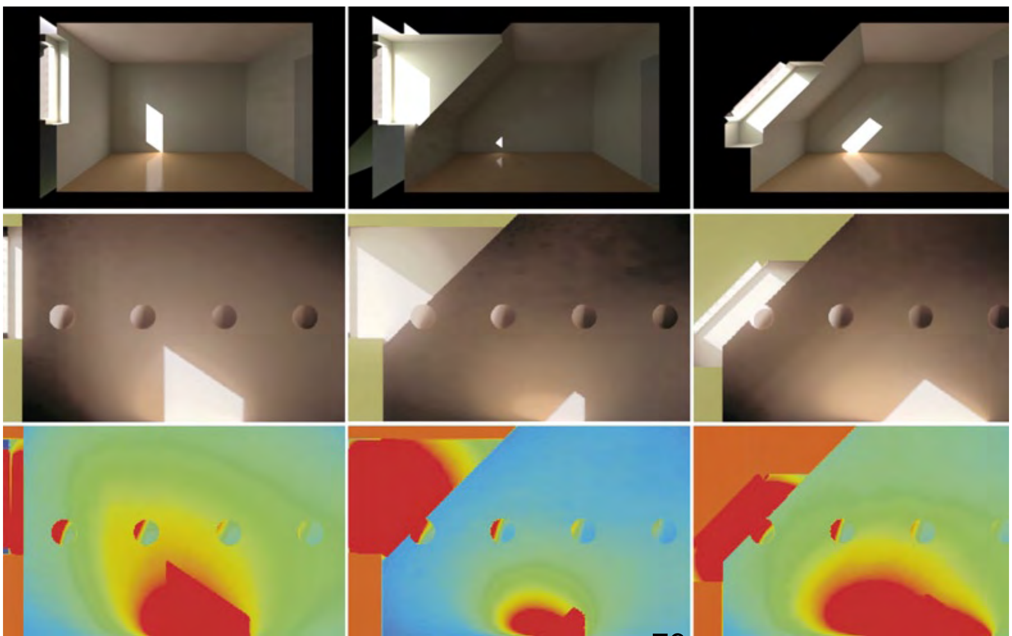
Assessment of daylight quality in simple rooms

Impact of three window configurations on daylight conditions, Phase 2



Statens Byggeforskningsinstitut
DANISH BUILDING RESEARCH INSTITUTE

Assessment of daylight quality in simple rooms

Impact of three window configurations on daylight conditions, Phase 2

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Contents

Preface

The present report documents the results of a study on daylight conditions in simple rooms of residential buildings. The work was carried out under the research project 751- 020: “Grundlag for metode til forenklet beskrivelse af dagslyskvalitet i simple rum i boliger, Fase 2” (Basis for a method to describe daylight quality in simple rooms, Phase 2). The overall objective of the study was to develop a basis for a method for the assessment of daylight quality in a room with simple geometry and window configurations. As a tool for the analyses the Radiance Lighting Simulation System was used. This study is a comprehensive extension of Phase 1, documented in By og Byg Documentation 047: *Impact of three window configurations on daylight conditions*. In the present study, a large number of simulations were performed for the three rooms (window configurations) under overcast, intermediate, and 40-50 sunny sky conditions for each window (7 months, three orientations and for every other hour with direct sun penetration through the windows).

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SBi
Danish Building Research Institute
Health and Comfort Department
April 2006

Claus Reinhold
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Introduction

This report presents the results of simulations of daylight conditions in three rooms with three different window configurations:

– a vertical window,
– a dormer window and
– a roof window.

The simulations were performed using the original UNIX-based Radiance Lighting Simulation System (Ward Larson & Shakespeare, 1998) as well as a Windows version included in the AutoCAD Desktop program. The aim of this project was to compare daylight conditions in three rooms under overcast, intermediate, and sunny sky conditions for different orientations at different months and times of the day. The three rooms studied had similar floor area and floor to ceiling height. They also had identical glazings (area and glass combination), glazing height and identical wall, floor, and ceiling reflectances. In order to establish a method for the assessment of daylight quality in a room, a number of daylight parameters were investigated:

– Horizontal illuminance and daylight factor
– Cylindrical illuminance, centre of room, horizontal and vertical plan
– Illuminance on cube, centre of room
– Vertical-to-horizontal illuminance
– Luminance distribution
– Luminance ratios, perspective view towards window
– Average luminance in the field of view, 40° band
– Daylight Glare Index (DGI)
– Luminance Difference Index (LD index)
– Scale of shadow

In addition, the need for using a solar shading device for each of the three windows was assessed over a whole year under typical weather conditions as defined in the Danish Design Reference Year (DRY). Finally, the differences in lighting conditions when using a 3-layer glazing unit with 2 low-e coatings, instead of a typical 2-layer low energy glazing with 1 low-e coating, were examined.

Main findings

General description of the lighting conditions in the three rooms

This study showed that the roof window provided significantly more light in the room than the vertical and dormer windows at all times except at solar altitudes below 25° (winter) under sunny conditions. Under these particular conditions, the vertical window resulted in higher illuminances than the roof window because of its geometry with respect to the sun and the way the direct sunlight patch was reflected from the inner surfaces of the room.

Despite an identical window area, the roof window yielded a daylight factor that was about twice as high as that of the vertical window and more than three times as high as that of the dormer window. This result is important because the daylight factor was measured under an overcast sky, a condition which prevails in Denmark more than 65 % of the time. A higher daylight factor certainly has important implications for visual performance (ability to see well because there is enough light) as well as energy savings because it means that artificial lighting has to be switched on less often with the roof window. From a perceptual point of view, the roof window will make the room appear substantially daylit (see CIBSE, 1994) since it is the only solution for which the daylight factor values exceed 5% for a substantial portion of the room (15%).

In addition, the roof window provided more acceptable light transitions in the view towards the window because of the linings surrounding the window area and because of reflected light from the back of the room towards the window wall. The roof window thus generated lower contrasts between the window area and surrounding surfaces, which also resulted in less glare, as confirmed by the Daylight Glare Index (DGI) calculations.

Finally, it is worth noting that the roof window created a slightly better modelling (on a three-dimensional object like a sphere) than the dormer window because it provided a strong component of direct light as well as diffuse, reflected light on the shaded side of the sphere. These lighting conditions are ideal for the appreciation of sculptures or three-dimensional objects like human faces as suggested in the general lighting literature (e.g. Lechner, 2000, and others).

The only negative result for the roof window concerned the extremely large size and intensity of direct sunlight patches during summer, which means that the need for using a shading device would be acute during this period. However, it is worth noting that the roof window also resulted in smaller direct sunlight patches during winter than the vertical window. Here, it should be mentioned that, from an energy point of view, it is preferable to use a shading device during the summer (to cut overheating) than during the winter when free solar heat gains and sunshine are welcome in the house.

The study also showed that the dormer window generally created a "tunnel" effect, yielding a more concentrated light beam and lower light levels in the room, with darker, gloomier interior surfaces (walls). The low illuminances and daylight factor found could severely affect visual performance and create a demand for switching artificial lights more often or increasing the window area (both of which have a negative impact on energy savings). Indeed, the daylight factor values were below 2 % for the whole room area, which means that there will be only 200 lux of illumination under an overcast sky of 10,000 lux (standard value used for Northern Europe). This amount of light is nearly sufficient for accomplishing visual tasks like reading a book, for example.

In addition, the dormer window created a poor light modelling on a sphere because of the lack of diffuse reflected light on the shaded side. This makes three-dimensional objects appear flatter, as suggested by Frandsen (1989).

However, it is worth noting that the dormer window provided better light transitions in the view towards the window than the vertical window because the dormer window had linings surrounding the window area, which were relatively bright since they were directly daylit. However, the contrast between the dormer window's linings and surrounding window walls was large and might in itself be a source of discomfort glare. This effect was not studied, but the non-conservative recommended luminance ratios of 1:20 (see IES, 1993) were largely exceeded in this case.

Finally, the study showed that there were generally less and (often not significant) differences in lighting conditions between the roof and vertical windows than between the roof and dormer windows. The vertical window had a lower vertical-to-horizontal illuminance ratio than the roof and dormer windows, indicating more balanced, three dimensional lighting, as suggested by Love and Navvab (1994). However, it should be mentioned that there is not enough scientific evidence at the moment proving that this indicator correlates with lighting quality and that the benchmark values (2-3) suggested by the authors are universal.

Conclusions concerning the methodology

The aim of this study was to develop *a basis for a method* to study and describe daylight quality in simple rooms. In this perspective, it makes sense to include some conclusions specifically related to the methodology used.

First of all, it was found that the large number of indicators, times (especially concerning sunny conditions) and orientations resulted in an extremely large data set to analyse. The analysis, handling and even transfer problems associated with such a large data set made it difficult to discuss and even represent all the results in detail in the final report and to come to a satisfying conclusion that faithfully represents what was found and observed and that is comprehensible for the reader.

It was also found that the mere *representation* of such large amount of results was a problem in itself (and demanded at one point the creation of a website and browser). Specifically, the inclusion of the time variable (a specific characteristic of daylight studies) introduced a problem of *representation on a two dimensional sheet of paper* (this report) since for each indicator (or variable) there are four dimensions to represent:

- the intensity of the variable or indicator (e.g. the luminance)
- the distribution in three dimensional space (x, y, z)
- the variation in time.

A solution for future studies would be to provide final results in the form of computer animations that make it possible to include the time dimension in compressed time.

The results found for the sunny situations suggest that it would be possible in future studies to substantially reduce the number of sunny times by making a preliminary analysis of the position of sunlight patches in the room and including times surrounding important changes in sunlight patch position or geometry. In the present study, it was found that the position of the sunlight patch was an important determinant of the general lighting levels in the room. When the sunlight patch on the light coloured walls became larger with the vertical than with the roof window due to lower sun position, the room suddenly became lighter with the vertical window. There was a sudden change in light conditions caused by the sunlight patch position and size. Since daylight conditions were fairly stable before and after this substantial change, it appears unnecessary to study a large amount of times in the intervals where the geometry and size of sunlight patch are fairly stable.

Finally, there were a large number of indicators included in this study. This allowed understanding and describing the geometry of daylight in the space in a very detailed and thorough manner. The inclusion of the daylight factor, horizontal illuminance, luminance distribution as well as cylindrical illuminance, and even the Daylight Glare Index (DGI), vertical-to-horizontal illuminance ratio and scale of shadow gave valuable information allowing a detailed description of the three-dimensional geometry of daylight in the space. The horizontal illuminance and daylight factor provided valuable information related to the general lighting level, which is connected with visibility (visual performance) and energy use. The luminance in the field of view gives information about contrasts and luminance transitions, which are closely connected to glare issues, visual comfort and quality of the view towards the window. This information was in accordance with the results from DGI calculations. The analysis of absolute luminance and sunlight patch size indicated the need for using a shading device for each season. The cylindrical illuminance is a quick calculation which provides valuable, complementary information and gives a comprehensive, overall picture of light geometry in space measured for horizontal or vertical plans. The vertical-to-horizontal illuminance ratios and scale of shadow are related to the three-dimensional light geometry in space and give additional indication about the way light is incident on objects in the room, how they will be perceived and appreciated. However, as mentioned earlier, there is not enough scientific evidence at the moment proving that the vertical-to-horizontal illuminance ratio correlates with lighting quality and that the benchmark values (2-3) suggested by the authors are universal.

Regarding the Luminance Difference Index, this study has shown that this indicator required long calculation times (about 8 hours for each point in the diagram) and still provided results that were difficult to interpret. The only observation that could be made in this case was that the results found for the different cases were similar except for a few times when the sunlight patch fell within the “measuring” plan. Since this indicator is meant to correlate with light variation and quality, the results found in this study would mean that there were no significant differences in light variation between the three cases, at least for the times studied. However, the results obtained from the horizontal illuminance and luminance distribution analyses indicated that there were in fact quite large differences between the three windows in the range of luminance and illuminance values obtained (i.e. higher amplitude in luminance and illuminance values for the roof window). As for the vertical-to-horizontal illuminance ratio, there is not enough scientific evidence at the moment (and no clearly identified benchmark value) proving that the Luminance Difference Index can reliably be used to assess light quality in a space similar to the one studied here. (It was developed from measurements in fully furnished and populated library buildings).

The Daylight Glare Index was developed by Hopkinson (1970-71, 1972) who modified the Glare Index for small glare sources to large glare sources such as windows. To validate his calculation method, he asked (small) groups of people to judge the level of discomfort due to glare in a daylit space (diffuse light from the sky). He found that people in general tolerated daylighting "glare" better than glare from other light sources. He suggested that this may be either because people are used to daylight glare and do not consider it to be stressful or because people value the view so high that it outweighs the problem of discomfort glare. The room used for this research was a standard rectangular room with a vertical window. There has been a number of subsequent studies (Iwata et al, 1991 and Parpairi et al, 2001) showing that this indicator can lead to unreliable results of glare estimation and correlates poorly with daylight quality. Furthermore, this indicator was never correlated with glare or light quality in a room with direct sunlight or with shading devices like Venetian blinds. Nevertheless, the Daylight Glare Index remains the most widely used indicator despite its accepted limitations (Wilks and Osterhaus 2003, Velds, 2001). Particular concerns exist about the treatment of source and background luminance relationship in DGI. In practical terms, this tends to lead to overestimation of the impact of background luminance in scenes with large glare sources covering most of the observer's visual field.

In conclusion, it should be mentioned that there is *no universal definition of light quality*. The approach in this study was to analyse differences in daylighting conditions for a number of lighting parameters. This included a detailed analysis of three-dimensional light geometry in 3 rooms with different window configurations. The results gave clear *indications* of, for instance, which room would be the brightest, under which conditions might glare be a problem and which type of window would yield the greatest variation (or visual interest). However, there is still not enough fundamental scientific research that enables us to put qualitative numbers for each of the indicators, or in any way "sum up daylight quality" for all parameters. Therefore it would be interesting to continue this research with either scale or full scale models and research subjects in order to establish which of the parameters (or combination of parameters) studied would result in the best correlation with daylight quality ratings by real subjects.

Horizontal illuminance and daylight factor

Overcast sky condition

– The roof window resulted in a significantly higher illuminance level and daylight factors on a horizontal plane (0.7 m above floor level), i.e. more than twice as high compared with those the vertical window, and more than three times as high compared with those of the dormer window.
– Under the roof window, nearly 100 % of all daylight-factor values were above 1 %, 50 % were above 2 % and about 15 % were above 5 %. In comparison, the dormer window had no values above 2 % and only 30 % of daylight-factor values above 1 %. With the vertical window there were 20 % of the values above 2 % and 80 % above 1 %.
– The roof window provided a wider range of daylight factor values compared with the vertical and dormer windows, which indicates a larger variation in lighting. This variation may be preferable since previous research found that people prefer an interior to possess a measure of “visual lightness” combined with a degree of “visual interest” (visual interest applies to the non-uniformity of the light pattern).

Intermediate sky conditions

– The simulations showed similar differences in the illuminance patterns as for the overcast sky conditions: Both with South and West orientations the general illumination level was significantly higher under the roof window, while the peak value was about 10 % higher than for the vertical and dormer windows.
– The variation or distribution in illuminance level was significantly wider under the roof window than with the two other windows. Both the vertical and the dormer window had quite narrow illuminance distribution curves, with 80 % of the values below 600 lux for the South orientation and 98 % of the values below 300 lux for the West orientation. This may be perceived as too uniform or even dull with lack of visual interest when compared with the variation under the roof window.

Sunny sky conditions

- At high solar altitude, above 30°, the illuminance levels on a horizontal plane (0.7 m above floor level) were often significantly higher with the roof window than with the two other windows.
- For the South orientation, peak values were typically 20 % higher, while averages were often 100 - 500 % higher with the roof window than with the vertical and dormer windows.
- At sun positions lower than 25° altitude, the illuminance was typically higher with the vertical window than with the roof window. However, even though the general level was somewhat higher with the vertical window, the peak illuminance was highest under the roof window.
- At sun positions in the interval 25° - 30°, the levels were about the same for the roof and the vertical windows. In almost all cases, the dormer window had the lowest illuminance levels.
- The patch of direct sunlight was often significantly bigger under the roof window than the patches in the rooms with the vertical and dormer windows, which also explained why the general illuminance levels were higher with the roof window.

Cylindrical illuminance (sunny sky conditions)

- The cylindrical illuminance patterns (for all months) of the three windows showed that the sunlight created a much brighter space under the roof window, especially when compared with the dormer window.
- The cylindrical illuminance patterns with the dormer window were quite narrow in the angle towards the window, especially for the summer and spring months. This indicated low luminances on the sidewalls (little reflected light) because the geometry of the dormer window and the linings act somewhat like a “light duct”.
- The sphere (or a person) at the centre of the room received much more light with the roof window from all angles of the room, while the dormer window provided the lowest illuminance in all directions.

Illuminance on cube, vertical-to-horizontal illuminance

- The recommended vertical to horizontal illuminance ratio of 2-3 was exceeded at the centre of the rooms for many hours of the year with all three window types. Generally the ratio was the lowest with the vertical window.
- The illuminances in the window direction were always highest for the roof window, except for hours when there was direct sunlight on the cube. The illuminances in the window direction were almost always lowest for the dormer window.
- Many hours of the year, especially during the summer months, the illuminance in the window direction exceeded 6,000 lux with the roof window, 5,000 lux with the vertical window and 4,000 lux with the dormer window. Even so, the DGI analyses indicated that the dormer window could cause a sensation of glare more often than the other windows, due to the lower background illuminance/luminance level.

Luminance distribution

Overcast sky conditions

- The luminance of the floor, walls and ceiling was higher with the roof window than with the other two windows. In contrast, the main inner surfaces

of the rooms were significantly darker with the dormer window, even compared with the vertical window.
- The mean luminance ratios between the window wall and the window were 1:119, 1:238 and 1:67, for the vertical, dormer and roof windows, respectively. This caused significant differences in contrast and a greater risk of a sensation of glare from the dormer window and the vertical window than from the roof window.
- In general the range of luminance values for the dormer window and roof window, was significantly wider for all surfaces compared with the vertical window where the interquartile range boxes were rather narrow (comprising 50 % of all values). This indicated that the luminance field was more balanced in the cases of the dormer and roof windows than in the case of the vertical window.
- The roof window provided higher wall luminance and softer luminance transitions from the window to the wall area compared with the other two window types

Sunny sky conditions

- At times when the sunlight patch fell on the floor with all three window types the general lighting level was significantly higher under the roof window.
- At times with low solar altitude, when the sunlight patch fell on the wall, the general lighting level was often higher with the vertical window than with the roof window.
- At almost all hours the lighting level was lowest with the dormer window.

Luminances in the field of view

- The dormer window resulted in a generally darker interior than the two other window types. The difference between the three cases was largest in the summer and for hours of high solar altitude.
- With the South orientation there were significant areas of luminances in the view towards the window above 2,000 cd/m^2 for all three windows from 10:00 - 14:00 hours in the months March – September. Depending on the transition between the brightest sunlight patches and the surroundings, these luminances (or even lower) could cause glare problems.
- The most severe problems with high luminance values in the field of view (looking towards the window from the centre of the room) occurred in March-April and August-September months for all three window types, with the highest frequencies for the roof and the vertical windows.
- In the summer months, May-July, the highest luminances occurred with the roof window, 3-4 % of the view above 10,000 cd/m². These high luminance values will certainly cause glare (independent of the background luminance level) and it would be essential, in these cases, to provide a shading device.
- Around noon, about 1 % of all values were above 10,000 cd/m^2 in the winter, October-February, for all window types. In March and September 4-5 % of the field of view had luminances above 5,000 cd/m², while in April and August 3-5 % of the view had luminances above 10,000 cd/m². The dormer window always gave lower percentage of high luminances than the two other windows but still higher values of the Daylight Glare Index than the two other window types.
- In the horizontal 40° band of the field of view towards the window the peak average luminance values of the window were always about the same. However, in all cases, the roof window provided higher wall luminance in the rest of the view field and softer luminance transitions from the window area to the wall area compared with the other cases. This is

one reason why the DGI values were lower for the roof window, in spite the fact that the luminances in most of the simulated hours were higher.

Daylight Glare Index

Overcast and intermediate sky conditions

- Under the overcast sky conditions all Daylight Glare Index (DGI) values were within the “acceptable” range of the scale.
- Under intermediate sky conditions the calculated DGI values for the North orientation were “noticeable” on the discomfort glare scale. For the West orientation the rating was “acceptable” for all windows, while for the South orientation the rating was “just acceptable”.

Sunny sky conditions

- For the South orientation the DGI rating was significantly worse in the summer months for the dormer window, in the “uncomfortable” range, while the ratings were almost the same for all windows “just uncomfortable” or “uncomfortable” during the winter months.
- The DGI rating seemed to be almost the same for the three window types when facing West, all going to the “just uncomfortable” range in the winter months and “uncomfortable” or “just intolerable” range in the summer months
- For the North orientation, the DGI ratings were significantly worse for the roof window than for the two other window types, rising to the “uncomfortable” range in the summer months, May-July. However previous research (Christoffersen, 1999) indicates that direct sun through North facing windows is likely to be appreciated in spite of the high illuminances.

Luminance Difference Index

- The Luminance Difference Index is meant to give a measure of light variation in space. This measure has been correlated with light quality by Parpairi et al (2001). For the South orientation, the results obtained for the LD45 index were almost identical for the three windows, almost all the time except at 10:00 and 12:00 hours, in June. At these hours, a sunlight patch fell within the “measurement zone” of luminance, affecting the results according to the luminance and size of the sunlight patch in each case.
- It is interesting to note also that the results obtained were somewhat higher on the LD45 scale in December (South) than for the other times, indicating that light varies more in the winter, according to a horizontal plan of measurement. This makes sense since the sunlight patch is incident on the walls (and not the floor) in December and a higher light variation should thus be expected at this time.
- The calculation of the LD180 index for the South orientation also shows similar results for the three windows, except in December. This is, again, a question of sunlight patch position and magnitude but it is hard to understand the differences obtained between LD45 et LD180 indices. Note that Parpairi et al (2001) obtained a weaker correlation between daylight quality and the LD180 index than with the LD45 index.
- The results obtained for the West orientation suggest that there were larger differences between the three windows than for the south orientation and that the light varied more than in the South since the results were higher on the LD45 scale.
- Overall, it is difficult to interpret the information provided by this index but the fact that the results are similar most of the time suggests that there

were small differences in light variation between the three windows, at least for the South orientation. More research is needed to correlate this index with daylight quality in rooms similar to the ones of this study. (This index was developed by empirical and physical measurements of luminance in full scale, furnished and populated library buildings in England). There is also a need to establish benchmark values of acceptable and unacceptable luminance variation (upper and lower limits on the LD scales).

Scale of Shadows

- The concept of "Scale of Shadows" as defined by Frandsen (1989) was introduced to verify if it was possible to see from Radiance renderings under which circumstances the shape of objects would be most easily recognised. The spheres modelled in Radiance were approximately the size of a human head. The concept proved to be useful in order to study the three-dimensional geometry of daylight space, especially for the area near windows. A careful observation of light distribution on the second sphere (probably the most strategic position in the room) showed that the roof window created a slightly better modelling than the dormer window because it provided a strong component of direct light as well as diffuse, reflected light on the shaded side of the sphere. These lighting conditions are ideal for the appreciation of sculptures or three-dimensional objects like human faces as suggested in the general lighting literature (e.g. Lechner, 2001 and others). (Note that photographers often use this lighting strategy when making portraits of people).
- A comparison of the spheres also showed that, for most times, there were smaller differences between the roof and vertical windows than between the roof and dormer windows. The roof window generally created a stronger reflected diffuse light component on the shaded side of the sphere - especially in the lower portion of the sphere – owing to reflected light from the floor. This made the sphere appear rounder, in most cases (see overcast sky situation, for instance).

Use of 3-layer glazing

- With the 3-layer glazing the illuminance dropped to 66 % of that found with the double-glazing, in accordance with the transmittance ratio for the glazing types.
- Under sunny skies with sunlight perpendicular to the window (e.g. March at 12:00 hours) the 3-layer glazing reduced the DGI values from "uncomfortable to a "just uncomfortable" level for the vertical and dormer windows, and to an "acceptable" level for the roof window.

Assessment of the need for solar shading

- The estimated number of hours when a shading device would be required for the South windows were around 520 hours with the vertical and the dormer windows, while around 840 under the roof window.
- For the West facing windows, the situation was about the same. Shading was needed 390 hours with the vertical window, 320 hours with the dormer window, and about twice the number of hours, about 700 hours, with the roof window.
- When using a dark grey screen the average luminance (40° band) dropped from around 5,000 cd/m² to around 1,000 cd/m² for all three window types. The luminance ratio between the window and the surroundings remained about the same, namely 10:1.

- The most significant luminance reduction with the blinds was on the floor, where the luminance was reduced to 1 % of that without the blinds
- The Venetian blind increased the DGI for all window types. For the roof window, the DGI raised from “just uncomfortable” to “uncomfortable” on the perception scale. The reason for this may be that the luminance of the window area was only reduced to about one third, while the luminance on all other surfaces dropped to 1-2 %.

Description of the method

Simulations with Radiance

The simulations presented in this report were performed using the original UNIX-based Radiance Lighting Simulation System (Ward Larson & Shakespeare, 1998) as well as a Windows version included in the Autocad Desktop program. Radiance is a suite of programs for the analysis and visualisation of lighting in design. It 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. Input files specify the scene geometry, materials, luminaires, time, date, and sky conditions (for daylight calculations). The primary advantage of Radiance over simpler lighting calculation and rendering tools is that there are no limitations on the geometry or materials that may be simulated. Calculated values include spectral radiance (i.e. luminance + colour), irradiance (illuminance + colour) and glare indices. Simulation results may be displayed as colour images, numerical values, and contour plots. Radiance is one of the most advanced daylighting/lighting simulation tools available today and it has been fully validated (Mardaljevic, 1999; Aizlewood et al., 1998; Ubbelohde & Humann, 1998; Jarvis & Donn, 1997, etc.).

Geometry of the rooms and windows

For the benefit of comparisons of daylight conditions, the studies of the three window types were performed in rooms that were identical on all possible measures. The rooms studied measured 3.25 m by 3.85 m (width by depth) and had a floor to ceiling height of 2.5 m. The glazing area measured 0.765 m by 1.15 m (width by height), the window area measured 0.887 m by 1.339 m (total wall-opening, width by height) and the frame was 0.072 m wide at the bottom, 0.061 m wide on the sides and 0.117 m wide at the top.

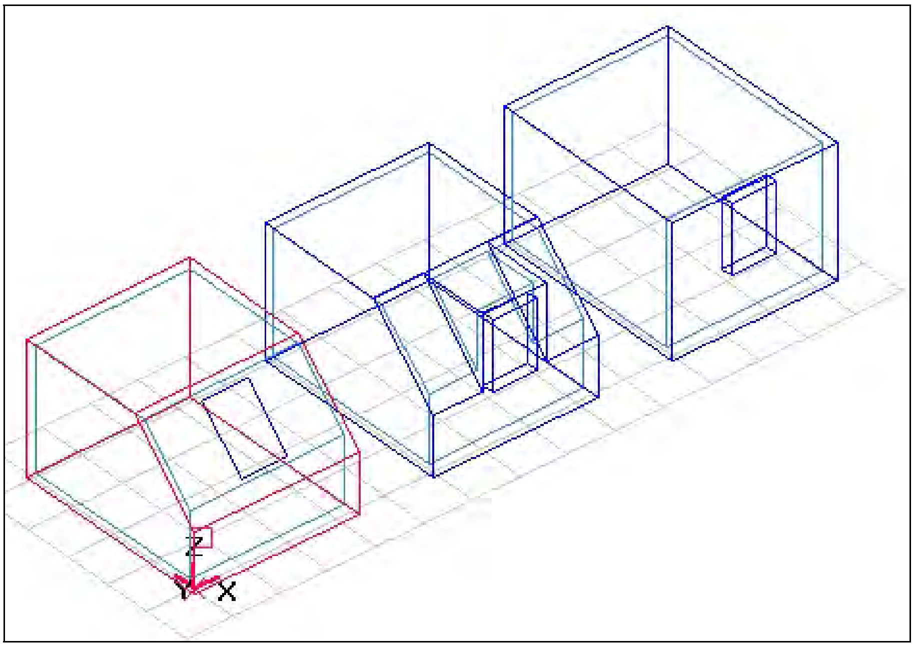
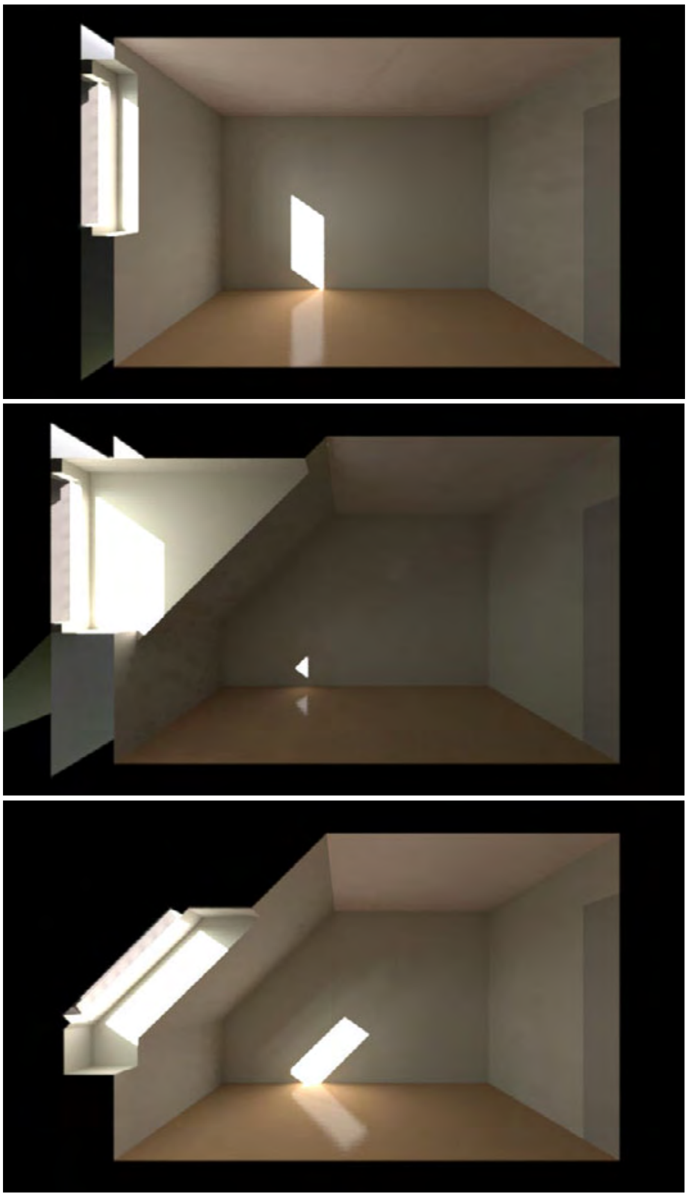


Figure 1. Isometric representation of the three models in the study: room with roof window, dormer window and vertical window (graphical view in BSim2002).

The frame depth was 0.083 m. In all three cases, the window was located at exactly 1.0 m above the floor level and was centred with respect to lateral walls. The small scale details of the frame and sash were not modelled in order to simplify the calculations[1]. Figure 1 shows the three rooms in a BSim generated graphical representation of the models (SBI, BSim 2004). Figure 2 shows a section-perspective from Radiance renderings of the three rooms.

As shown in Figure 2, the exterior surfaces were not modelled, except in the case of the dormer window where the roof slope under the window was added. The exterior surfaces had no impact on interior lighting conditions when they were parallel to the window plane (none of the light rays reflected off the surfaces meet the window). In the case of the dormer window, the roof slope under the window did have an impact on interior lighting conditions because it was not parallel to the window plane.



a) Vertical window.

b) Dormer window.

c) Roof window.

Figure 2. Rendering showing a longitudinal section-perspective of the three rooms modelled in Radiance.

[1] The details of the sash and frame have a negligible impact on daylight conditions at the scale of the room and their impact will be the same in all three rooms provided that the details are exactly the same in all three rooms. Adding those details will cause the simulation program to sample a much larger number of rays around small insignificant surfaces, which will substantially increase the length of calculations and may even cause the program to "overkill".

Properties of inner surfaces, glazings and shading devices

The red (r), green (g), blue (b) and integrated reflectance (R) and transmittance (T) for inner surfaces, glazing and shading screen are presented in Table 1. “Spec” is the value for specularity in the input to Radiance. The *specularity* is the amount of light reflected (or transmitted) by specular (mirror-like, not diffuse) mechanism (Ward Larson & Shakespeare, 1998). “Rough” is the value for roughness in the input to Radiance. The *roughness* is a measure of the average instantaneous slopes of a polished surface, which determines to what degree a semi-specular highlight will be dispersed (Ward Larson & Shakespeare, 1998). The specularity and roughness control the way light will be reflected off the material. If both are set to zero, the surface is perfectly diffuse and reflects light equally in all directions. On the other hand, if the material is purely specular (high specularity) and has a roughness of zero, it is a mirror (Larson in Ward, 1996). All exterior and interior surfaces except the floor were assumed to be totally diffuse (Spec = 0) and smooth (Rough = 0).

Table 1. Red (r), green (g), blue (b) and integrated reflectance (Rtot) and transmittance (Ttot), specularity (Spec) and roughness (Rough) of inner surfaces, glazing and shading screen modelled in Radiance.

Surfaces/ element	Colour/ material	Digital sample*	R(r) (%)	R(g) (%)	R(b) (%)	Rtot (%)	T(r) (%)	T(g) (%)	T(b) (%)	Ttot (%)	Spec. -	Rough. -
Walls Slopes Linings	light grey paint (1k102)		58.3	57.3	50.7	57.0	n.a.	n.a.	n.a.	n.a.	0.00	0.00
Floor	chestnut wood		52.5	34.4	19.0	37.9	n.a.	n.a.	n.a.	n.a.	0.00	0.00
Ceiling	pure white (RAL 9010)		92.3	80.8	76.1	83.5	n.a.	n.a.	n.a.	n.a.	0.00	0.00
Door	light grey paint (1k108)		39.1	39.0	36.7	38.8	n.a.	n.a.	n.a.	n.a.	0.00	0.00
Glazing, 2-pane		-	n.a.	n.a.	n.a.	n.a.	78.0	85.0	80.0	78.0	n.a.	n.a.
Glazing, 3-pane			n.a.	n.a.	n.a.	25	50.5	54.6	43.7	52.8	n.a.	n.a.
Roof (exterior)**	grey		30.0	30.0	30.0	30.0	n.a.	n.a.	n.a.	n.a.	0.00	0.00
Shading screen	grey	-	3.3	3.3	3.3	3.3	18.7	18.7	18.8	18.7	1.00	0.00
Ventian blinds, slats	white side specular side	- -	75.8 76.1	81.3 72.0	84.8 58.9	n.a.	n.a.	n.a.	n.a.	n.a.	0.00 0.05	0.00 0.00

n.a.: not applicable i.e. either the value is not present in the input or it is not relevant.

* The sample shown is affected by settings in the computer screen and printer.

** Only relevant for the dormer window

Context and orientation

The rooms were modelled for South, West and North orientations. A free horizon (no external obstructions) was assumed thus representing rooms on the first floor or higher, and the ground light reflectance was set to 15 % and assigned a green colour.

Simulation months and hours

The simulations were performed for the location of Copenhagen (latitude 55.4 ° N; longitude 12.35 ° E) under the following sky conditions:

1 CIE overcast sky
2 Intermediate sky, one day (in March)
3 CIE Sunny sky, for seven months on selected (sunny) days from the Danish Design Reference Year at the hours indicated in Table 2 below.

Table 2. Months and hours of Radiance simulations for sunny days. The day of each month was selected from the Danish Design Reference Year as representative for a sunny day in that month.

Month	Jan	Feb	Mar	Apr	May	Jun	Dec	Total
South	(hours)							
Vertical	10,12	10,12	8, 10,12	8, 10,12	8, 10,12	8, 10,12	10,12	18
Dormer	10,12	10,12	8, 10,12	8, 10,12	8, 10,12	8, 10,12	10,12	18
Roof	10,12	10,12	8, 10,12	8, 10,12	8, 10,12	8, 10,12	10,12	18
North	(hours)							
Vertical					6, 18, 20	6, 18, 20		6
Dormer				6	6, 18, 20	6,20		6
Roof				6, 8, 18	6, 8, 10, 12, 14, 16, 18, 20	6, 8, 10, 12, 14, 16, 18, 20		19
West	(hours)							
Vertical	14	14, 16	14, 16	14, 16,18	14, 16, 18, 20	14, 16, 18, 20	14	17
Dormer	14	14, 16	14, 16	14, 16,18	14, 16, 18, 20	14, 16, 18, 20	14	17
Roof	12, 14	12, 14, 16	12, 14, 16	10,12, 14, 16,18	10, 12, 14, 16, 18, 20	10,12, 14, 16, 18, 20	12, 14	27
Total	**10**	**13**	**16**	**24**	**37**	**36**	**10**	**146**

A total of 146 hours were thus analysed under sunny sky conditions, Table 2. For most of these hours the following indicators of Table 3 were analysed.

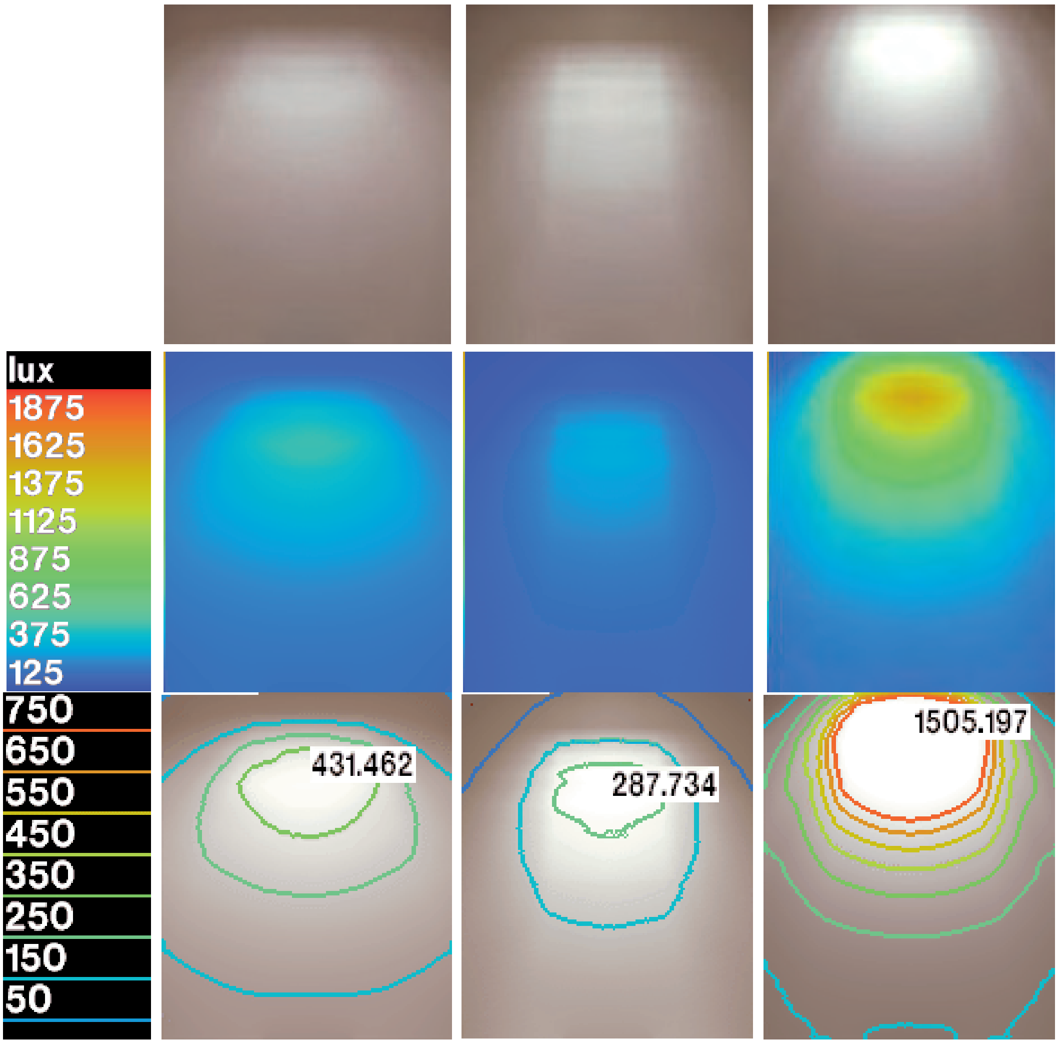
Table 3. Overview of lighting quality indicators and the analyses.

Parameter	Analyses
Illuminance distribution on a horizontal plane 0.7 m above floor level	Daylight factors. Light intensity, distribution and variation.
Cylindrical illuminance in horizontal and vertical planes	Luminous flux at the centre of the room. Light distribution, directional and diffuse components
Illuminance on cube, centre of room Vertical-to-horizontal illuminance	Vertical to horizontal illuminance, evaluation of contrasts and potential glare problems
Luminance distribution. Luminance ratios, perspective view towards window (vw) and door (vd)	Radiance renderings for visualisation of views and detection of sun patches of high luminances. Luminance ratios as indicator of potential visual problems
Average luminance, 40° band	Evaluation of Radiance renderings for luminances of all "pixels" in the field of view for glare detection
Daylight glare index (DGI)	Glare evaluations with Radiance of the subjective magnitude of glare discomfort with high values illustrating uncomfortable or intolerable sensation of discomfort
Luminance difference index (LD index)	Evaluation of glare according to the new proposed index and the possible value of this index as indicator
Scale of shadows, section perspective showing half the room in perspective with spheres (vsp)	Radiance renderings with "spheres" for analyses of the intensity of directional light and diffuse to determine the shadow type on the Scale of Shadows as an indication of the light quality for a certain task at that point of the room
Assessment of the need for solar shading	Sunlight patches, luminance value, size and position as indicators of the need for solar protection against glare
Use of 3-layer glazing and impact of solar screen and Venetian blinds	Influence on illuminance and luminance distribution and intensity. Influence on daylight glare index, DGI.

Horizontal illuminance and daylight factor

Overcast sky condition

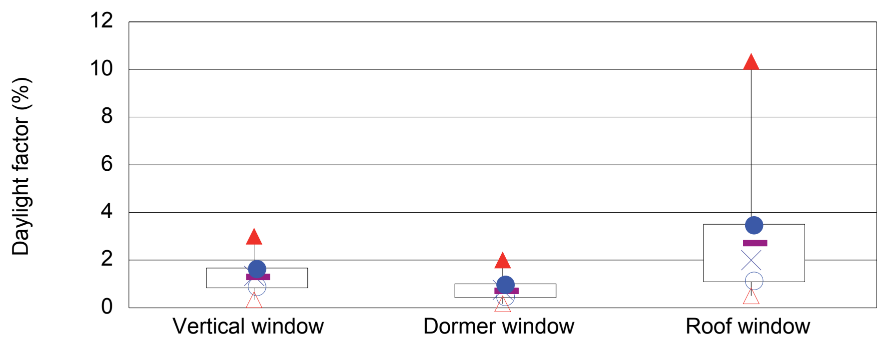
Simulations were made to calculate the illuminance on a horizontal plane located at 0.7 m above floor level. The results showed that the roof window produced significantly higher illuminance values in a unique pattern with a large oval area of high illuminance in the area under the window, as illustrated in Figure 3. The vertical and dormer windows produced lower illuminance levels in similar distribution patterns. The illuminance pattern was more concentrated in the case of the dormer window. The illuminance level was also generally lower in this case.



a) Vertical window b) Dormer window c) Roof window

Figure 3. Rendering of a horizontal plane at 0.7 m above floor level, false colour rendering and isolux contours showing illuminance (lux) for the a) vertical, b) dormer, c) roof windows, under overcast sky conditions. The exterior horizontal illuminance was 14,613 lux (divide by this number to obtain the daylight factor).

Statistical analysis of the illuminance in all calculated points (n=5000) clearly illustrates the differences in the pattern of each window, as shown in Figure 4. The vertical window resulted in slightly higher daylight factors, in average, than the dormer window, but the difference between the two cases was small.



	Vertical window	Dormer window	Roof window
○ Q1 25%	0,98	0,57	1,29
△ Min	0,33	0,17	0,47
× Median	1,29	0,74	1,97
▲ Max	2,97	1,98	10,33
▬ Mean	1,41	0,85	2,86
● Q3 75 %	1,78	1,07	3,61

Figure 4. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for the daylight factor (%) on a horizontal plane, at 0.7 m above floor level, overcast sky conditions.

The figure also shows that the roof window produced much higher mean, median, minimum, maximum and interquartile range[2] values for the daylight factor compared with the other cases.

The roof window produced a wider range of daylight factor values. This is evident from Figure 4, but may also be visualised clearly in a diagram showing the frequency distribution of daylight factors for the three cases, as shown in Figure 5. The figure shows that the illuminance distribution is much wider for the roof window than for the vertical and dormer windows.

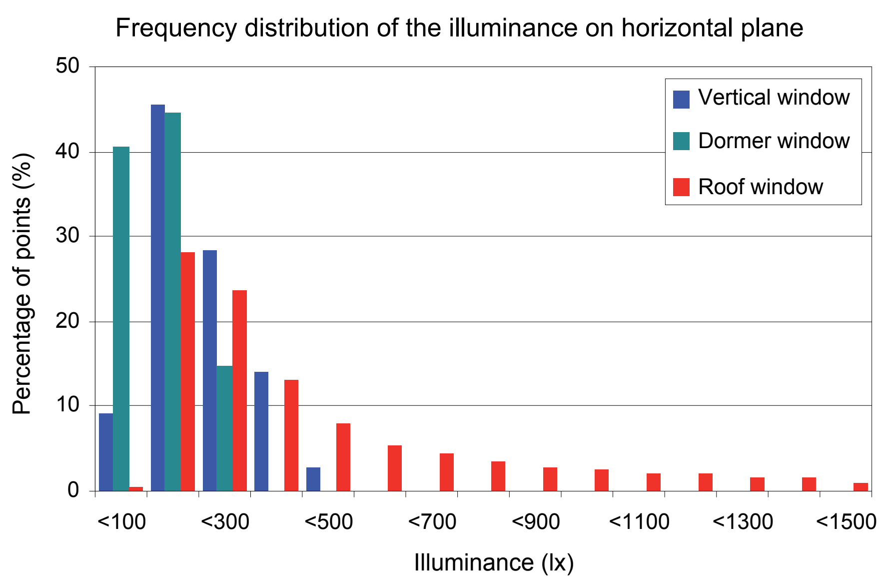


Figure 5. Frequency distribution for the illuminance (lx) on a horizontal plane, 0.7 m above floor level, overcast sky conditions.

A plot of the daylight factors along an axis perpendicular and centred about the window also shows that the roof window produced a much higher amplitude of daylight factors Figure 6.

[2] The interquartile range comprises the values of 50 % (n=2500) of all calculated points (n=5000). Thus, 25 % (n=1250) of the points have a daylight factor below the interquartile range box and 25 % have a daylight factor above the interquartile range box.

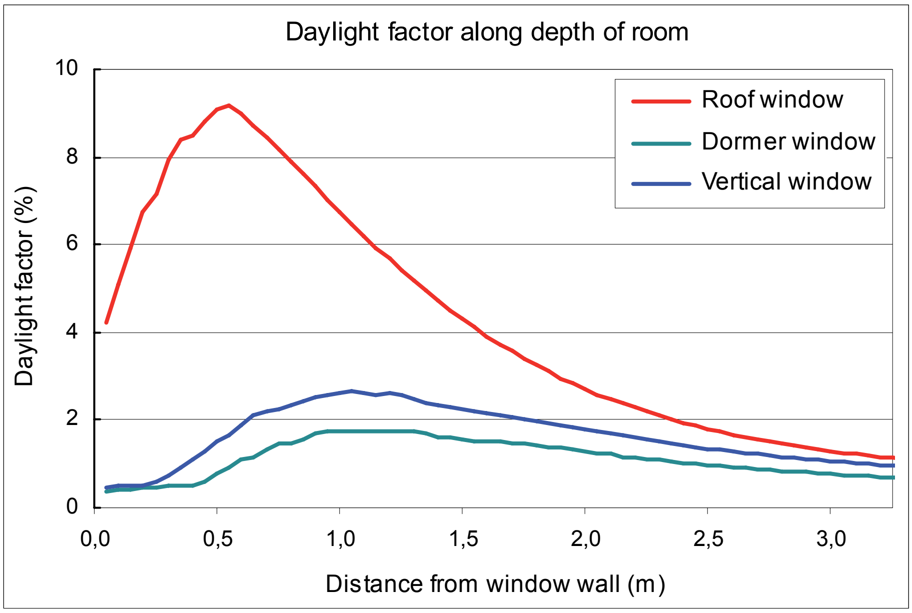


Figure 6. Daylight factors (%) at 0.7 m above floor level along an axis perpendicular and centred about the window, overcast sky conditions.

While extreme variations of the daylight factor should be avoided, it is not desirable to create totally even light distributions either. Dull uniformity in lighting, though not harmful, is not pleasant, and can lead to tiredness and lack of attention (Hopkinson, Petherbridge & Longmore, 1966). According to Loe (1997), people prefer an interior to have a measure of "visual lightness" combined with a degree of "visual interest" (visual interest applies to the non-uniformity of the light pattern). According to IES (1993), it is important to provide enough variation in the light pattern to contribute to a stimulating, attractive environment. Small visual areas that exceed the luminance-ratio recommendations are desirable for visual interest and distant eye focus (for periodic eye muscle relaxation throughout the day). Veitch (2000) recommends using meaningful luminance patterns to create interest and integrating luminance variability with architecture to satisfy attention and appraisal processes.

Figure 7 shows the daylight factors levels (%) for each window type along a line across the room at 2 m from the window wall.

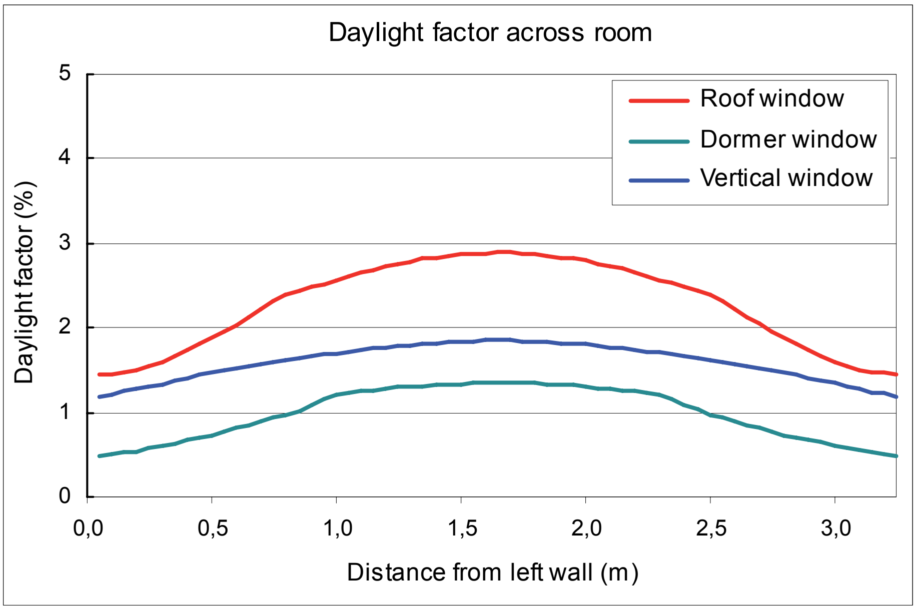


Figure 7. Daylight factors (%) at 0.7 m above floor along a line across the room, parallel to the window wall at a distance of 2 m. Overcast sky conditions.

In the case of the roof window, nearly 100 % of all daylight-factor values were over 1 %, 50 % were above 2 % and about 15 % were above 5 %, as shown by a cumulative frequency distribution diagram, Figure 8. In comparison, the dormer window had no values above 2 % and only 30 % of daylight-factor values above 1 %. The vertical window performed slightly better with 20 % of values above 2 % and 80 % above 1 %.

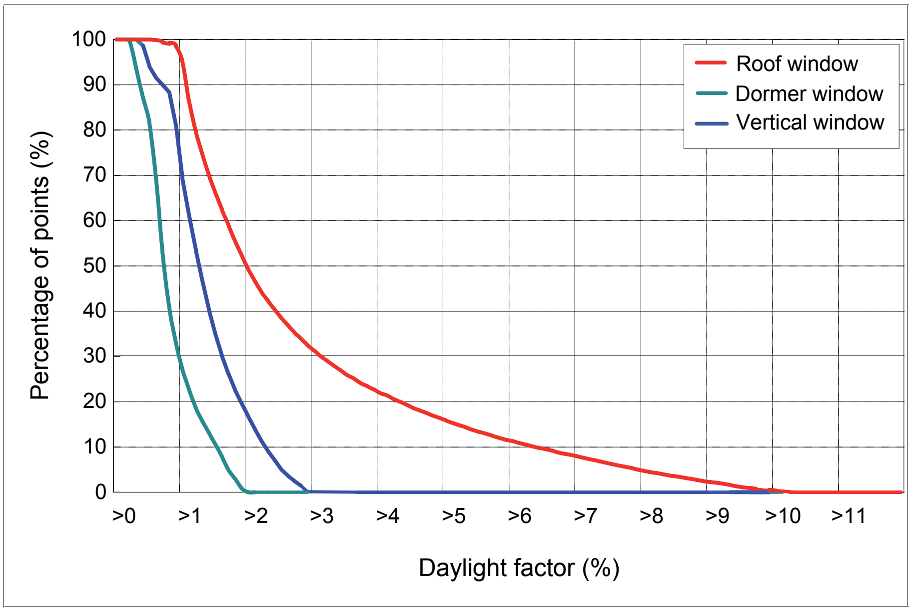


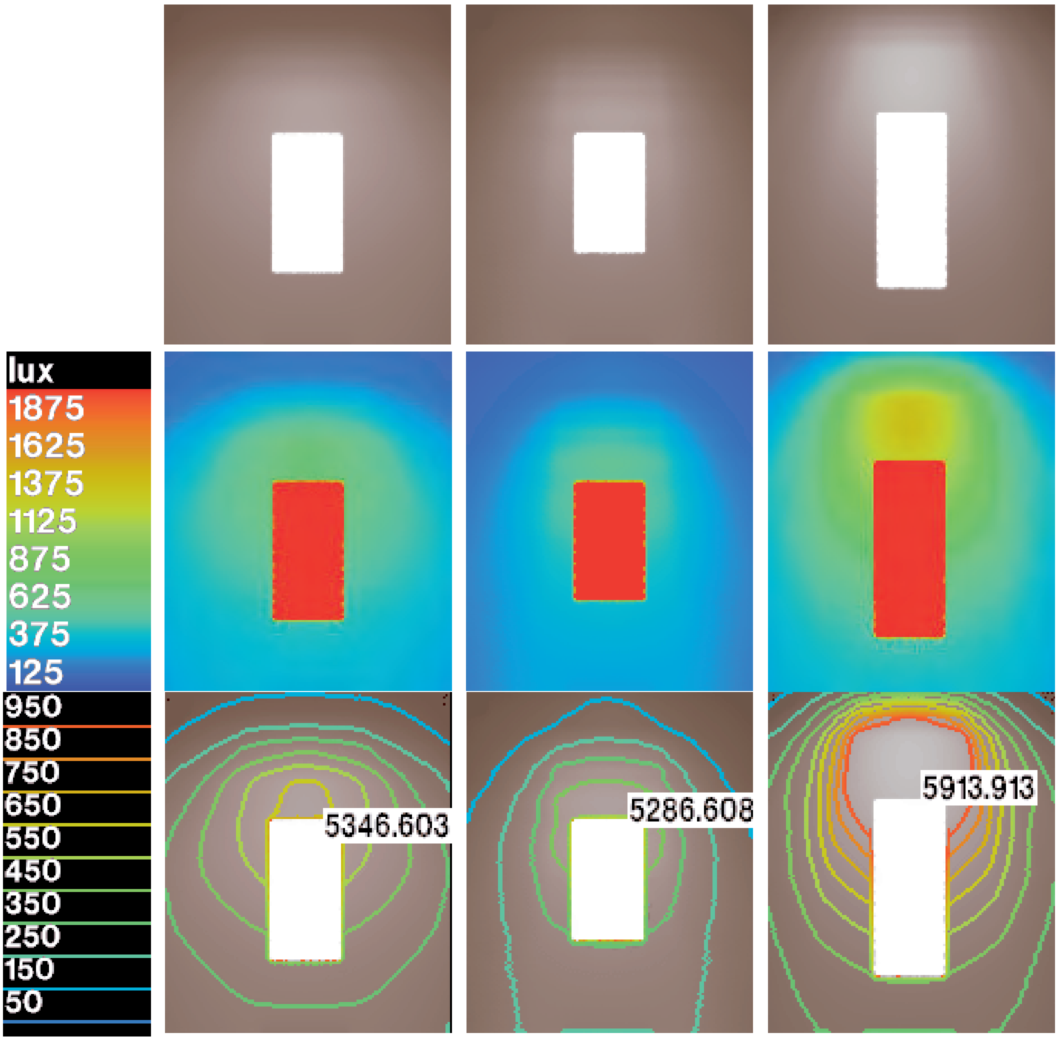
Figure 8. Cumulative frequency distribution for the daylight factor (%) on a horizontal plane, at 0.7 m above floor level, overcast sky conditions.

A daylight factor of 5 % means that there will be 500 lux on the "work plane" under an overcast sky of 10 klux (which is commonly used as reference in northern Europe). Note that in Denmark, the diffuse illumination from the sky is over 10 klux 60 % of the working time (8-17 hours) (Christoffersen & Petersen, 1997).

According to a British Lighting Guide (CIBSE, 1997), an average daylight factor of 5 % or more will ensure that an interior looks substantially daylit, except early in the morning, late in the afternoon or on exceptionally dull days. An average daylight factor below 2 % generally makes a room look dull; electric lighting is likely to be in frequent use. In domestic interiors, however, 2 % will still give a feeling of daylight, though some tasks may require electric lighting. The BS 8206 code of practice (1992) recommends average daylight factors of at least 1 % in bedrooms, 1.5 % in living rooms and 2 % in kitchens, even if a predominantly daylit appearance is not required. Figure 4 shows that the average daylight factor was 1.41 % for the vertical window, 0.85 % for the dormer window and 2.86 % for the roof window. The daylight factor was thus more than twice as high with the roof window compared with the vertical window.

Intermediate sky conditions

The day and hour for intermediate sky conditions was chosen to be 21 March at 12:00 hours. Three orientations were analysed: South, West and North. The simulations showed similar differences in the illuminance patterns as for the overcast sky conditions. Figure 9 shows the renderings, false colour images and iso-lux contours when the windows are facing South. The general level was significantly higher under the roof window, and the peak value was about 10 % higher than for the vertical and dormer windows.



a) Vertical window b) Dormer window c) Roof window

Figure 9. Renderings of a horizontal plane at 0.7 m above floor level, false colour rendering and isolux contours showing illuminance (lux) for the a) vertical, b) dormer, c) roof windows, under intermediate sky conditions oriented South (21 March at 12:00 hours).

The cumulative frequency diagrams for the illuminance under intermediate sky on a horizontal plane at 0.7 m above the floor level are shown for South and West facing windows in Figure 10 and Figure 11, respectively.

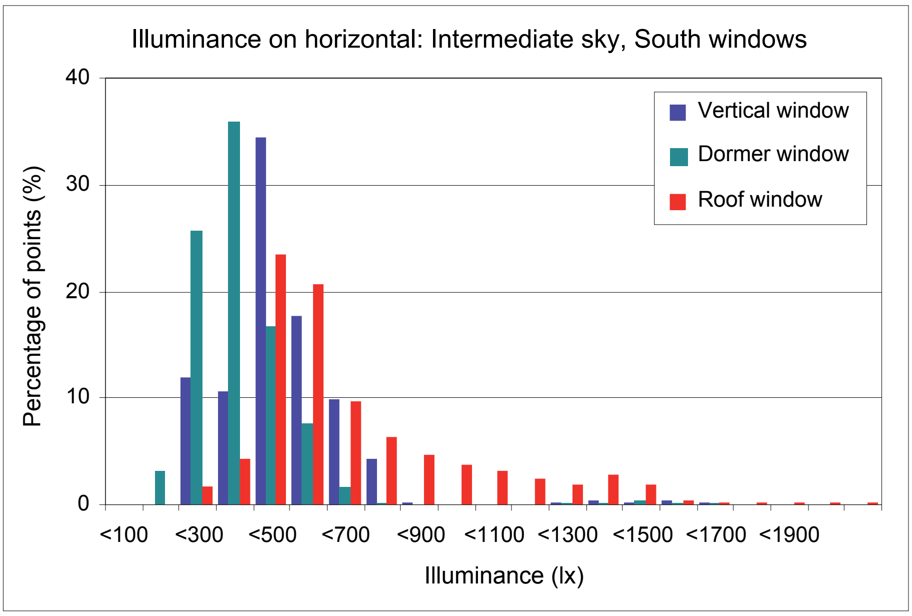


Figure 10. Cumulative frequency distribution for the illuminance (lx) on a horizontal plane, at 0.7 m above floor level, intermediate sky conditions, South orientation. The high illuminances of the direct sunlight patches (5,000 – 6,000 lux) are not included in the diagram.

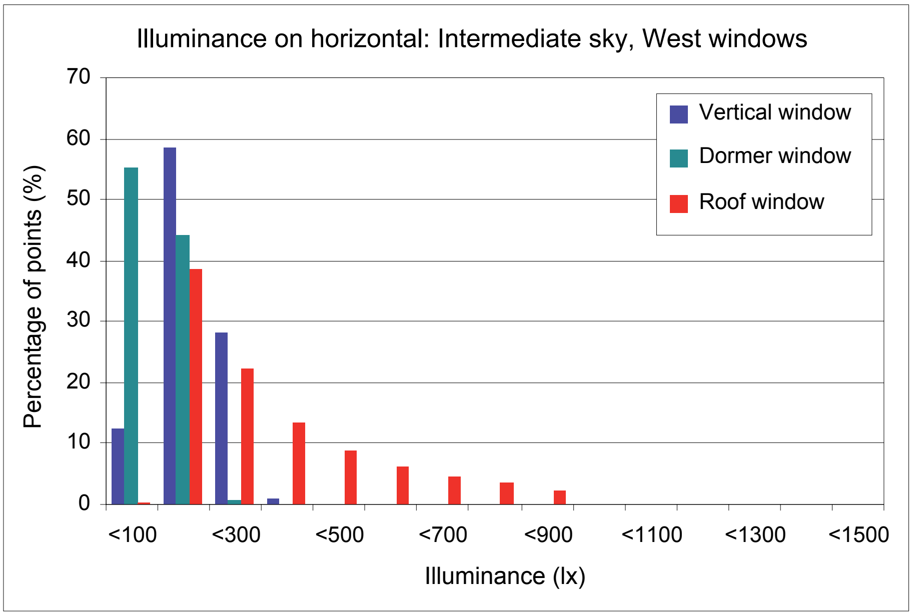


Figure 11. Cumulative frequency distribution for the illuminance (lx) on a horizontal plane, at 0.7 m above floor level, intermediate sky conditions, West orientation.

Both figures illustrate that (except for the illuminance values of the direct sunlight patches, which were above 5,000 lux) the distribution curves are much narrower for the vertical and dormer windows than for the roof window.

Sunny sky conditions

A total of 146 hours under sunny sky conditions were analysed, cf. Table 2. An analysis of the illuminance levels on a horizontal plane 0.7 m above floor level showed that when the sun was at a high altitude (above 30°), the illuminance levels were often significantly higher with the roof window than with the two other windows. For the South facing window, peak values were typically 20 % higher, while averages were often 100 - 500 % higher with the roof window than with the vertical and dormer windows. At sun positions lower than 25° in altitude, the illuminance was typically higher with the vertical window than with the roof window. At sun positions in the interval 25 ° - 30 °, the levels were about the same for the roof and the vertical windows. In almost all cases, the dormer window had the lowest illuminance levels.

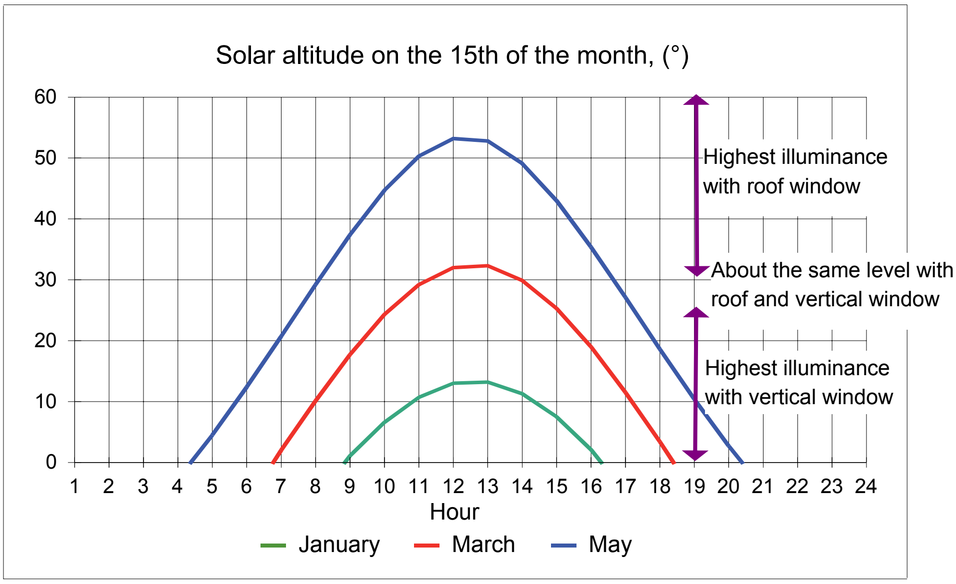
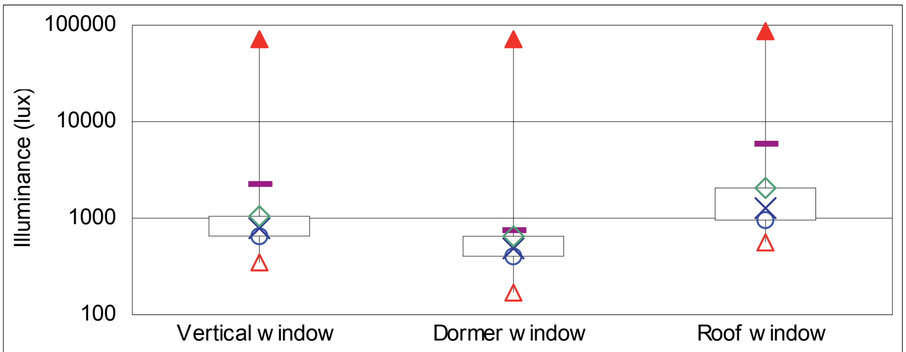


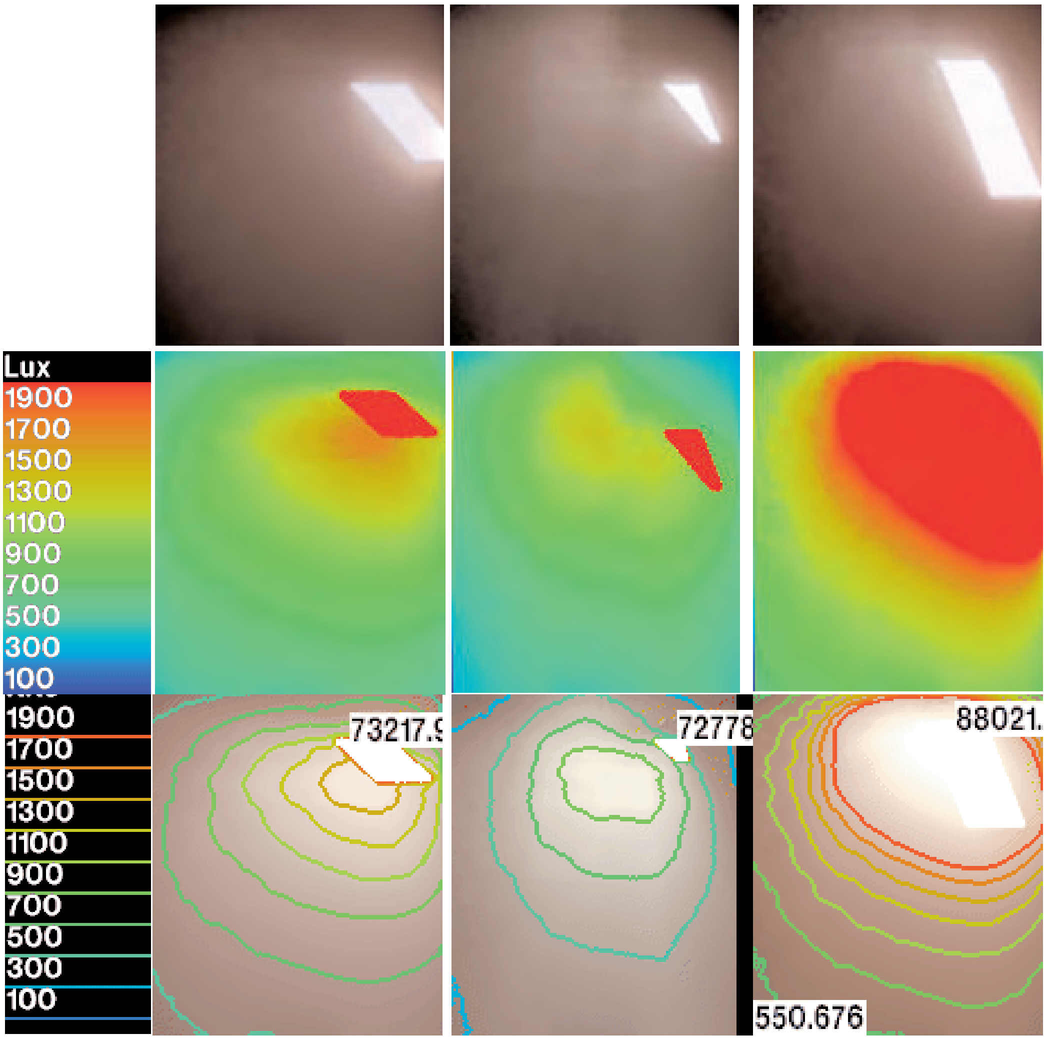
Figure 12. Graph of solar altitude angle for the months January, March and May. At solar heights above 30° the average illuminance level was higher with the roof window, i.e. for May month, for instance, all hours from 8:00 to 16:00.

Figure 12, which shows the solar altitude angle for 15 January, March and May, indicates which of the window types will result in the higher illuminance levels according to the time of the year.



	Vertical window	Dormer window	Roof window
Q1 25%	645	405	947
Min	347	173	574
Median	787	484	1285
Mean	2212	761	6001
Max	72853	72406	87406
Q3 75 %	1050	646	2033

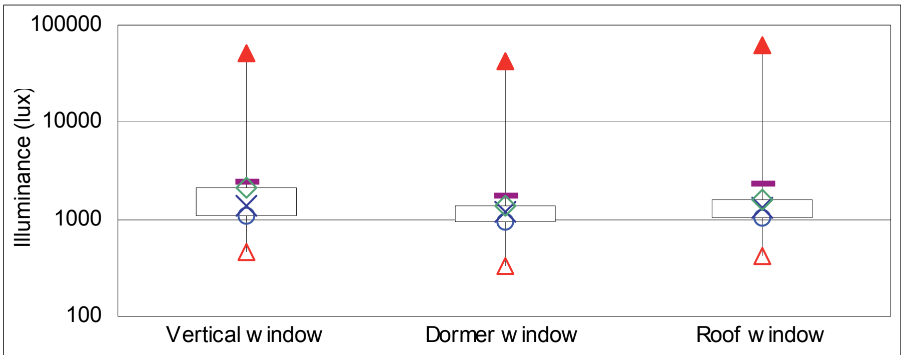
Figure 13. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for the illuminance on a horizontal plane, at 0.7 m above floor level. South facing windows, sunny sky conditions June at 10:00 hours.



a) Vertical b) Dormer c) Roof

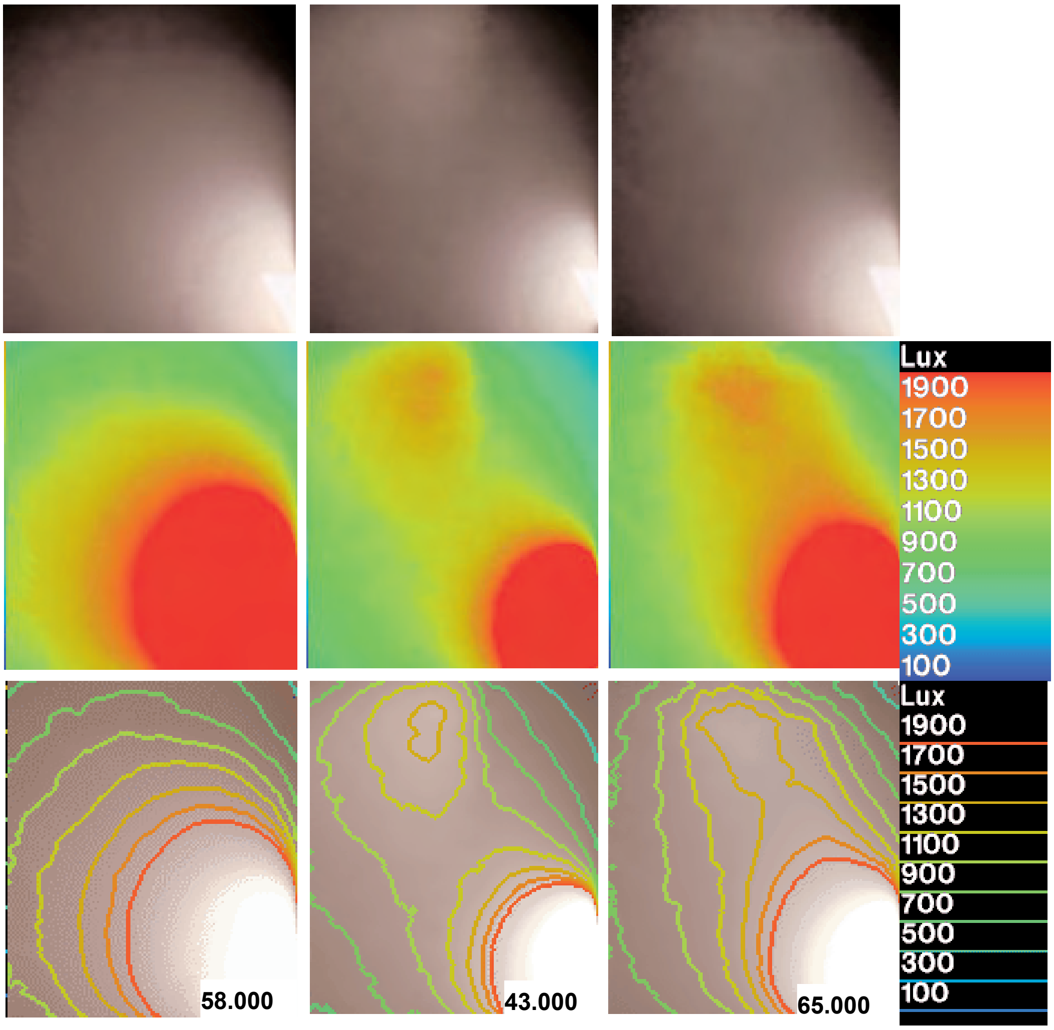
Figure 14. Illuminance distribution on horizontal plane, at 0.7 m above floor level, false colour rendering and iso-lux contours. South facing windows under sunny sky conditions in June at 10:00 (window at the top of image).

An example of the differences under high solar altitude is shown in Figure 13, which shows the statistical analysis of the illuminances in June at 10:00 hours. The illuminance distribution on a horizontal plane, false colour rendering and iso-lux contours are shown in Figure 14.



	Vertical window	Dormer window	Roof window
○ Q1	1075	954	1028
△ MIN	468	329	423
× MEDIAN	1395	1172	1317
▬ MEAN	2442	1715	2292
▲ MAX	50281	42674	62185
◇ Q3	2121	1395	1612

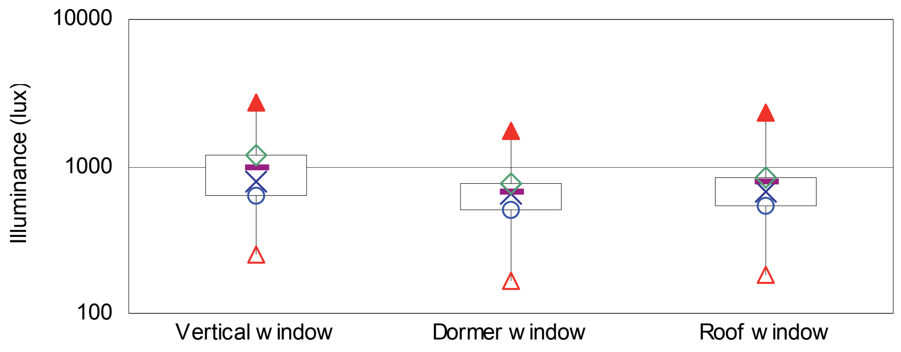
Figure 15. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for the illuminance on a horizontal plane, at 0.7 m above floor level. West facing windows, sunny sky conditions in March at 16:00 hours.



a) Vertical b) Dormer c) Roof

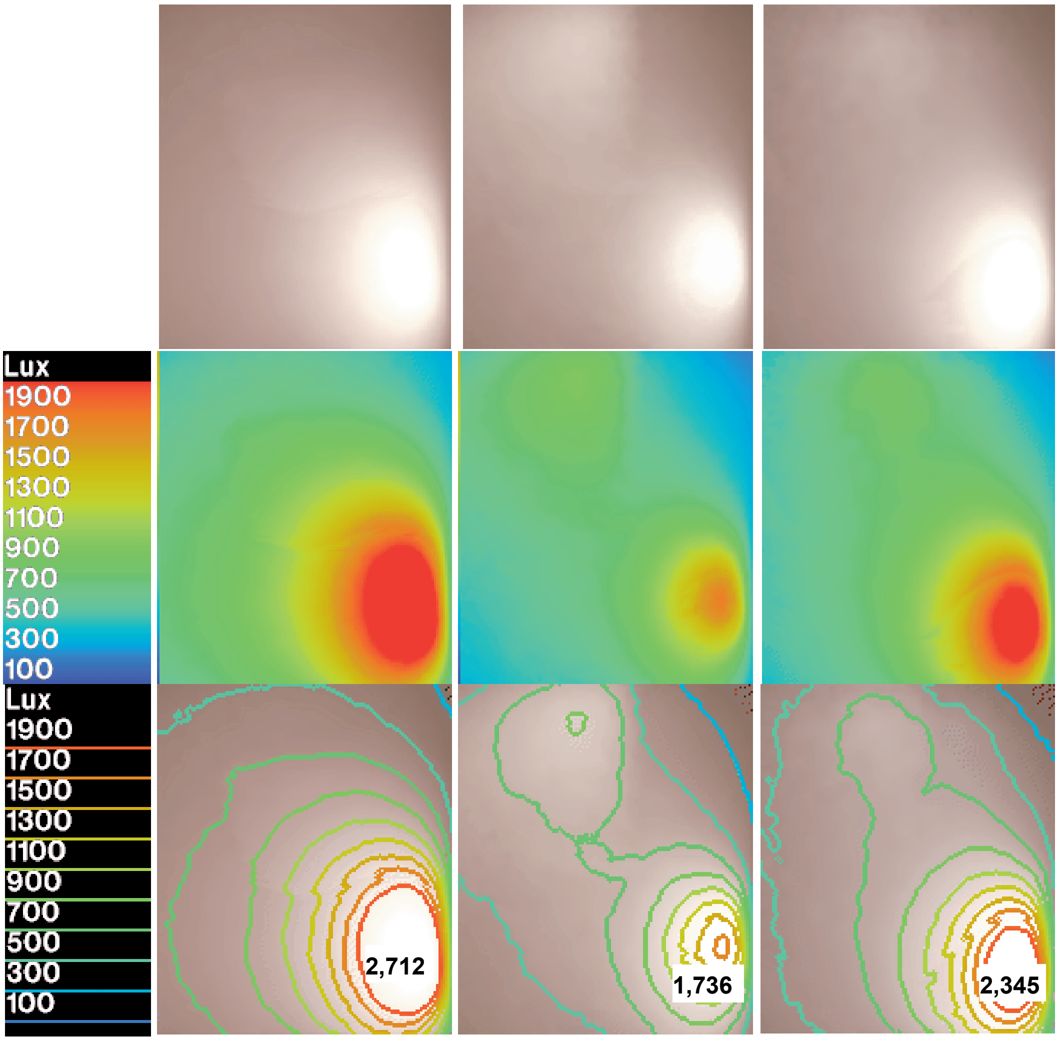
Figure 16. Illuminance distribution on horizontal plane, at 0.7 m above floor level, false colour rendering and iso-lux contours. West facing windows (window at the top of image) under sunny sky conditions in March at 16:00. Note that the peak value is highest under the roof window.

Figure 14 shows that the main reason for the higher illuminance values with the roof window is the fact that the patch of direct sun is often significantly bigger than the patches in the room with the vertical and dormer windows.



	Vertical window	Dormer window	Roof window
○ Q1 25%	629	503	542
△ Min	248	165	183
× Median	800	642	677
▬ Mean	984	670	790
▲ Max	2699	1737	2352
◇ Q3 75 %	1193	768	848

Figure 17. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for the illuminance on a horizontal plane, at 0.7 m above floor level, sunny sky conditions in January at 10:00 hours.



a) Vertical window b) Dormer window c) Roof window

Figure 18. Illuminance distribution on horizontal plane, at 0.7 m above floor level, false colour rendering and iso-lux contours. South facing windows under sunny sky conditions in January at 10:00 hours.

When the sun irradiates the West facing windows, it is at a relatively low solar altitude. The illuminance patterns become different as shown in Figure 15 and Figure 16, and the average illuminance levels are typically higher with the vertical than with the roof window. Note however that in Figure 16 even though the general level is somewhat higher with the vertical window, the peak illuminance is highest under the roof window. The same patterns can be seen early in the morning with the South facing windows, as shown in Figure 18, however at significantly lower levels. In all cases the illuminance levels with the dormer window were lower.

Average daylight factor

Although the daylight factor principally is defined for an overcast sky, it is in the following used to give an impression of the relative illuminance levels for the three window types under sunny sky conditions. Figure 19 and Figure 20 show the "daylight factor" for South oriented windows for each month at 10:00 and 12:00 hours, respectively.

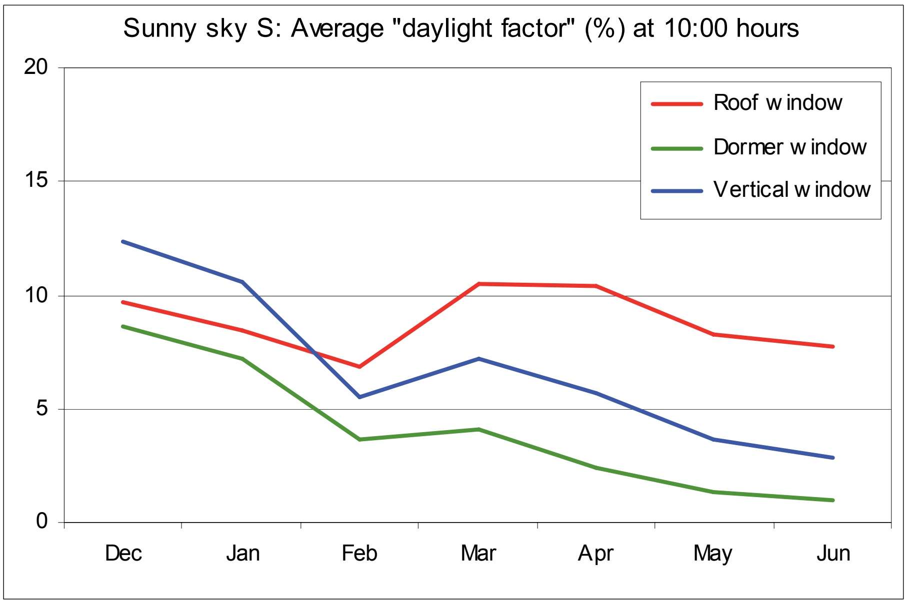


Figure 19. Average daylight factor (%) on a horizontal plane 0.7 m above floor level at 10:00 hours for the months December-June. In the spring and summer months the average illuminance level is significantly higher under the roof window than the level with the vertical window, which again is significantly higher than with the dormer window. In the winter months the level with the vertical window is highest.

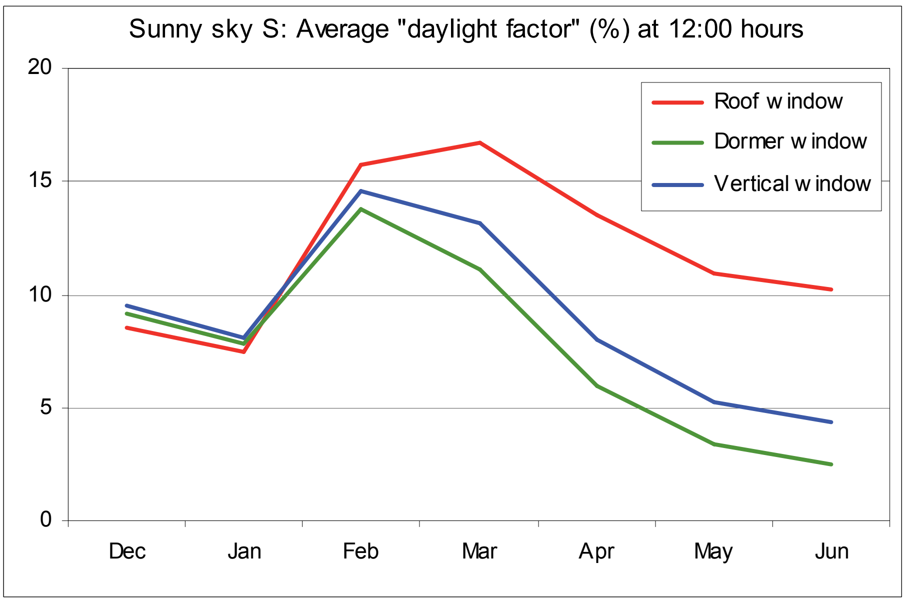


Figure 20. Average daylight factor (%) on a horizontal plane at 0.7 m above floor level at 12:00 hours for the months December-June. In the spring and summer months the average illuminance level is significantly higher under the roof window than the levels with the other two window types.

The *daylight factor* is normally used to evaluate if there, under overcast sky conditions, is sufficient daylight at a given place in the room for a certain visual task. While a high daylight factor in this case is considered to be an indication of a high daylight level and an advantage for most tasks, it is important to notice that the same assumption is not made for a high daylight factor under a sunny sky. The daylight factor should always (also under overcast sky conditions) be considered in combination with an analysis of the light distribution in the room and with a study of the directional part and the diffuse part of the daylight at the spot of the room of interest. Evaluation of the daylight in a room, regarding qualitative aspects, based on the *average daylight factor* is even more difficult. A high average illumination level may be caused by a disturbing bright spot on a surface, or, in the question of the daylight factor, on the work plane. Figure 21 shows for each of the three West facing windows the average daylight factor in the months December-June at 14:00 hours.

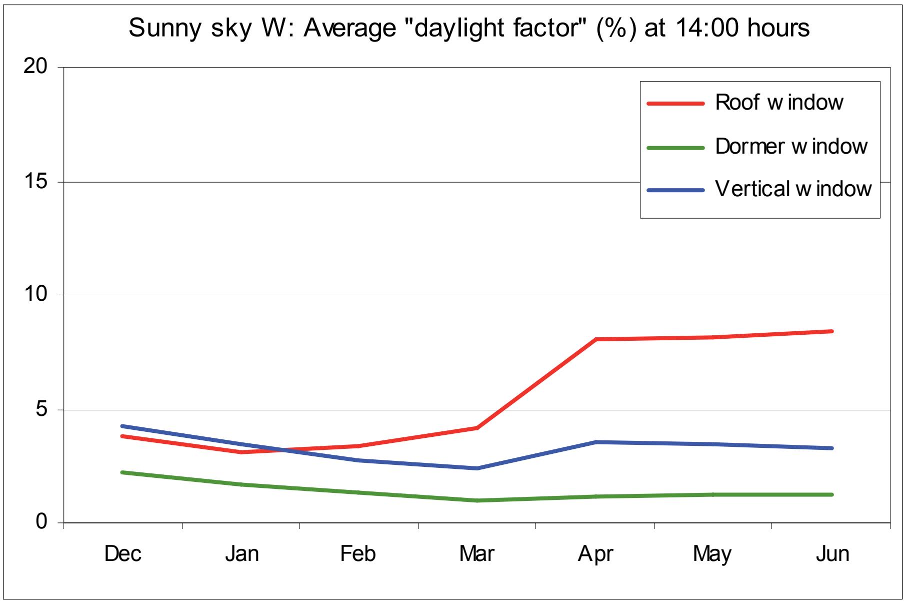


Figure 21. Average daylight factor (%) on a horizontal plane at 0.7 m above floor level at 14:00 hours for the months December-June with West facing windows. In the spring and summer months the average illuminance level is significantly higher under the roof window than the levels with the other two window types.

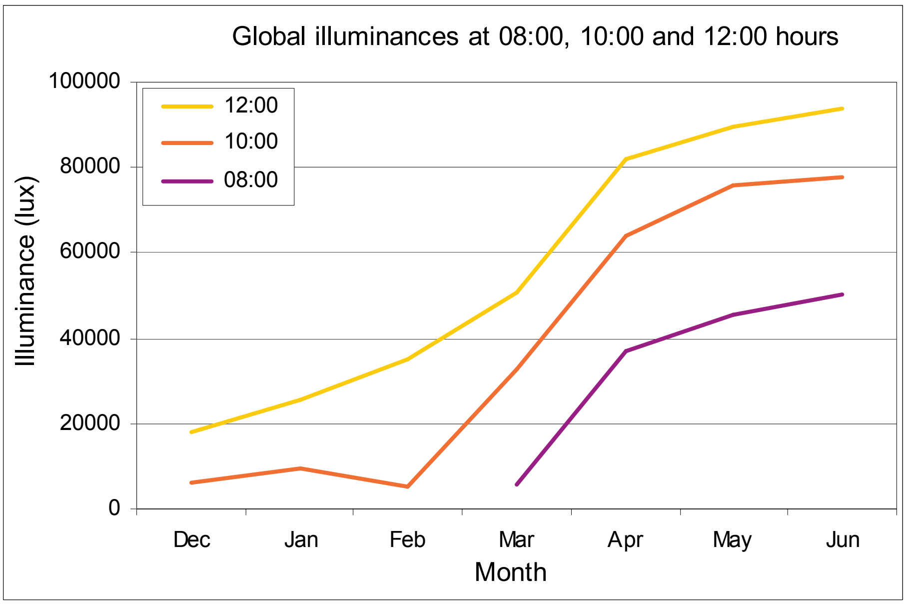


Figure 22. Global illuminance values at 08:00, 10:00 and 12:00 hours for the selected days of the months December-June. The values include the direct component from the sun and the diffuse sky component. The low value for February at 10:00 hours is due to overcast sky for this particular hour.

Figure 22, Table 4 and Figure 23 can be used to get an impression of the general illuminance level in the three rooms for the whole year. Figure 22 shows the global illuminance values for the days chosen in each of the seven months December – June, while Table 4 lists the normal number of minutes and hours of sunshine in each month. It can be seen, for instance, that on a sunny day in December the global illuminance is typically 7,000 – 18,000 lux (from 10:00 –14:00 hours), while in March the global illuminance is typically 20,000 – 50,000 (from 9:00 – 15:00 hours). Table 4 shows that there can be expected 43 hours, respectively 110 hours of sunshine in these months. Figure 23 then shows the cumulated frequency of the global illuminance for all hours in the months December – June. From the calculated daylight factors under overcast sky, intermediate sky, and clear sky, one can get an idea of the illuminance level in each room under these sky conditions.

Table 4. Normal sunshine duration for the Danish weather. (Laursen and Rosenørn, 2003).

Month	Normal, 1961-1990 minutes	Normal, 1961-1990 hours
January	2566	43
February	4159	69
March	6618	110
April	9717	162
May	12511	209
June	12559	209
July	11741	196
August	11146	186
September	7655	128
October	5219	87
November	3269	54
December	2556	43
Year	89716	1495

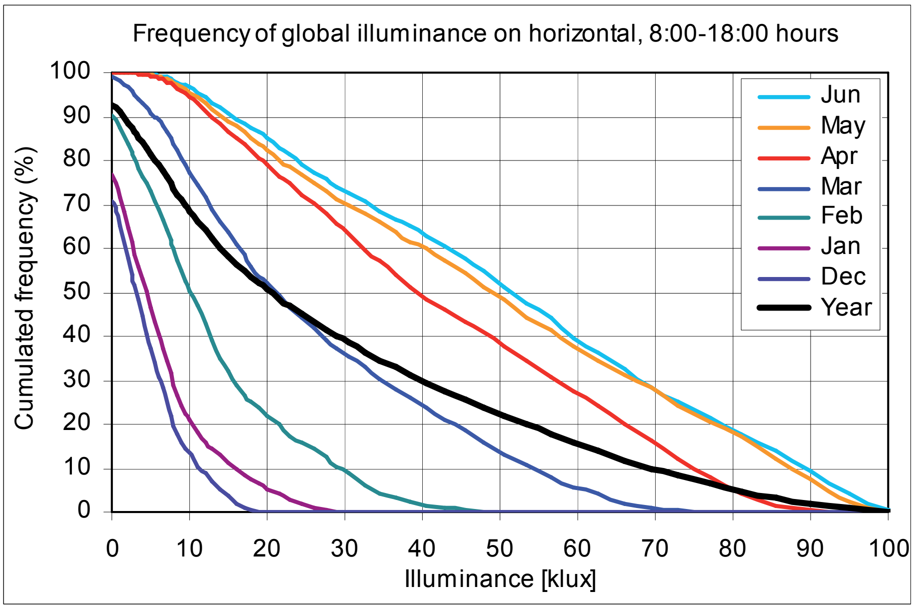
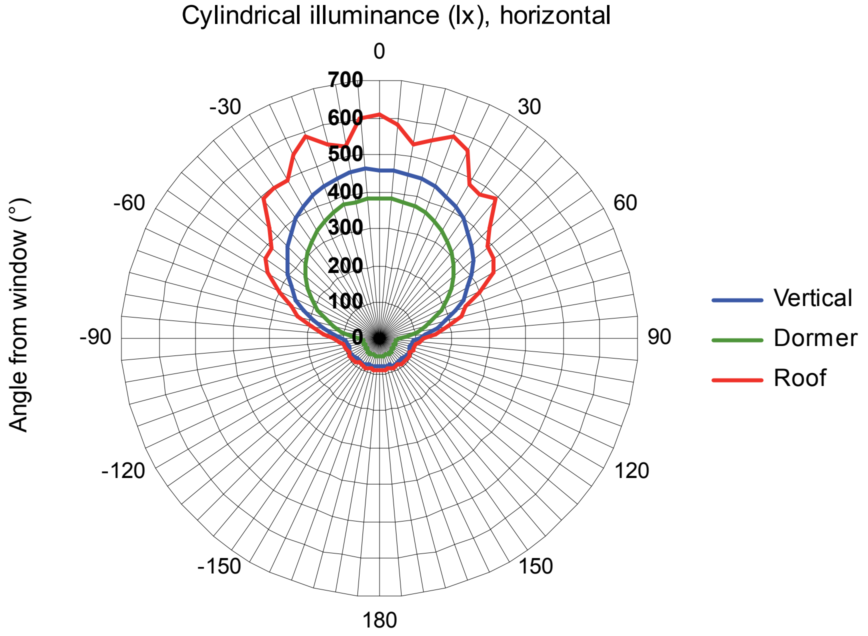


Figure 23. Cumulated frequency of the global illuminance on horizontal for the months December – June within 8:00 – 18:00 hours. The curves show the percentage of hours in each month where the illuminance is above the corresponding value. For example is the illuminance above 30,000 lux in 65 % of the hours in April (66 % of 300 hours, i.e. 195 hours).

Cylindrical illuminance

As a way to analyse the luminous flux in the rooms, the illuminances on a sphere in the centre of the room were calculated for every 5° in horizontal and vertical planes.



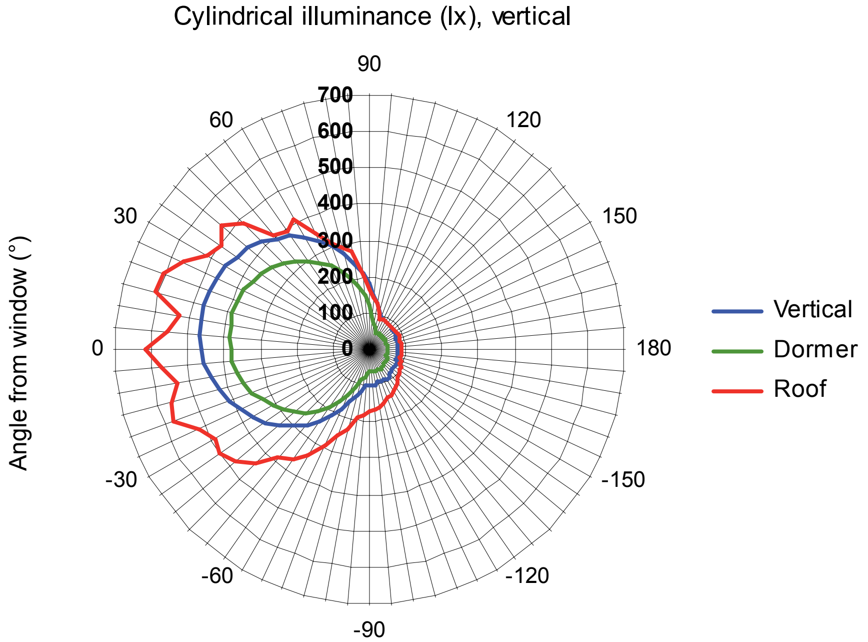


Figure 24. Cylindrical illuminance on horizontal and vertical planes under overcast sky conditions. The graphs show that there are significant differences in the illuminance levels for the three window configurations. The roof window gives significantly higher illuminances in all directions than the two other window types. The ????????????????

Sunny sky conditions

Figure 26, Figure 27 and Figure 28 show for sunny sky conditions the cylindrical illuminances for each of the three windows, i.e. the values on the sphere at the "equator" (the horizontal circle) for 6 months and the hours 06:00 – 21:00. A narrow pattern, like for instance for January and February, just means that there were few hours of direct sunlight in that month. A wide pattern in the angle towards the window means that sunlight penetrates deeply into the room and hits the sidewalls from where it is reflected onto the sphere in the centre of the room. An example of this is shown in Figure 25 with the fish eye rendering for the vertical window in April at 10:00 hours. This situation is also showed in Figure 26 with the red lines, see text of the figure.

Figure 25. Fish eye rendering for the vertical window in April at 10:00 hours.

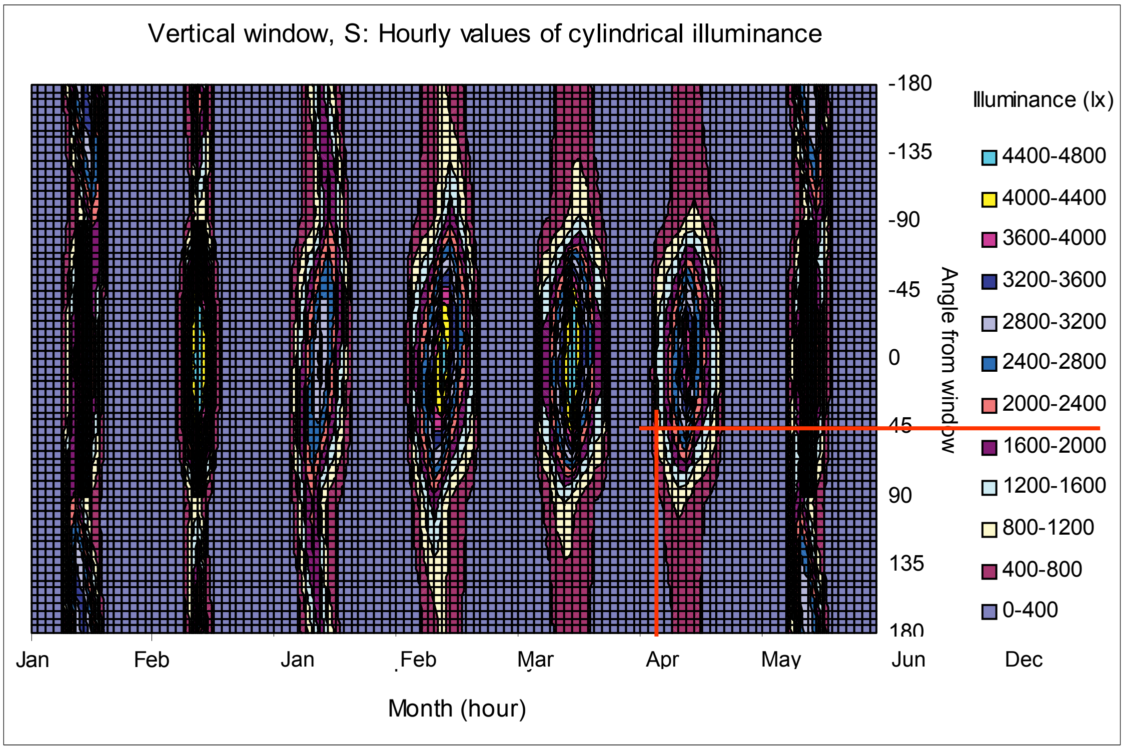


Figure 26. Cylindrical illuminance calculated in the centre of the room with the vertical window. Values are given for seven months and for the hours 06:00 – 21.00. As an example to read the figure, the red lines show that on a sunny day in April at 10:00 hours, the illuminance in the centre of the room on a vertical plane with a horizontal normal pointing 45° to the right from the window will be 3,600 – 4,000 lux. Because of the symmetry for the South oriented window, the same value will occur at 14:00 in the direction 45° to the left (- 45°) from the window.

Comparing the monthly cylindrical illuminance patterns of the three windows showed that the sunlight created a much brighter space under the roof window, especially when compared to the dormer window. Figure 27 shows that patterns of the cylindrical illuminance with the dormer window were quite narrow in the angle towards the window, especially for the summer and spring months. This is also illustrated in Figure 29 and Figure 30 that show the cylindrical illuminances in the morning hours of March and May.

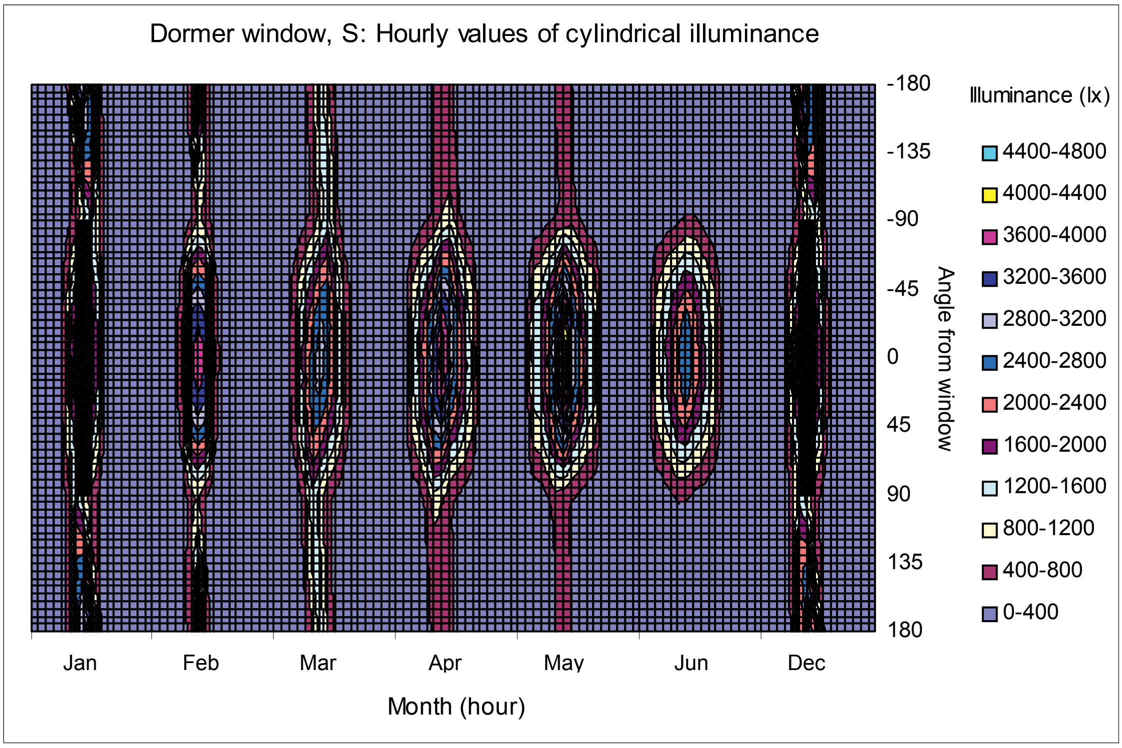


Figure 27. Cylindrical illuminance calculated in the centre of the room with the dormer window. Values are given for seven months and for the hours 06:00 – 21.00.

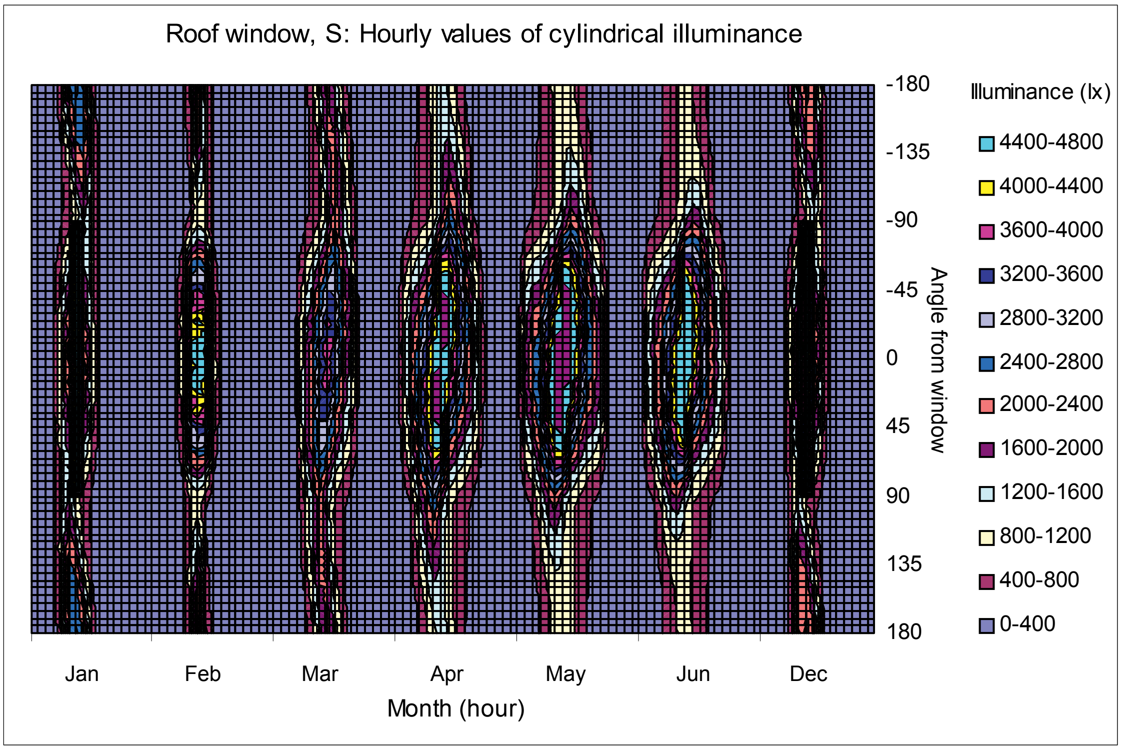
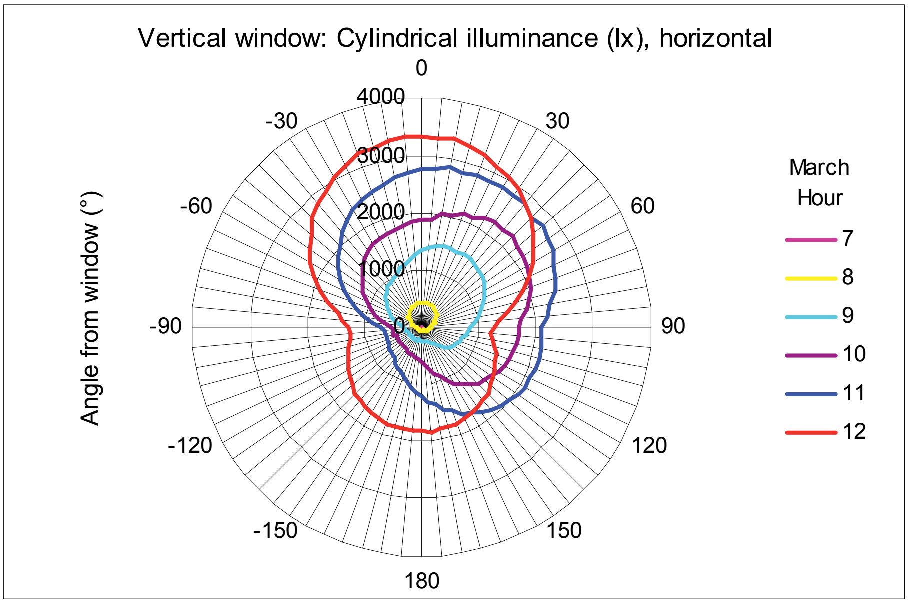
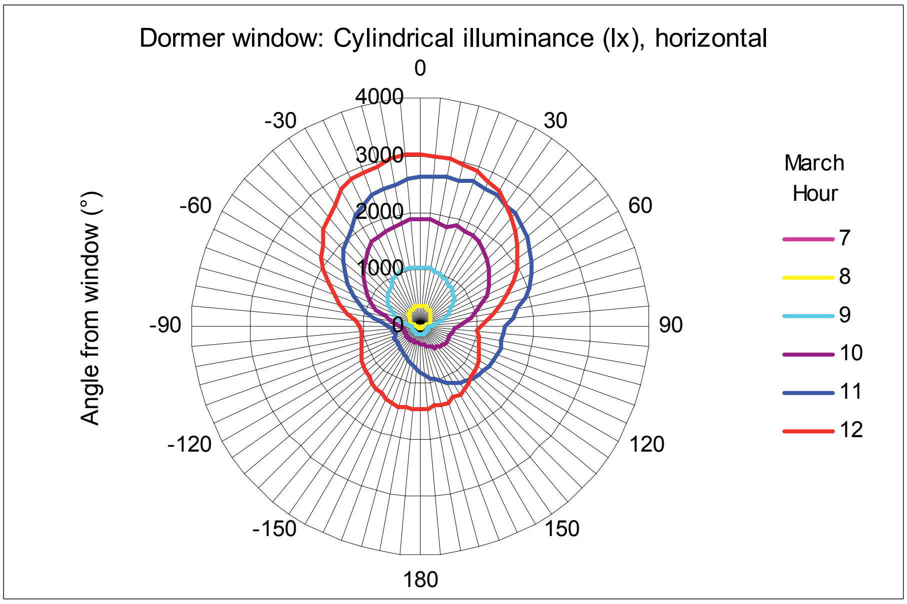


Figure 28. Cylindrical illuminance calculated in the centre of the room with the roof window. Values are given for seven months and for the hours 06:00 – 21.00.

Figure 29 and Figure 30 show the differences in the cylindrical illuminances in the morning hours of March and May for the three windows. It is obvious that the sphere (or a person) at the centre of the room received much more light with the roof window from all angles of the room. Also, it can be seen that the dormer window provided the lowest illuminance in all directions.





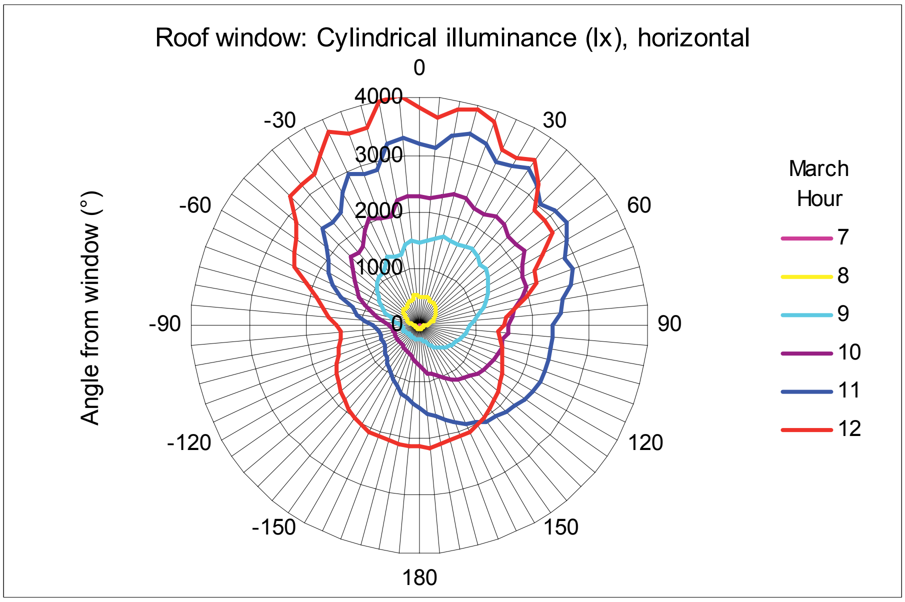


Figure 29. Cylindrical illuminances, horizontal circle, in the morning hours of March for the three windows.

In March, the typical ratio (maximum) of the illuminances for the roof, the vertical and the dormer window were 4,000 : 3,300 : 3,000 lx , while in May these ratios were 8,000 : 6,000 : 5,000 lx.

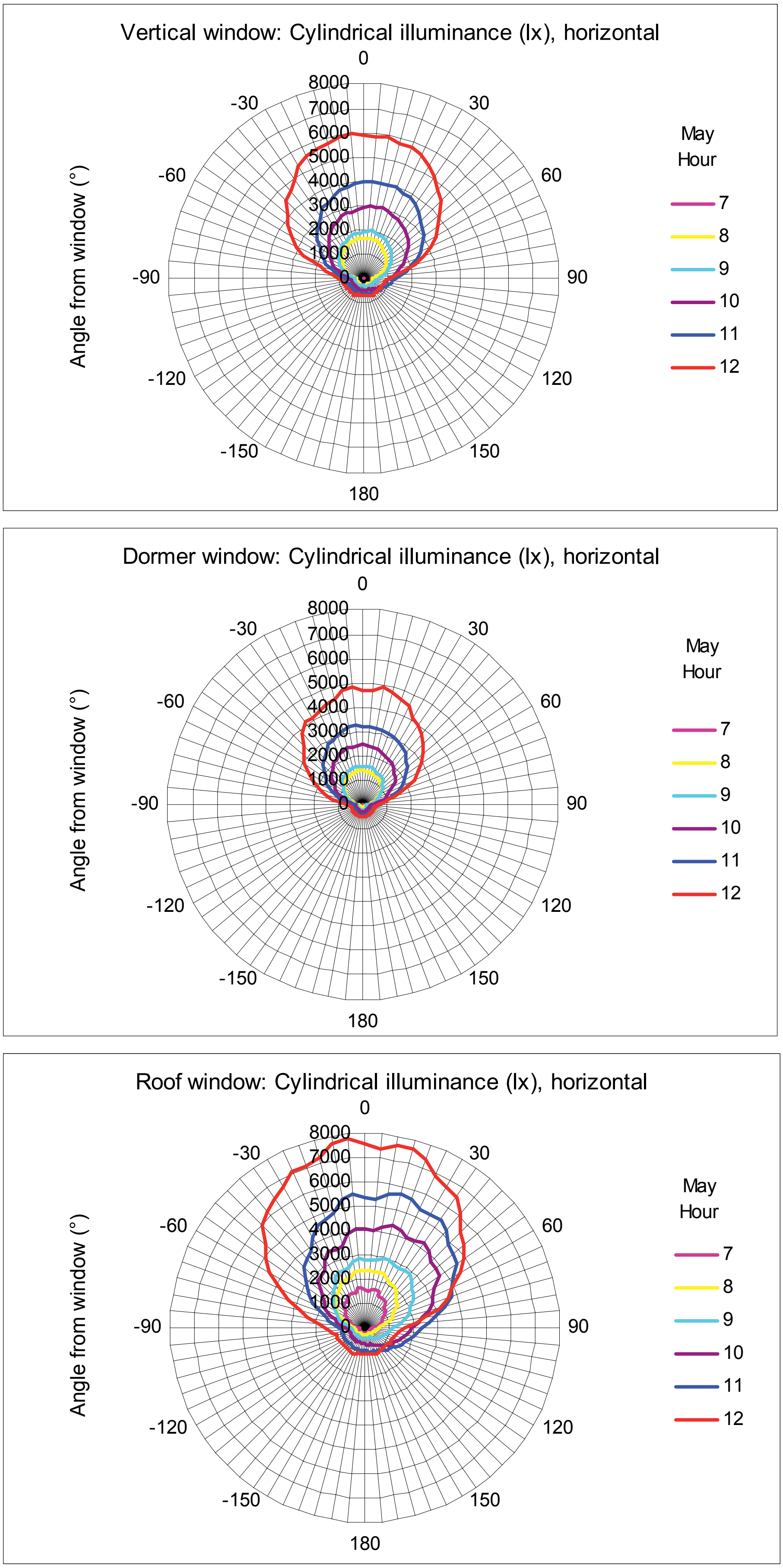


Figure 30. Cylindrical illuminances, horizontal circle, in the morning for May and for the three windows

Vertical-to-horizontal illuminance

From the calculated values on the sphere at the centre of the room, the absolute illuminance values were computed in all directions in order to establish the cubic illuminance or the three dimensional illuminance. One pair of interest in the evaluation of potential glare problems is the vertical to the horizontal illuminance. Normal recommendations are that the vertical to horizontal illuminance ratio should not exceed 2-3 (lit.). Table 5 shows the illuminance values in all directions from a cube placed at the centre of the room as well as the calculated vertical to horizontal ratio of illuminances for the three window types.

Table 5. Illuminances on cube at centre of room, overcast sky conditions.

Side of cube	Vertical window	Dormer window	Roof window
Left	106	57	124
Back	76	50	85
Right	106	57	129
Window	460	379	581
Up	178	119	172
Down	97	59	172
Average, all directions	171	120	210
Vertical to horizontal ratio	2,58	3,20	3,38

The table shows that there were significant differences in the illuminance levels with the three windows, indicated by the average values, 120, 171 and 210 lux, for the dormer, the vertical and the roof window, respectively. At the centre of the room, the vertical to horizontal ratio was 3.38 under the roof window, 3.20 with the dormer window, and 2.58 with the vertical window. This shows that even though the roof window gave high illuminances on horizontal plane near the window, the recommended value of 2-3 is exceeded in the back half of the room.

Sunny sky conditions

Figure 31 shows the illuminances for the three windows in the view towards the window (win) and the view towards the ceiling (up) under sunny sky conditions. The figure shows all (relevant) hourly values for all months studied. The illuminance at the plane of the viewer's eye has shown good correlation with the sensation of glare in several studies (Velds, 2000, etc.). However, the sensation of glare is not merely a question of absolute illuminance (or luminance) but involves other aspects of the luminous environment, such as distance to the glare source, background luminance and more. The vertical to horizontal luminance ratio, which has also been used to assess the quality of the visual field, in a very simple way, incorporates some of these aspects.

Figure 31 shows that the illuminances in the window direction were always highest for the roof window, except for hours when there was direct sunlight on the sphere (values at noon in October - February). Illuminances in the direction towards the window above 5,000 lux may not in itself be a problem, but when the horizontal illuminance is only around 2,000 lux, it will most likely cause glare sensation.

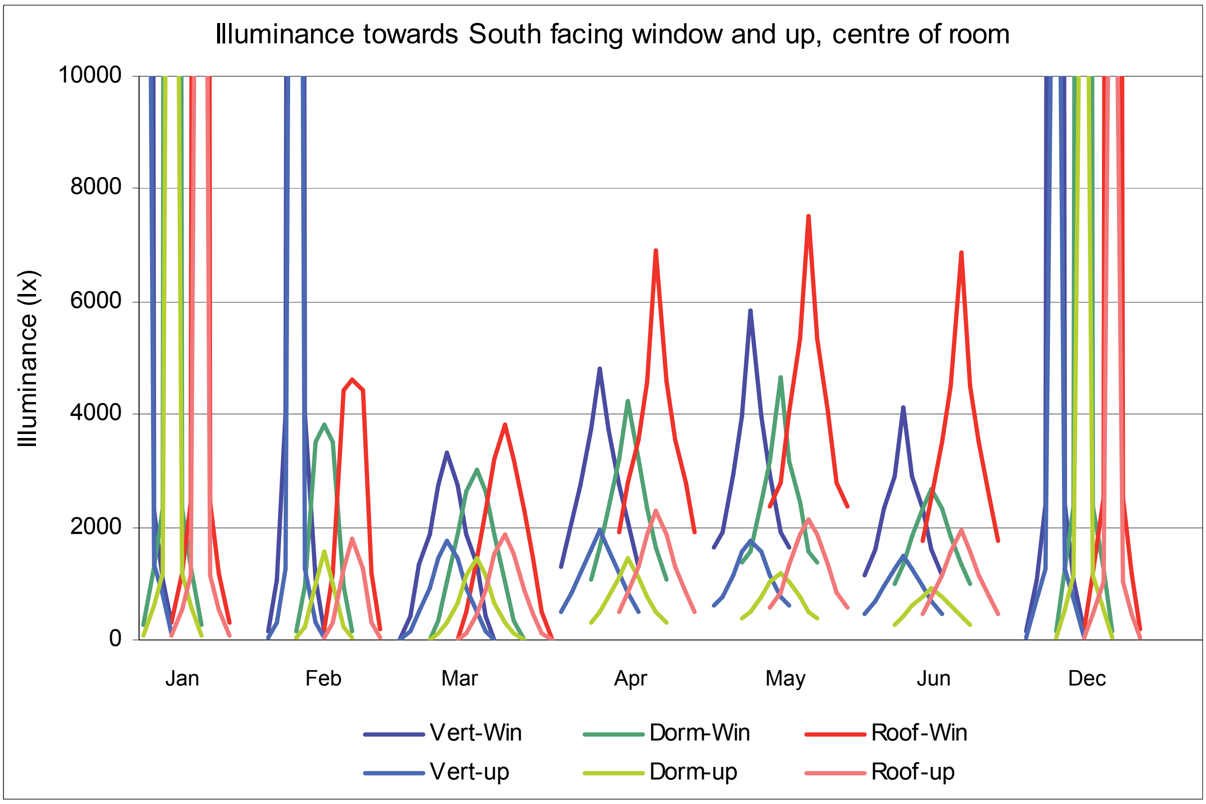


Figure 31. Illuminance in the direction towards the window (win) and towards the ceiling (up) for the three windows and for all (relevant) hours. Each graph represents the hours from sunrise to sunset (within 6:00 - 21:00 hours) for each month. In January and December there is direct sun on the sphere with all windows, while this is also the case for the vertical window in February (and its "symmetrical" month, October).

Figure 32 shows the calculated ratios for the three South oriented windows and for the first six months of the year, while Figure 33 shows the ratio for the West oriented windows. The figures show that the roof and dormer windows exceeded the recommended limit for many hours of the year. It should be noted, however, that the ratio has no meaning in the case of direct sunlight in the reference points.

Figure 31 shows, for instance, that there was direct sun with all three windows in January, while in February this was only the case for the vertical window.

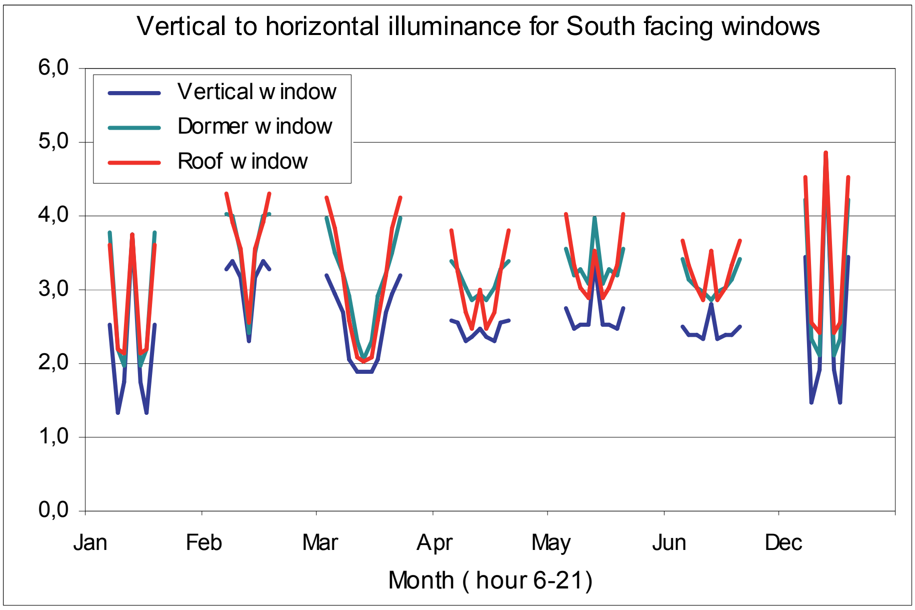


Figure 32. The vertical to horizontal illuminance ratio for windows facing South. The ratio was about the same for the dormer window and the roof window, while it was generally lower for the vertical window.

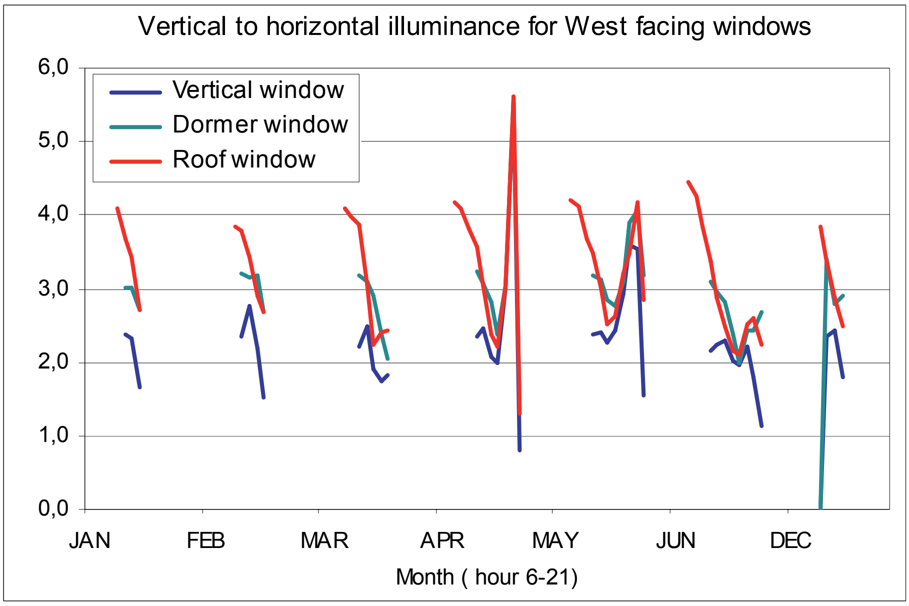


Figure 33. The vertical to horizontal illuminance ratio for windows facing West. The ratio was about the same for the dormer window and the roof window, while it was generally lower for the vertical window. The significant difference for the vertical window in the winter months was irrelevant, since there was direct sunlight on the cube in these cases.

Luminance distribution

Renderings of the room were produced for each month and hour studied. Half of the renderings showed half of the room towards the window wall, and half of the renderings showed the other half of the room (towards the back or north wall). Both renderings are complementary and contained 100 % of the luminance points in the room. The first series of images showed a view mimicking human vision (using the pcond program[3] included in Radiance) while the second series presented a false colour rendering where the luminance of each pixel is replaced by a colour corresponding to a luminance value (in Nits, 1 nit = 1 cd/m^2).

Overcast sky conditions

Under overcast sky conditions, the luminance of the floor, walls and ceiling was higher with the roof window than with the other two windows, see Figure 34. In contrast, the main inner surfaces of the rooms were significantly darker with the dormer window, even compared with the vertical window. This is also indicated by Figure 35 - Figure 37, which gathers minimum, maximum, mean, median and interquartile range values of luminances for all surfaces in the view towards the window wall.

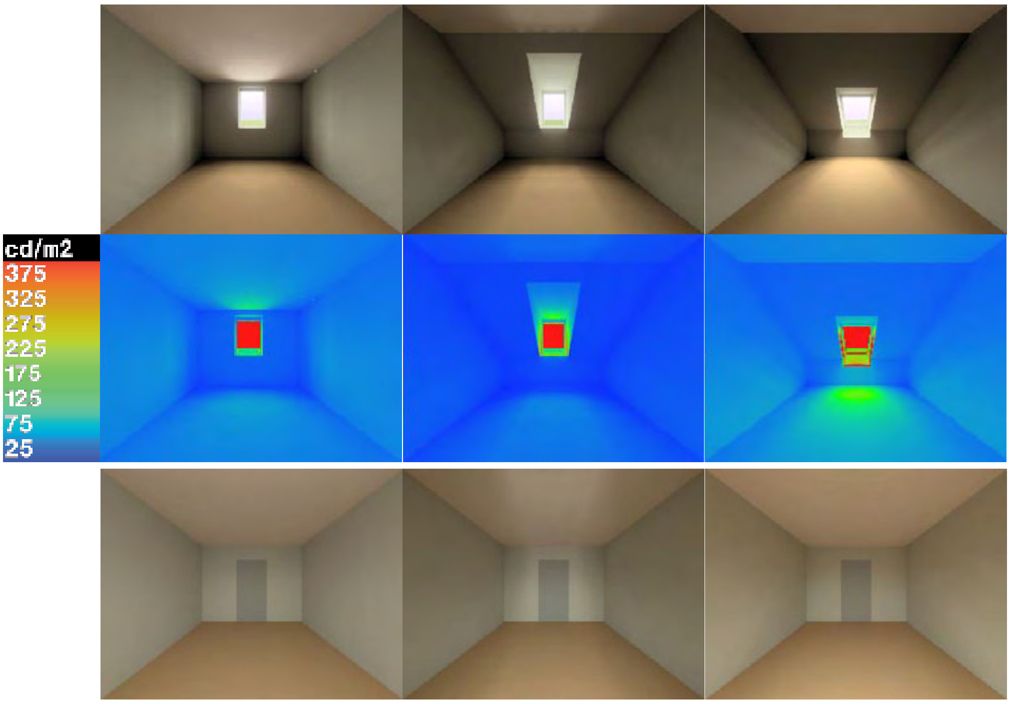


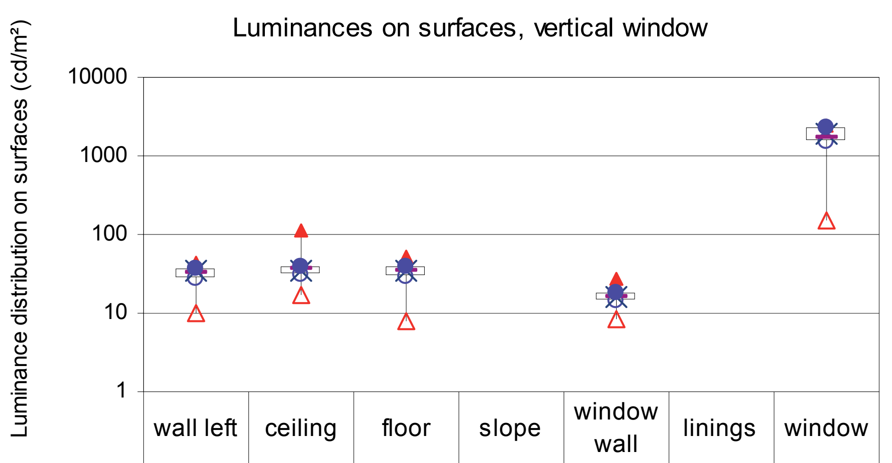
Figure 34. Pcond and false colour renderings. First and third row show the renderings (mimicking the human vision) of the view towards the window wall and towards the back wall, respectively. The second row shows the false colour renderings of the view towards the window wall. Overcast sky conditions.

[3] The pcond program provides powerful tools for easy manipulation of Radiance's map of spectral radiance into a displayed image that causes a response in the viewer that closely matches the response a viewer of the real-world equivalent environment might experience. Pcond uses a variety of mathematical techniques to determine an appropriate exposure and simulate loss of acuity and veiling glare, loss of focus, and loss of colour sensitivity.

Figure 35 - Figure 37 show that the mean luminance ratios between the window wall and the window are 16:1908, 8:1908 and 28:1883, corresponding to 1:119, 1:238 and 1:67, for the vertical, dormer and roof windows, respectively. This gives significant differences in contrast and a greater risk of a sensation of glare from the dormer window and the vertical window than from the roof window. The linings surrounding the dormer and roof windows were rather bright, and might contribute to make the high window luminance more acceptable than was the case of the vertical window. While the luminance ratio between the linings and the window surfaces was more favourable in the case of the roof window than in the case of the dormer window (1:10 and 1:37 respectively), it should be noted that the area of the linings was larger in the case of the dormer window and therefore may provide an equally good luminance transition from the high sky luminance to the luminance of the main inner surfaces.

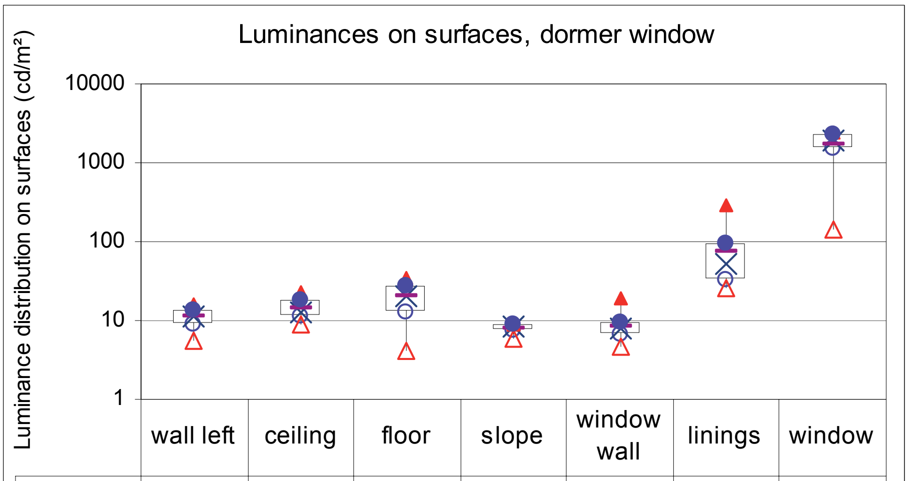
In general, all surfaces had a wider range of luminance values for the dormer window (Figure 36) and roof windows (Figure 37) compared with the vertical window where the interquartile range boxes (comprising 50 % of all values) was rather narrow (Figure 35). This indicated that the luminance field was more balanced in the cases of the dormer and roof windows than in the case of the vertical window.

As a whole, the luminance ratio between the window, window linings and adjacent walls was preferable for the roof window compared with the dormer window. Figure 38 shows the average luminance of surfaces located within a band of 40º about the eye height (for a sitting person). Loe, Mansfield & Rowlands (1994) showed that the field of luminance within a 40º band about the eye height is the most important to consider for visual comfort. The figure clearly shows that the roof window provided higher wall luminance and softer luminance transitions from the window to the wall area compared with the other cases.



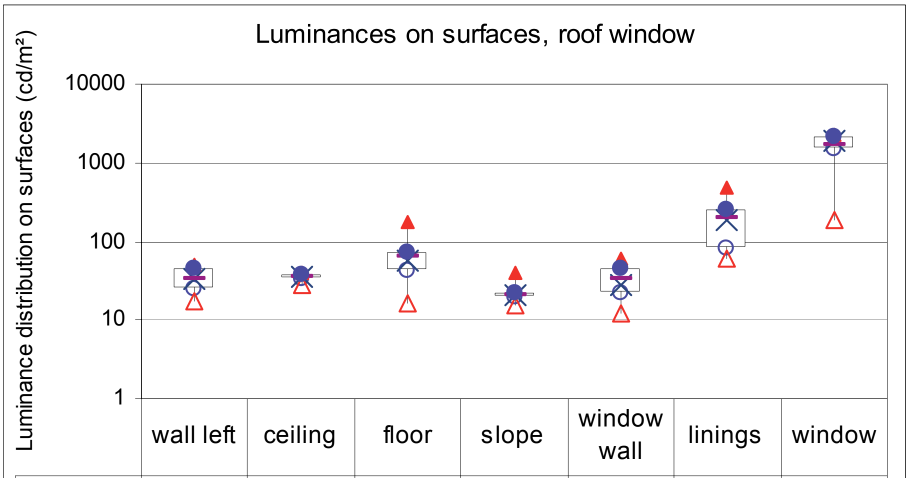
	wall left	ceiling	floor	slope	window wall	linings	window
○ q1	27	31	29		14		1482
△ min	10	17	8		8		154
× median	34	35	35		16		1908
– mean	32	38	34		16		1745
▲ max	43	112	53		27		2409
● q3	37	39	39		18		2225

Figure 35. Vertical window. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for luminances (cd/m^2) of surfaces in the view towards the window wall, under overcast conditions.



	wall left	ceiling	floor	slope	window wall	linings	window
○ q1	9	11	13	8	7	33	1482
△ min	6	9	4	6	5	25	144
× median	11	13	21	8	8	52	1908
▬ mean	11	15	20	8	8	76	1745
▲ max	16	23	35	9	19	291	2409
● q3	14	18	28	9	9	95	2225

Figure 36. Dormer window. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for luminances (cd/m²) of surfaces in the view towards the window wall, under overcast conditions



	wall left	ceiling	floor	slope	window wall	linings	window
○ q1	24	32	42	19	22	81	1513
△ min	17	27	16	16	12	60	190
× median	32	36	57	21	28	188	1883
▬ mean	34	35	63	21	33	192	1726
▲ max	51	40	179	41	62	478	2300
● q3	45	38	74	22	45	252	2114

Figure 37. Roof window. Minimum, maximum, median, mean and interquartile range (Q1, Q3) for luminances (cd/m²) of surfaces in the view towards the window wall, under overcast conditions.

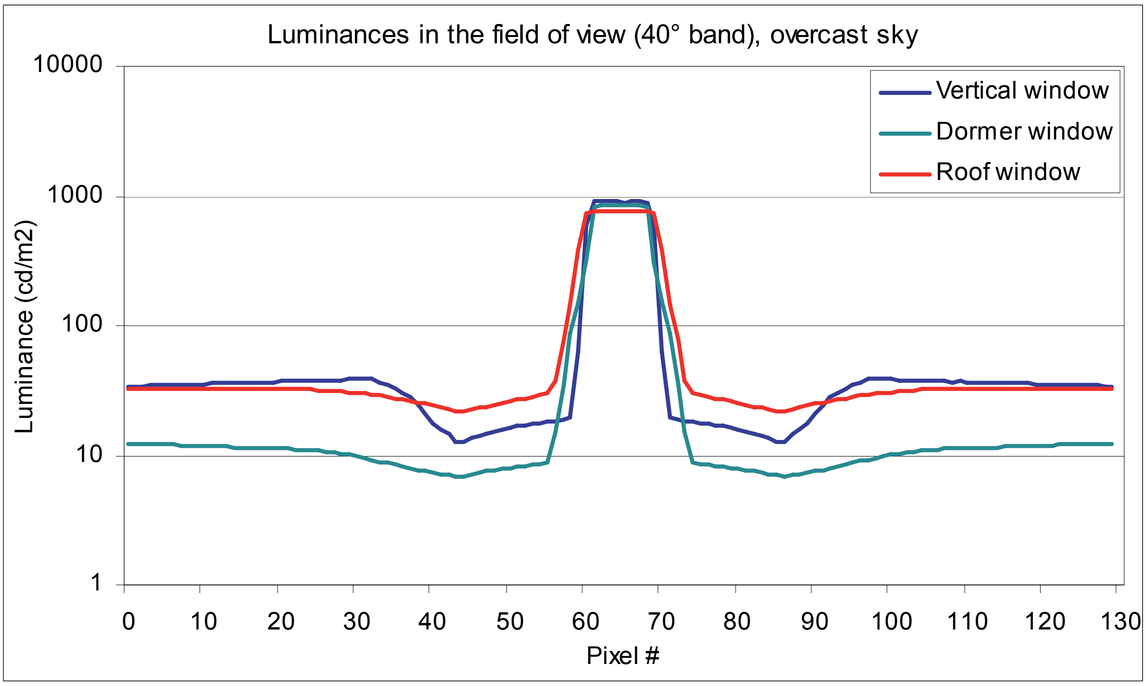


Figure 38. Average luminance within a 40° band centred around the observer's eye looking straight ahead towards the window under overcast sky conditions. The roof window provides higher wall luminance and softer luminance transitions from the window to the wall area compared with the other windows.

Sunny sky conditions

Preliminary studies of sun-patches on room surfaces

A preliminary analysis of months and hours over the year that might be of interest in the evaluation of luminance distribution, glare indicators, and the need for a solar shading device was carried out. A quick series of Radiance simulations were made to reveal the patterns of direct sun on the room surfaces, shown by examples in Figure 39. The times for which a direct sunlight patch appeared on at least one room surface were analysed while all other times were discarded in this study. The size and average luminance of the sun patch on each surface was calculated as part of the analyses.

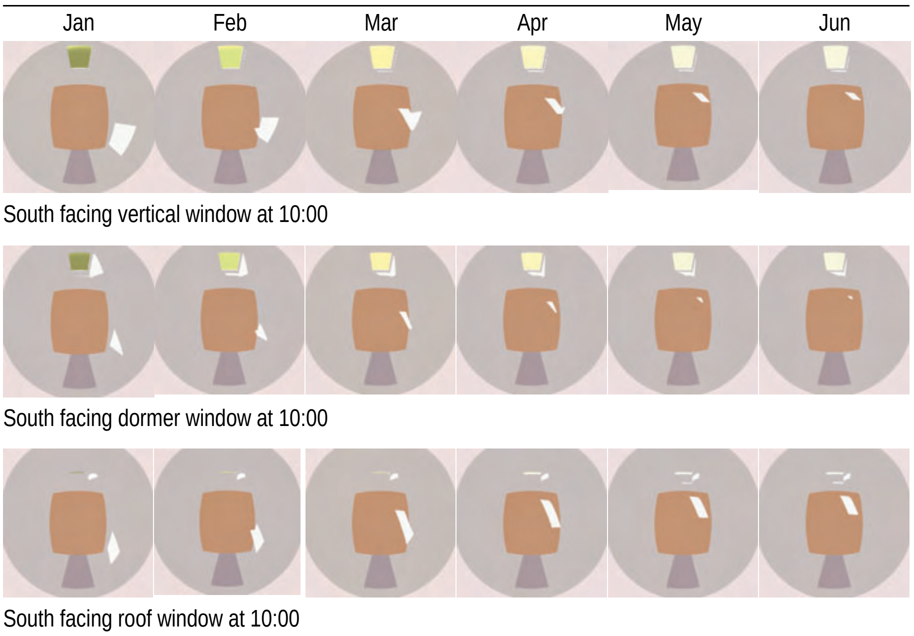
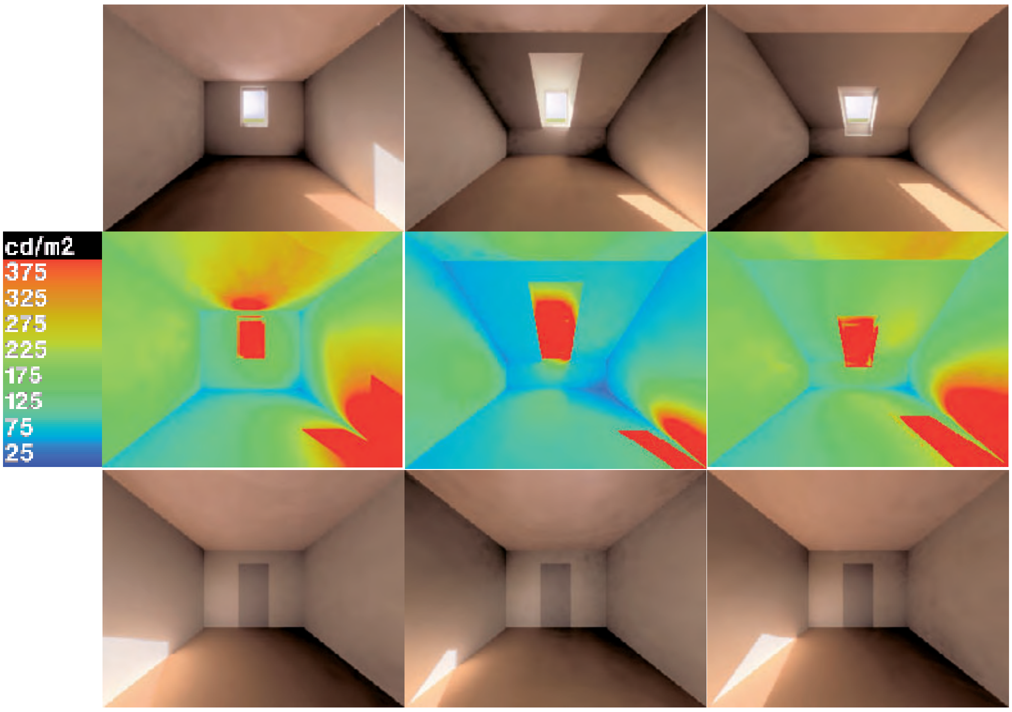


Figure 39. Fish-eye view (quick rendering) showing the whole room from above looking down (window at the top of each image) and the sunlight patch patterns for window, January – June at 10:00 hours.

Example days with sunny sky conditions

The following pages give examples of the differences in daylight conditions in each of the three rooms on a day with sunny sky conditions. The daylight conditions are presented by a pcond rendering for the view towards the window, a false colour rendering of the same view, a rendering towards the back of the room and the cumulative frequency distribution of luminances for each room on that day.



a) Vertical window b) Dormer window c) Roof window

Figure 40. Luminance distribution under sunny sky in March, 10:00. With the vertical window a major part of the sunlight patch fell on the sidewall. For the dormer window the corresponding part of the direct sunlight was on the window linings, while for the roof window the sunlight patch was almost entirely on the floor.

Because of the higher reflectance of the walls compared with that of the floor, the general lighting level was higher when the sunlight patch fell on the wall than when it was on the floor, as can be seen in Figure 41.

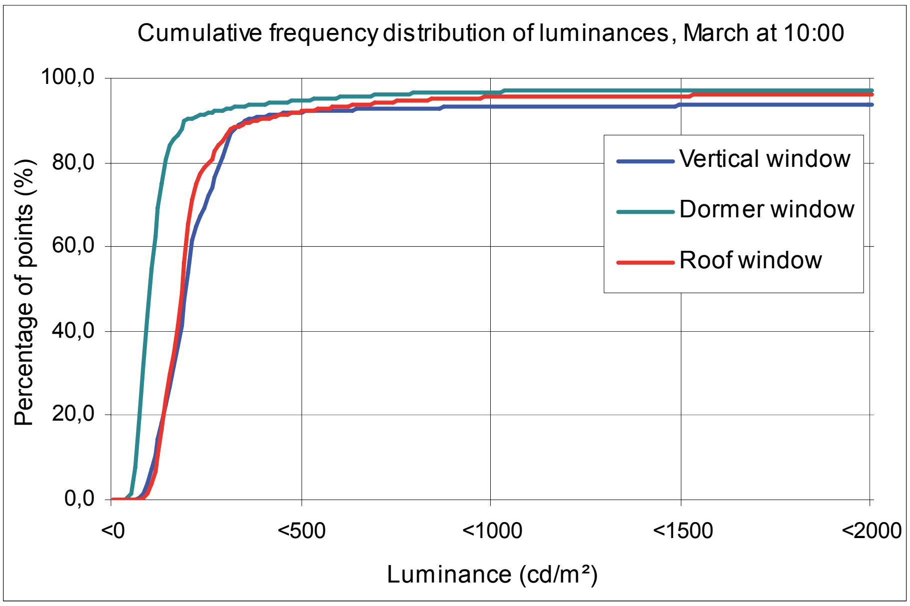


Figure 41. Cumulative frequency distribution of the luminance (cd/m²) in the view towards the window. With the vertical window the sunlight patch was on the sidewall, while is was mainly on the floor with the roof light. Therefore the general luminance level was higher with the vertical window.

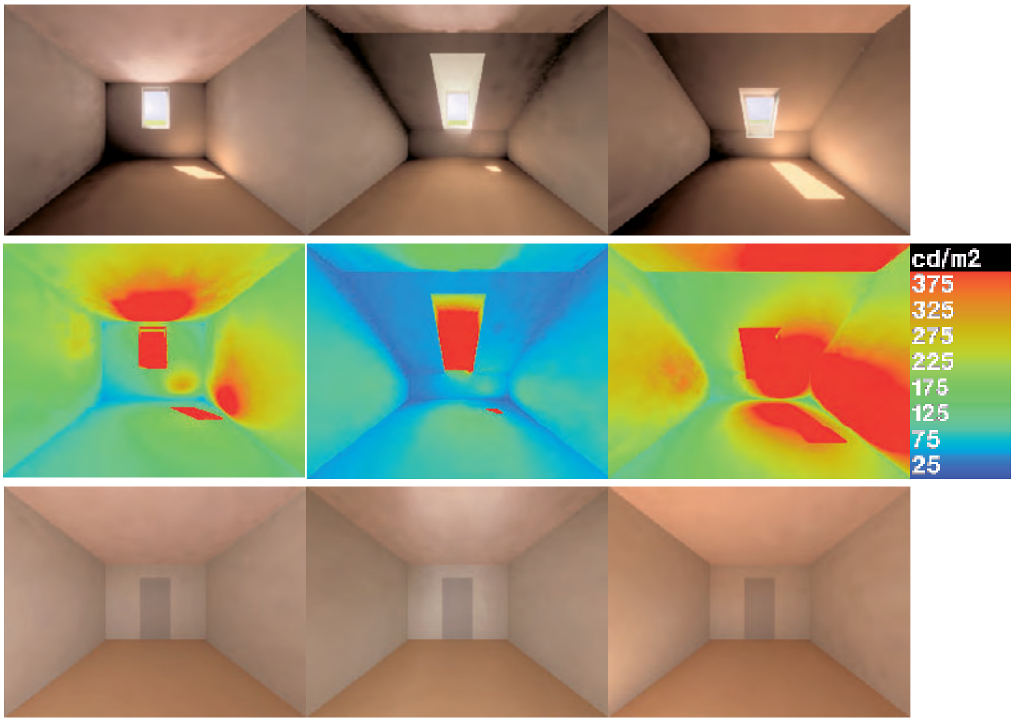


Figure 42. Solar and luminance distribution in June at 10:00 hours. The first and third rows show the renderings (mimicking the human vision) of the view towards the window wall and towards the back wall. The third row shows the false colour rendering of the view towards the window wall.

At times when the sunlight patch fell on the floor with all three window types the general lighting level was significantly higher under the roof window, see Figure 43 and Figure 44.

Figure 42 and Figure 43, as well as Figure 44 and Figure 45, clearly show that the roof window resulted in the brightest room, while the dormer window gave the darkest room, as also shown previously in the analysis of the illuminances on a horizontal plane.

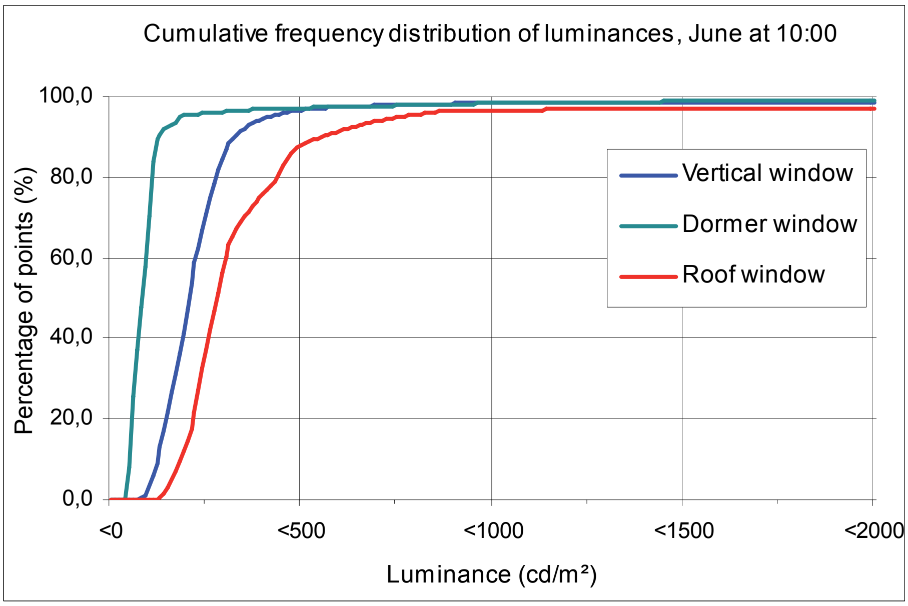


Figure 43. Cumulative frequency distribution of the luminance (cd/m^2) for the three window types in the view towards the window under sunny sky in June at 10:00 hours.

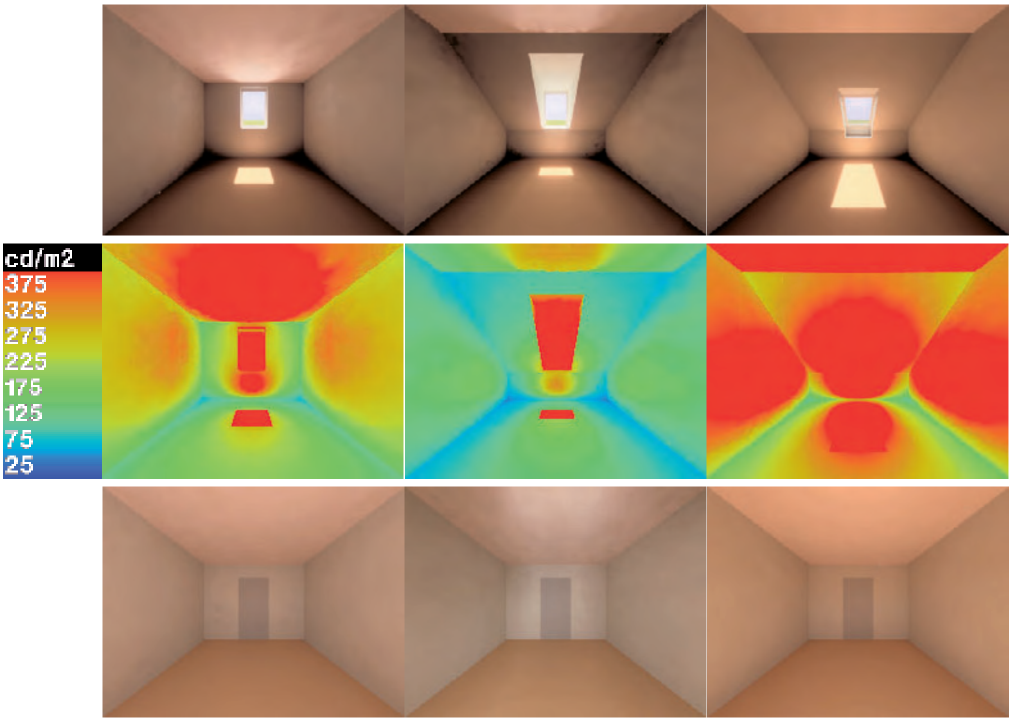


Figure 44. Luminance distribution in May at 12:00 hours. The first and third rows show the renderings (mimicking the human vision) of the view towards the window wall and towards the back wall. The third row shows the false colour rendering of the view towards the window wall.

Figure 44 and Figure 45 show the luminance distributions in May at noon. As for June at 12:00 hours, the roof window gave significantly higher luminance levels than the vertical window, which again provided significantly higher luminance levels than the dormer window.

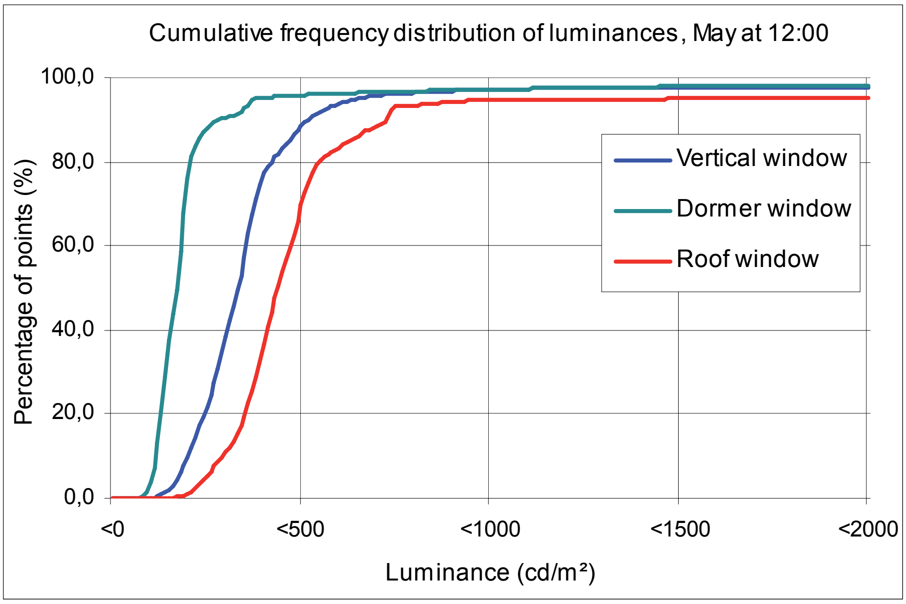


Figure 45. Cumulative frequency distribution of the luminance (cd/m²) for the three window types in the view towards the window under sunny sky in May at 12:00 hours.

Variation in cumulative frequency distribution of luminances

Figure 46 - Figure 51 show the cumulative frequency distribution of the luminances in the view towards the window for different months and different hours. The figures give indications of the relative brightness of the room at all hours of the year.

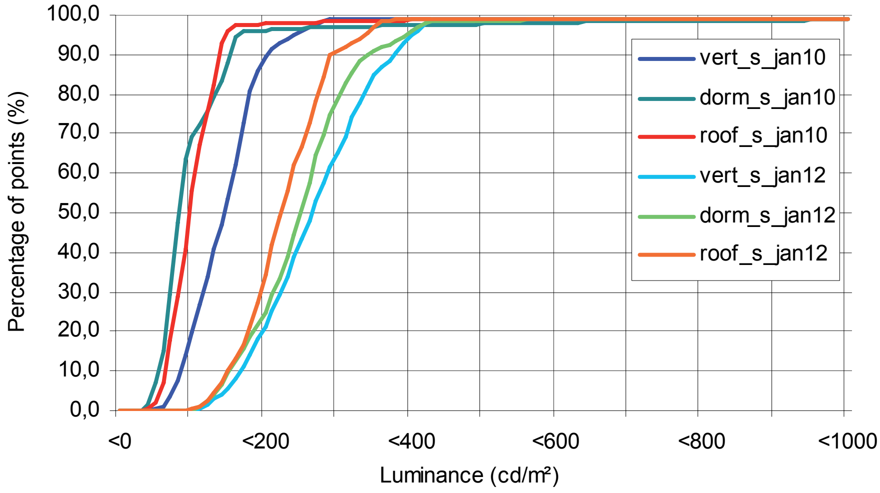


Figure 46. Cumulative frequency distribution of luminances in the view towards the window, South orientation, sunny day in January at 10:00 and 12:00 hours.

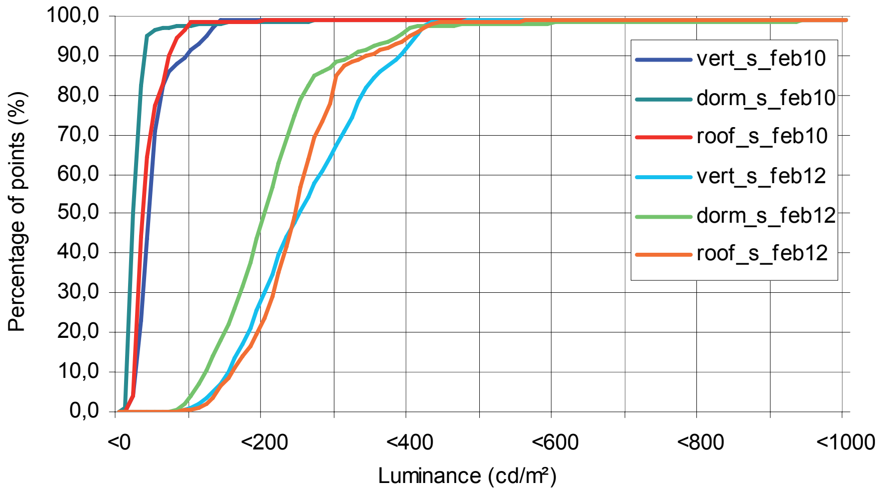


Figure 47. Cumulative frequency distribution of the luminances in the view towards the window, South orientation, sunny day in February at 10:00 and 12:00 hours.

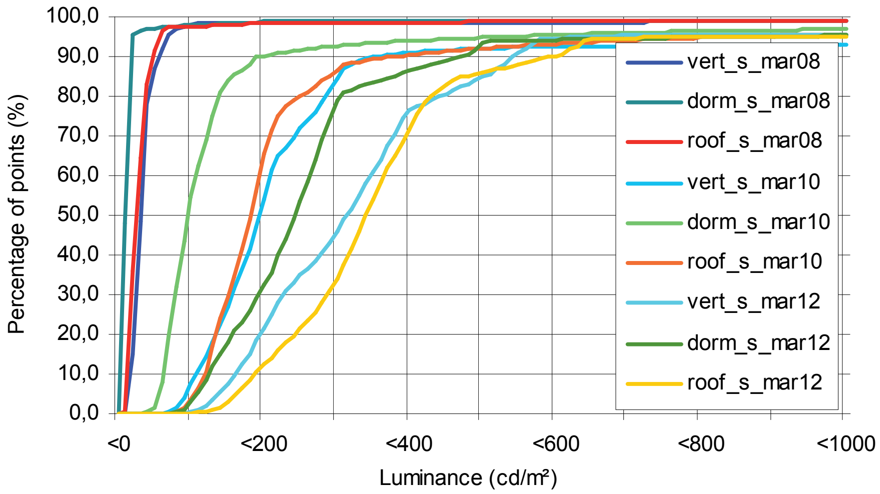


Figure 48. Cumulative frequency distribution of the luminances in the view towards the window, South orientation, sunny day in March at 8:00, 10:00 and 12:00 hours.

The figures clearly show that the dormer window results in the lowest luminance levels in almost all cases. The roof window provides much higher luminance levels at high sun positions, while the vertical window gives slightly higher levels at low sun positions.

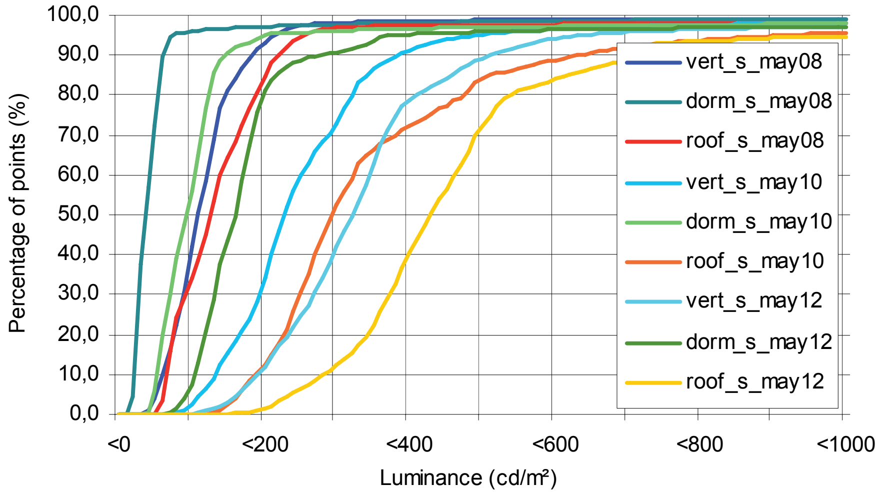


Figure 49. Cumulative frequency distribution of the luminances in the view towards the window, South orientation, sunny day in May at 8:00, 10:00 and 12:00 hours.

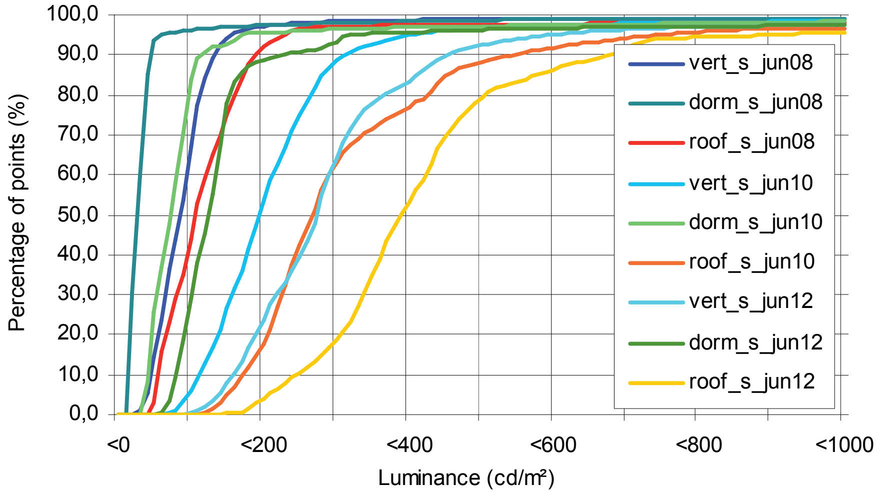


Figure 50. Cumulative frequency distribution of the luminances in the view towards the window, South orientation, sunny day in June at 8:00, 10:00 and 12:00 hours.

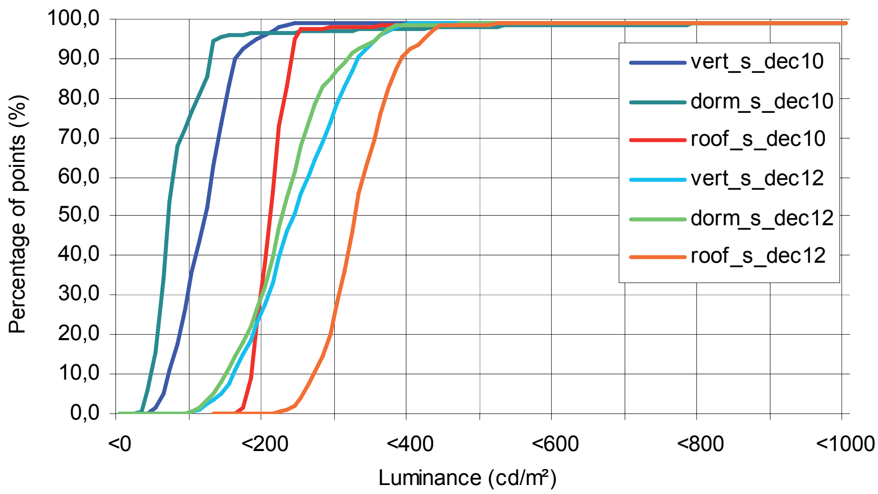


Figure 51. Cumulative frequency distribution of the luminances in the view towards the window, South orientation, sunny day in December at 10:00 and 12:00 hours.

Luminances in the field of view

The renderings for sunny conditions showed that the dormer window resulted in a generally darker interior, which can be seen from Figure 46 - Figure 51. The difference between the three cases was largest in the summer and for hours of high solar altitude, see for example Figure 49 for May and Figure 50 for June. An important difference between the three cases was that the sunlight patch penetrated deeper into the room with the roof window and there was therefore more light in the back of the room in that case. Table 6 shows the luminance values for the view towards the window (South orientation, seen from the centre of the room) for seven months and the hours 8, 10 and 12 (where relevant). Depending on the transition between the brightest sunlight patches and the surroundings, luminances above 1,000 cd/m^2 or even lower may cause glare problems. Values above 2,000 cd/m^2 will most likely cause glare in any case. Table 6 shows that there were significant areas of luminances above 2,000 cd/m^2 for all three windows from 10:00 - 14:00 hours in the months March - September. Around noon there were about 1 % of all values above 10,000 cd/m^2 in the winter, October-February. In March and September 4-5 % of the field of view had luminances above 5,000 cd/m², while in April and August 3-5 % of the view had luminances above 10,000 cd/m². In the summer months, May-July, the highest luminances occurred with the roof window, 3-4 % of the view above 10,000 cd/m². These high luminance values will certainly cause glare and it would be essential, in these cases, to provide a shading device.

Table 6. Percentage of the view with values over a given luminance (cd/m^2) for the view towards the window wall for seven months and hours 8, 10 and 12 (where relevant). Each square gives the percentage of points for the three windows: vertical (v), dormer (d) and roof (r) window.

Hour luminance cd/m²	January			February			March			April			May			June			December		
08:00	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r
>500							1	1	1	1	2	2	1	2	2	1	1	2			
>1000							1	1	1	1	1	2	1	1	2	1	1	2			
>2000							0	0	0	1	1	1	1	1	1	1	1	1			
>5000							0	0	0	0	0	1	1	1	1	0	0	1			
>10000							0	0	0	0	0	0	0	0	0	0	0	0			
>20000							0	0	0	0	0	0	0	0	0	0	0	0			
10:00	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r
>500	0	0	0	1	1	1	8	5	8	11	4	19	5	3	16	3	3	12	1	2	1
>1000	0	0	0	1	1	1	7	3	4	5	2	8	2	2	4	2	2	3	1	1	1
>2000	0	0	0	1	1	1	6	3	4	4	2	5	2	1	4	2	1	3	1	1	1
>5000	0	0	0	1	1	1	4	1	1	3	1	4	1	1	3	1	1	2	0	0	0
>10000	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	1	0	0	0
>20000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:00	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r	v	d	r
>500	1	1	1	1	2	1	15	7	14	24	9	44	11	4	27	8	4	20	1	1	1
>1000	1	1	1	1	1	1	5	5	5	6	5	6	3	3	5	2	2	4	1	1	1
>2000	1	1	1	1	1	1	4	4	5	5	3	6	2	2	5	2	1	4	1	1	1
>5000	1	1	1	1	1	1	4	4	5	5	3	6	2	1	5	2	1	3	1	1	1
>10000	1	1	1	1	1	1	1	1	1	5	3	5	2	1	4	1	1	3	1	1	1
>20000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 52 / Figure 53, Figure 54 / Figure 55, Figure 56 / Figure 57 and Figure 58 / Figure 59 show the fish eye rendering for selected sunny days and hours and the corresponding average luminance of the surfaces located within a band of 40º about the eye height (for a sitting person). Loe, Mansfield & Rowlands (1994) showed that the field of luminance within a 40º band about the eye height is the most important to consider for visual comfort. All the 40° luminance graphs clearly show that the peak luminance values of the window were about the same. However, in all cases, the roof window provided higher wall luminance in the rest of the view field and softer luminance transitions from the window area to the wall area compared with the other windows.

Vertical Dormer Roof

Figure 52. Fish-eye rendering of the view toward the window wall under sunny sky conditions in June at 10:00 hours.

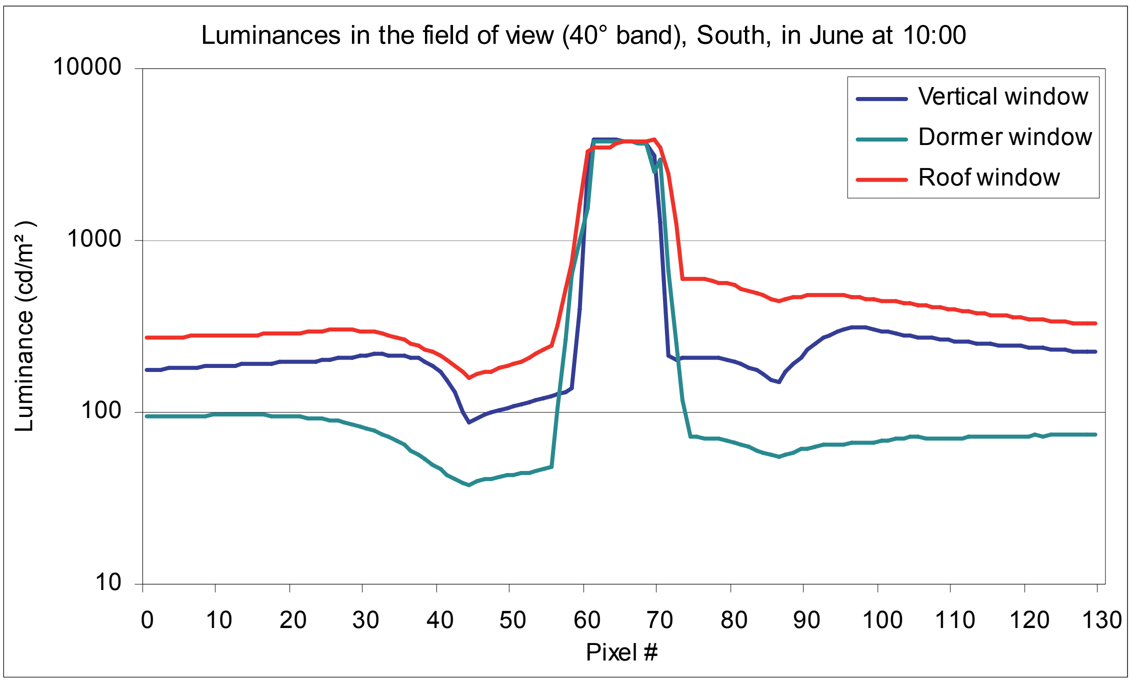


Figure 53. Average luminance within a 40º band centred around the observer's eye looking straight ahead towards the window, under sunny sky conditions, in June at 10:00 hours. The graphs show that the peak values of the window are about the same, while the luminance level of the other surfaces in the 40° band of the rooms are significantly different, with the highest values for the roof window and the lowest values for the dormer window.

Figure 53 shows that the transition between the high window luminance and the surrounding surfaces were much smoother in the case of the roof window compared with the other windows.

Vertical Dormer Roof

Figure 54. Fish-eye rendering of view toward the window wall under sunny sky conditions in May at 8:00 hours.

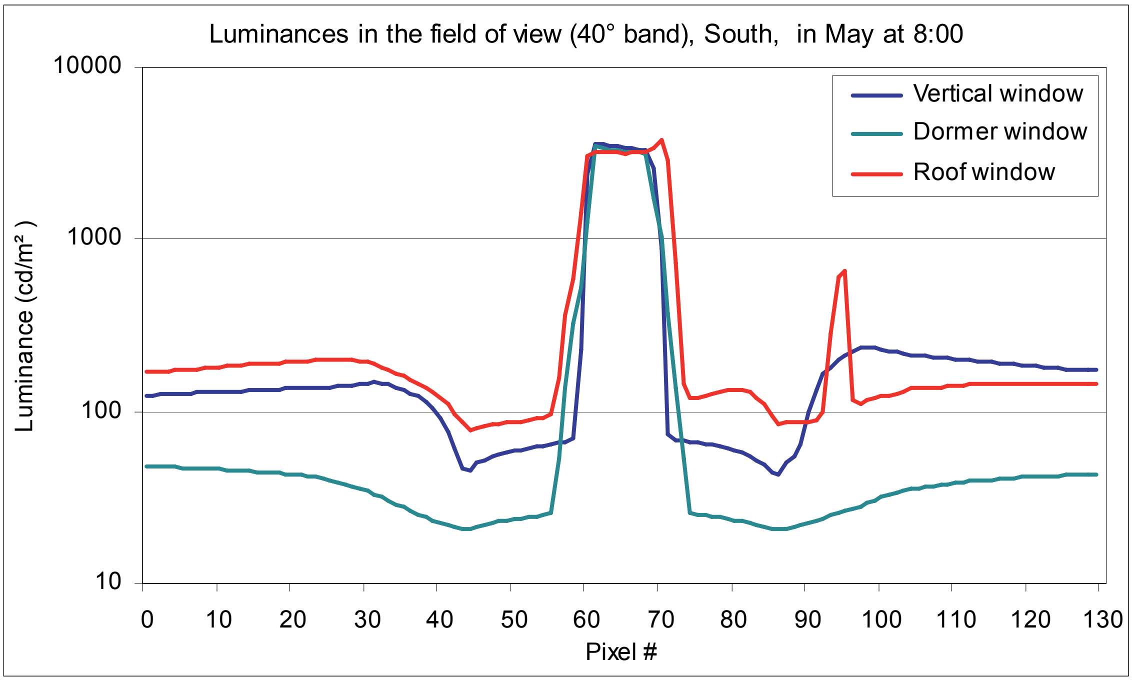


Figure 55. Average luminance within a 40º band centred around the observer's eye looking straight ahead towards the window, under sunny sky conditions, in May at 8:00 hours. The graphs show that the peak values of the window are about the same, while the luminance level of the other surfaces in the 40° band of the rooms are significantly lower with the dormer window.

Vertical Dormer Roof

Figure 56. Fish-eye rendering of view toward the window wall under sunny sky conditions in March at 8:00 hours.

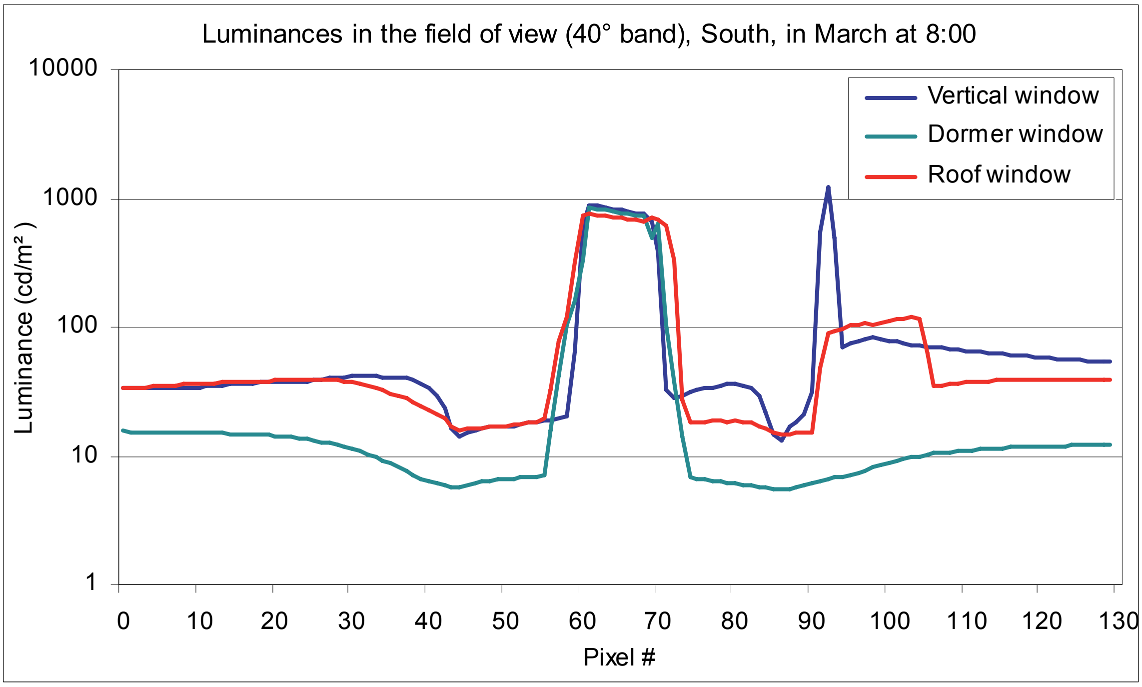


Figure 57. Average luminance within a 40º band centred around the observer's eye looking straight ahead towards the window, under sunny sky conditions, in March at 8:00 hours. The graphs show that the peak values of the window are about the same, while the luminance level of the other surfaces in the 40° band of the rooms are significantly lower with the dormer window than the two other window types.

Vertical Dormer Roof

Figure 58. Fish-eye rendering of view toward the window wall under sunny sky conditions in December at 12:00 hours. The images show that the sunlight comes directly into the field of view in all three cases. For the roof window however, the sunlight seems to cause less glare problems.

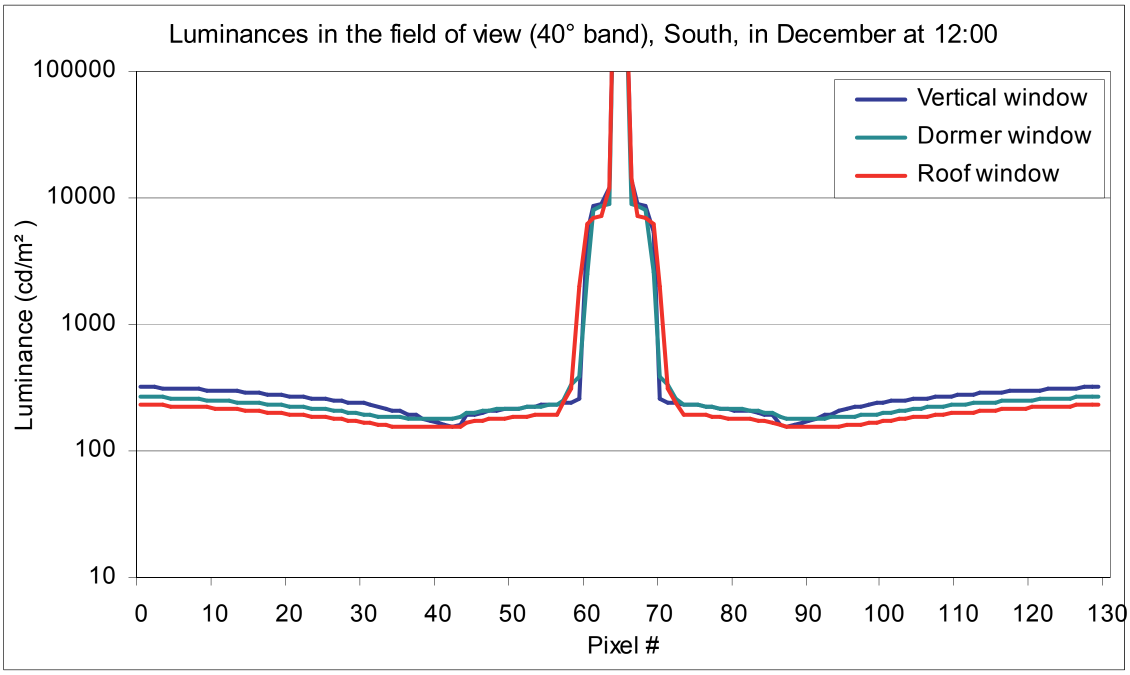


Figure 59. Average luminance within a 40º band centred around the observer's eye looking straight ahead towards the window, under sunny sky conditions, in December at 12:00 hours. The graphs show that because of the direct sunlight penetrating to the back of the rooms in all three cases, the general luminance levels are about the same.

Daylight Glare Index

A glare index describes the subjective magnitude of glare discomfort with high values illustrating uncomfortable or intolerable sensation of discomfort. It also provides the designer with an indication of how to control and limit glare discomfort. However, most of the equations developed do not (unfortunately) predict the sensation of glare from daylight accurately.

In studies about visual comfort, it has been the custom to use a (discomfort) glare index to assess the degree of visual discomfort in a particular situation. A glare index is simply an empirical formula connecting directly measurable physical quantities (e.g. source luminance, solid angle of the glare source, background luminance, etc.) with the glare experienced by persons exposed to the given conditions. The important variables are:

- The luminance of the glare source.
- In the case of windows: the luminance of the sky as seen through the window (the brighter the source or sky, the higher the index);
- The solid angle subtended by the source. In the case windows: the apparent size of the visible area of sky at the observer’s eyes (the larger the area, the higher the index);
- The angular displacement of the source from the observers line of sight. In the case of windows: the position of the visible sky within the field of view (the further from the centre of vision, the lower the index);
- The general field of luminance controlling the adaptation levels of the observer's eye (also called the background luminance). In the case of windows: the average luminance of the room excluding the visible sky (the brighter the room, the lower the index).

The Daylight Glare Index (DGI) remains the most widely used indicator for sensation of glare despite its accepted limitations. Particular concerns exist about the treatment of source and background luminance relationships in the DGI. In the present case of analysing potential glare problems in a simple room with a relatively small window, the latest literature indicates that the DGI may overestimate the glare when assessed from a position near the window. However, when assessed from the centre or the back of the room the glare assessment may be more reliable. Therefore the DGI values were calculated from a position at the centre of the room.

The interpretation of the DGI values have been discussed in the literature, and Table 7 shows the typical scale of perception.

Table 7. The perception of the DGI.

DGI	Perception
>28	Intolerable
28	Just intolerable
26	Uncomfortable
24	Just uncomfortable
22	Just acceptable
20	Acceptable
18	Noticeable
16	Just perceptible

In the following pages the calculated DGI values are shown as predicted by the Radiance Lighting Simulation System for different sky conditions and predicted for a person positioned in the centre of the room looking towards the window.

Overcast sky conditions

Figure 60 shows the calculated DGI values for the three window under overcast sky conditions. All values were within the range of "acceptable" values.

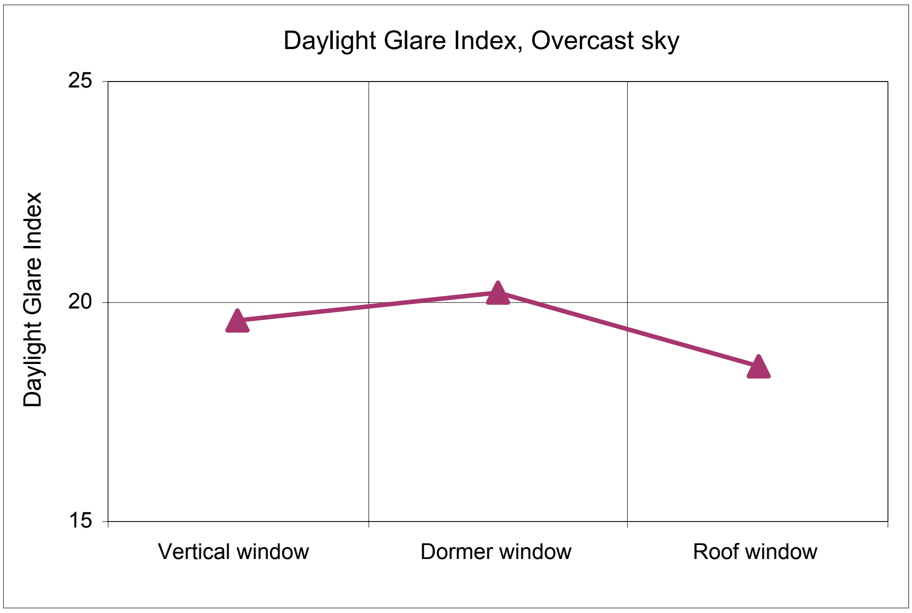


Figure 60. Daylight Glare Index calculated for overcast sky conditions for the three window types. All values were within the range of "acceptable" perception. The DGI value was somewhat higher with the dormer window than with the vertical window, which again was higher than for the roof window.

Intermediate sky

For the intermediate sky condition (October at 12:00 hours), the calculated DGI values for the North oriented windows were "noticeable" on the discomfort glare scale. For the West windows the ratings were "acceptable" for all windows, while for the South windows the rating were "just acceptable".

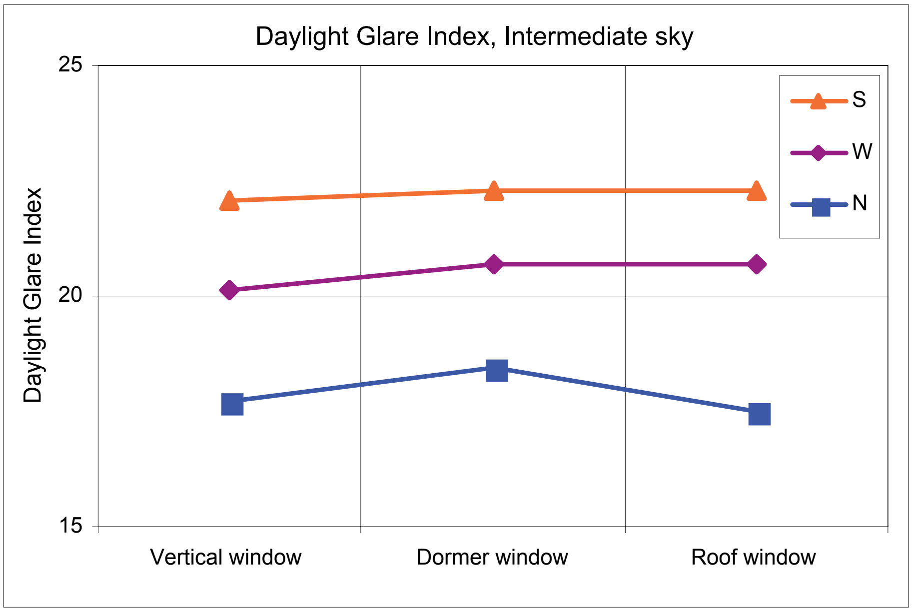


Figure 61. Daylight Glare Index calculated for intermediate sky conditions for the three windows and three orientations.

Sunny sky conditions

For the cases of sunny sky conditions there was much more variation over time and for the three window types. Figure 62, Figure 63 and Figure 64 show the calculated results for the South facing, the West facing and the North facing windows, respectively.

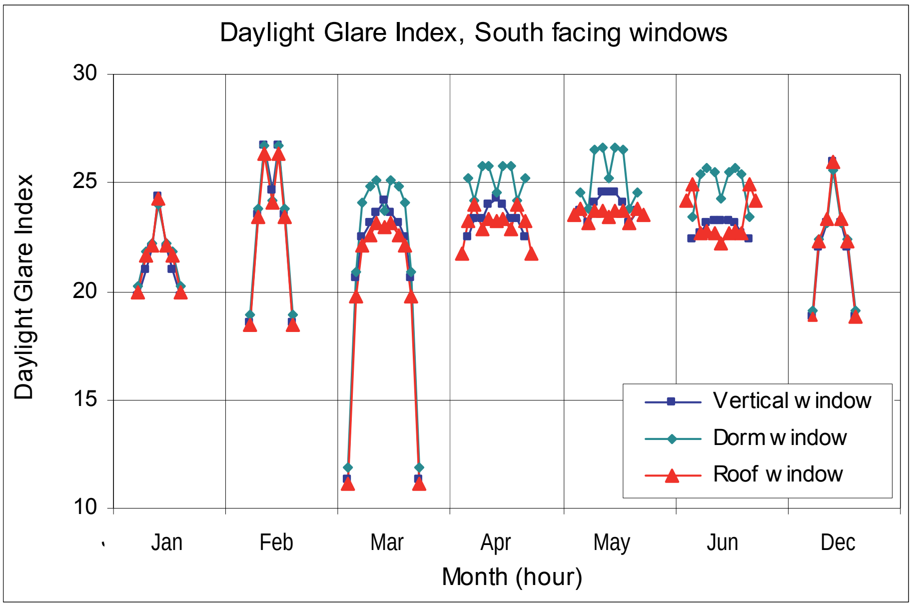


Figure 62. Radiance calculated Daylight Glare Index from centre of the room when viewing towards the South facing windows. For each month DGI was calculated for all hours when direct solar radiation penetrated the room. In the summer months the DGI ratings were significantly worse for the dormer window, while the ratings were almost the same during the winter months.

Figure 62 shows that for the South facing windows the DGI rating were significantly worse in the summer months for the dormer window, in the "uncomfortable" range, while the ratings were almost the same for all windows "just uncomfortable" or "uncomfortable" during the winter months.

For the West facing windows, the DGI rating seemed to be almost the same for the three window types, all going to the "just uncomfortable" range in the winter months and "uncomfortable" or "just intolerable" range in the summer months, see Figure 63.

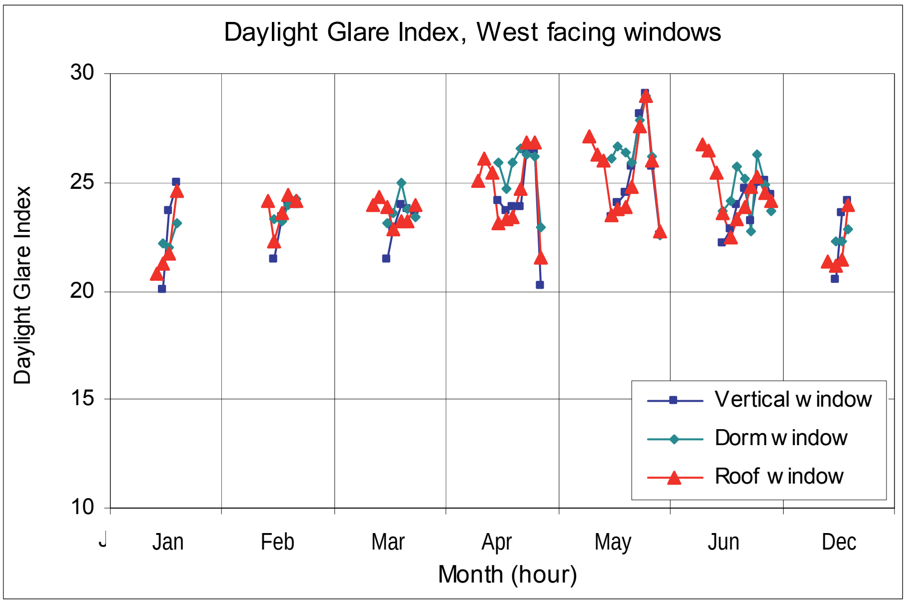


Figure 63. Radiance calculated Daylight Glare Index from centre of the room when viewing towards the West facing windows. For each month DGI was calculated for all hours when direct solar radiation penetrated the room. The DGI rating seemed to be almost the same for the three window types, all going to the "just uncomfortable" range in the winter months and "uncomfortable" or "just intolerable" range in the summer months.

Figure 64 indicates that for the North facing rooms, the DGI ratings were significantly worse for the roof window than for the two other window types, rising to the "uncomfortable" range in the summer months, May-July. The reason for this may be that bright patches of sunlight fall on the window linings, without really penetrating into the room. An example of this is shown in Figure 65 of the Radiance pcond rendering for May at 10:00 hours. However previous research (Christoffersen, 1999) indicates that direct sun through North facing windows is likely to be appreciated in spite of the high illuminances.

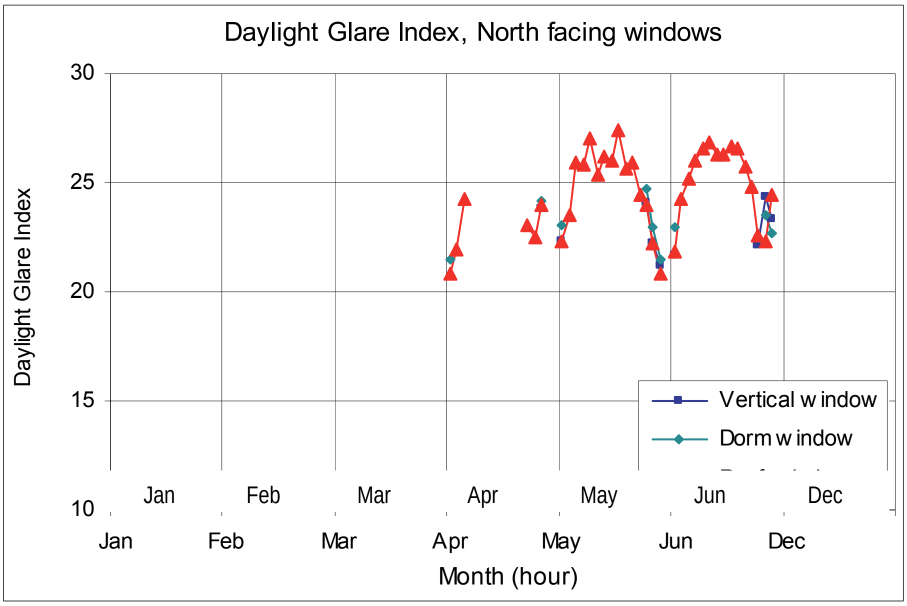


Figure 64. Radiance calculated Daylight Glare Index from centre of the room when viewing towards the North window. For each month DGI was calculated for all hours when direct solar radiation penetrated the room. For the North facing roof window this occurred in early morning hours and late afternoon/early evening hours. The DGI ratings were significantly worse for the roof windows than for the two other window types, rising to the "uncomfortable" range in the summer months, May-July.

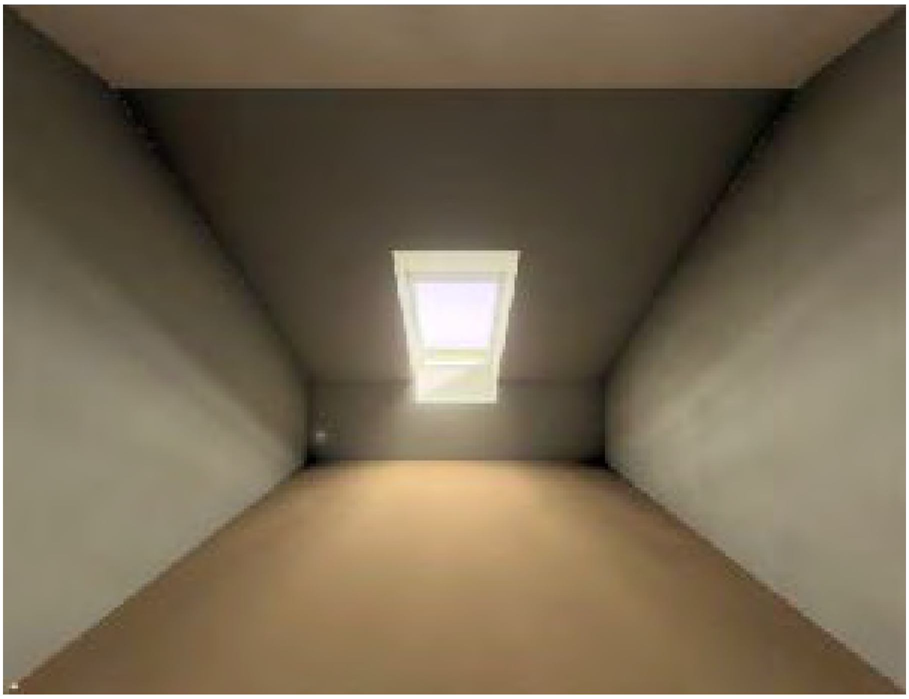


Figure 65. Radiance pcond rendition for North facing roof window in May at 10:00 hours.

Luminance Difference Index

The Luminance Difference index (LD) was developed by Parpairi et al. (2003) through a field study investigation in three library buildings in England. The field study included subjective evaluations with questionnaires.

The Luminance Difference index is a number calculated by summing the logarithm of the absolute difference in luminance between subsequent points of a cylindrical luminance map. The cylindrical luminance map is obtained by measuring the luminance from a point and rotating the luminance meter 360° on a horizontal or vertical plan (measurements taken every 15°).

It should be noted that this mathematical model makes it possible to differentiate between one big peak difference in the pattern of variations and a number of smaller differences, (which is the main interest of this model).

Parpairi et al. (2003) found a moderately strong correlation coefficient (0.65) accounting for 42 % of the variance on the dependent scale (R^2=42) for LD 45h and LD 180h (Lumininance Difference index with points measured 45° apart and 180° apart, horizontal cylindrical plan). Note that the significantly and moderately strong correlation found between brightness ratings and LD 45h and LD 180h indicate that the higher the LDs, the brighter the space is perceived. In other words, the noisier (variable) the field of view in terms of luminance, the brighter the space will appear.

The Luminance Difference index, LD45h, was calculated for selected sunny days and hours as shown in Figure 66. There are small differences between the LD45h values of the three cases, except for the values on midday in June. A higher LD45h index indicates that the room has a higher variation in luminances in the “horizontal field of view”, and is likely to be perceived as being more bright, more pleasant, more cheerful and more radiant on the semantic scales: Unpleasant–Pleasant, Gloomy–Cheerful, Dim–Bright and Dull–Radiant, respectively. However, compared with the differences found in luminance distributions and the Daylight Glare Index, the LD45h index seemed to give little information for these particular room and window configurations.

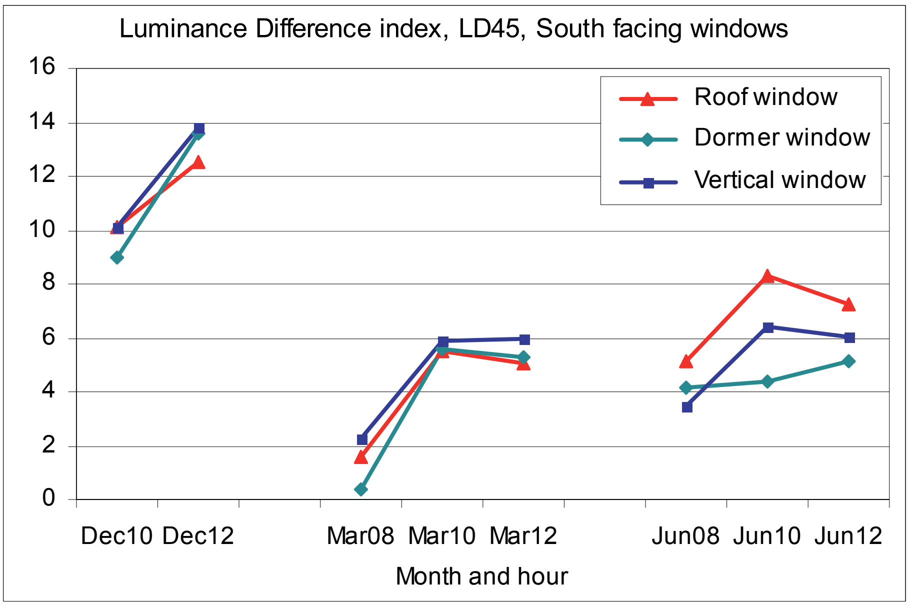


Figure 66. The calculated Luminance Difference index (LD45h) for selected hours and months of the year, and for South facing windows. The higher the LD-index, the brighter the room is perceived. The graph shows that the room with the roof window would be perceived as the brightest in the summer.

Figure 67 shows the calculated LD180h index for the same cases as in Figure 66. There seems to be no consistency between the two indices, except for the fact that there are only minor differences for the three window types. The concept of the LD index does not in itself express that above a certain value of the LD the lighting quality of the room is "high", or below a certain value the quality is "poor". Therefore the value of the two indices LD45h and LD180h would normally be different, as they were here. Great variation (high LD value), meaning that there are many luminance peaks within the angle of view (i.e. 45° for the eye movement or 180° for the movement of the head) is highly appreciated, in contrast to a bland, monotonous environment (low LD value).

In principle the LD index would be best in comparisons of different room or window configurations, as tried here. Unfortunately, the calculated results for the three windows did not provide useful information.

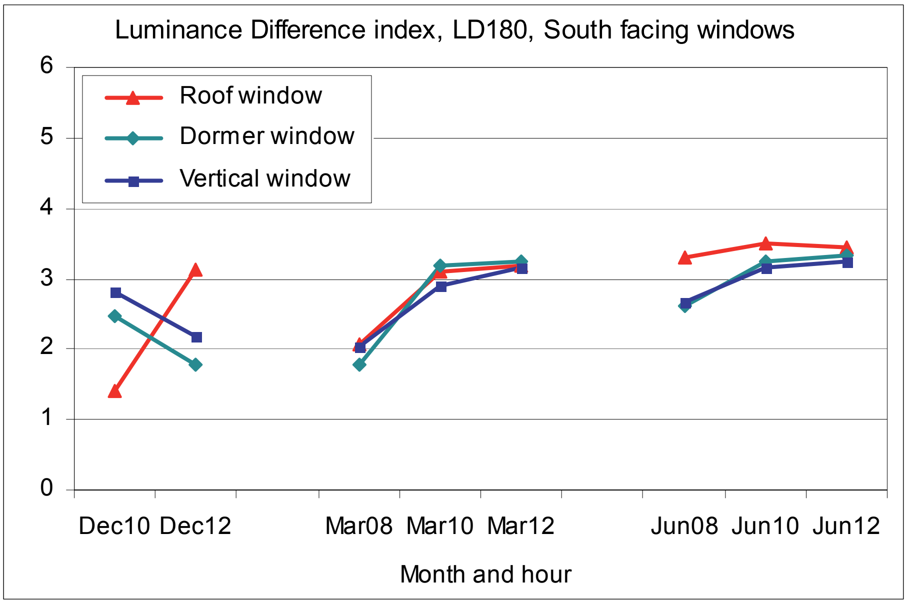


Figure 67. The calculated Luminance Difference index (LD180h) for selected hours and months of the year. The higher the LD-index, the brighter the room is perceived. The graph shows that in general there were only small differences in the LD180 index for the three rooms.

Figure 68 shows the calculated LD45h values for the West facing windows. Again, there seemed to be little information on the lighting quality of the room, or differences in expected visual perception between the three rooms.

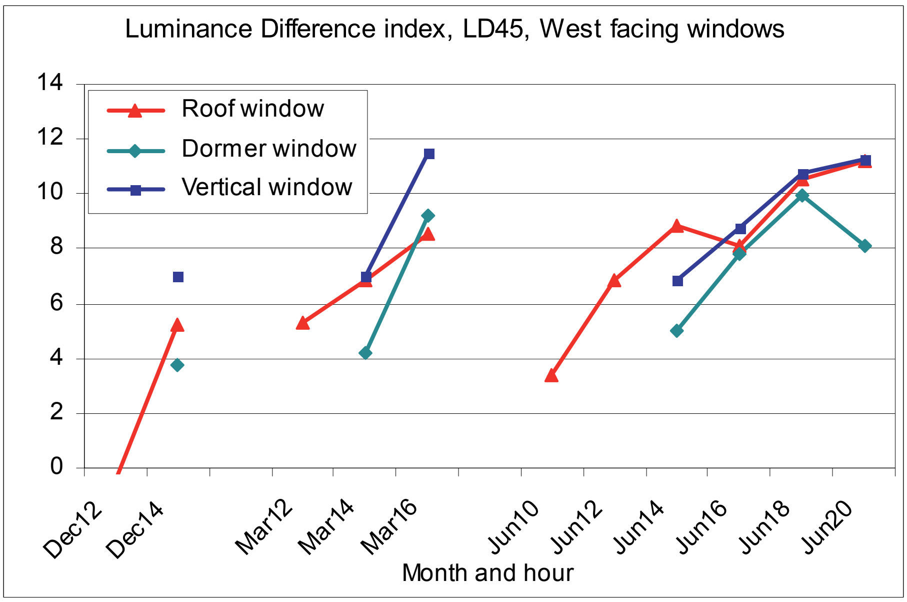


Figure 68. The calculated Luminance Difference index (LD45h) for selected hours and months of the year, and for West facing windows. Only hours with direct sun entering then rooms are included.

Scale of Shadows

The Scale of Shadows developed by Sophus Frandsen (Frandsen, 1989) is a systematic description of the relation between the light source and the object. The scale has 10 subjectively evaluated equal intervals, showing on a sphere the result of the change from a parallel to a diffuse light source. Geometrically it is defined by the percentage of the (partially) shaded areas on the sphere (0 %, 10 %, 20 %, etc.) and produced by a circular light source of which the maximum, corresponding sky factor is 0 %, 1 %, 4 %, etc. – all the whole squares from 1 to 100. In parallel light the shadows are so sharp and so dense that objects almost loose their form. Even tiny pits on the object's surface are big enough to create harsh and disturbing shadows. In the very diffuse light the lack of shadows means lack of three-dimensional form. A sphere looks flat and not spherical, and texture is missing.

The "optimal" combination of parallel light and diffuse light depends on the type of visual task that takes place in the room. The greater the difference between the physical size of the main form and that of the detail, the more difficult it becomes to simultaneously optimise the lighting on both. The greater the interest of the detail and texture, the smaller a shadow type is needed, and the greater the interest of the room and the totality, the greater a shadow type is needed. Frandsen have also defined the Four Shadows (Frandsen, 1989), described by the prevailing shadow types in an ordinary sidelit room: A. the big room shadow, B. the big object shadow, C. the small object shadow, and D. the small detail/texture shadow. The combination of the Four Shadows and the Scale of Shadows, also called the Scale of Light, is indicated in Table 8, which may help in evaluating the appropriate lighting conditions for different tasks.

Table 8. The relation of the four types of shadows to the scale of shadows, according to Frandsen.

The Four Shadows	The Scale of Shadows
A. The big room shadow	Shadow types 4,5-10
B. The big object shadow	Shadow types 3-7
C. The small object shadow	Shadow types 1,5-4,5
D. The small detail/texture shadow	Shadow types 0-1,5

The light from a window in a real room is not parallel, but the relative intensity between the primarily directional light and the primarily diffuse light in any point of the room determines the shadow type on the Scale of Shadows. This may then be used as one indication or one parameter of quality for a certain task at that point of the room.

In the Radiance simulations a series of four spheres were placed in the centre line of the three rooms, 1, 2, 3 and 4 m from the windows and at 1.2 m above the floor level. The following pages show examples of the renderings for overcast sky conditions and for a few sunny sky conditions. Probably the area of greatest interest for performing a certain task, which may include recognising details or texture of an object, would be in the half of the room nearest the window. This is also the part of the room where the concept of the Scale of Shadows makes most sense, since it is here that the directional light is more intense than the diffuse. At the back of the room the reflected light will often be dominating, creating shadow types 9 and 10, while the window itself (if all surfaces were black) would create shadow type 0 to 2. However, as mentioned, this is beyond the concept of the Scale.

When choosing an appropriate illuminance scale (lux) or luminance scale (cd/m²), the false colour rendering sometimes (but not always) helps in establishing the type of shadow on each of the spheres, as shown in the following figures.

Overcast sky conditions

For the overcast sky, see Figure 69, the form of the spheres is perhaps most easily recognised at some distance (at the second sphere) with the vertical and the roof window, while with the dormer window it seems to be better shown closer to the window. The shadow types for the sphere closest to the window seem to be 5 (vertical), 5-6 (dormer), and 7-8 (roof), respectively. For the second of the spheres, the shadow types seem to be 4 (vertical), 5 (dormer), and 5 (roof), respectively. The form of the spheres is perhaps most easily recognised at some distance (at the second sphere) with the vertical and the roof window, while with the dormer window it seems to be better shown closer to the window.

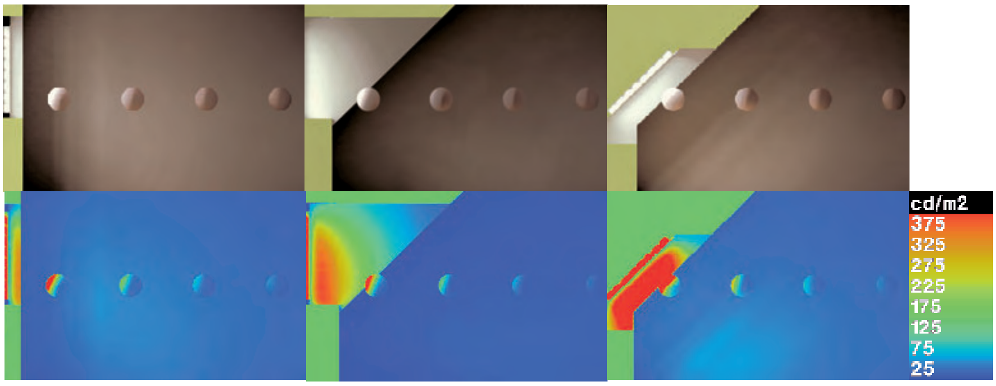


Figure 69. Overcast sky conditions. Section of the three rooms illustrating the scale of shadow. Mainly the 2 or 3 spheres closest to the window have interest. The shadow types for the sphere closest to the window seem to be 5 (vertical), 5-6 (dormer), and 7-8 (roof), respectively. For the second of the spheres, the shadow types seem to be 4 (vertical), 5 (dormer), and 5 (roof), respectively. The form of the spheres is perhaps easiest recognised at some distance (at the second sphere) with the vertical and the roof window, while with the dormer window it seems to be better shown closer to the window.

Sunny sky conditions

For a number of months and hours under sunny sky conditions the Scale of Shadows was investigated by Radiance simulation of the rooms with the four spheres. Figure 70, Figure 71 and Figure 72 show the result for June at 12, March at 10 and December at 10, respectively. From the Radiance renderings one can easily see that the in the room with the roof window the luminance level is much higher and the interreflected (diffuse) component of the light on the spheres plays a more significant role than in the other two rooms.

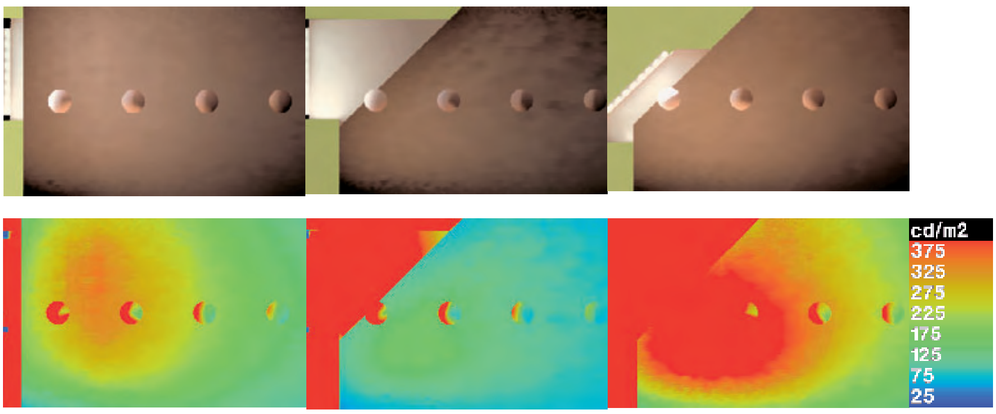


Figure 70. Sunny sky conditions for South facing windows in June at 12:00. Mainly the 2 or 3 spheres closest to the window have interest. The images show that the luminance level and the interreflected component of the light is significantly higher under the roof window than with the other window types.

Figure 71 shows the three rooms at times where the sun hits the sidewalls near the window. With the dormer window a great part of the sun patch hits the window linings, and therefore the lighting level and the diffuse part of the lighting in this room is significantly lower than in the other two rooms. For the second sphere from the windows this can be seen as a somewhat “smaller” value on the shadow scale, i.e. type 2 with the dormer window, in comparison with types 3 and 4 in the other two rooms.

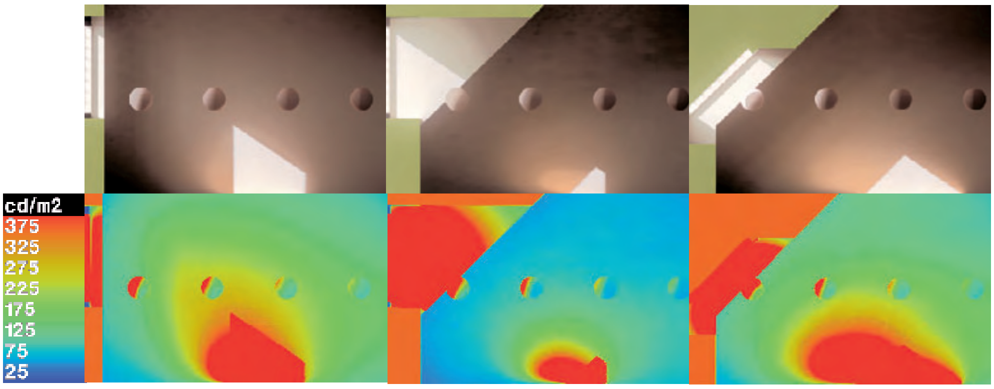


Figure 71. Sunny sky conditions. South facing in March at 10:00. The images show that the lighting level and the diffuse lighting component is signinficantly smaller with the dormer window than with the two other types.

Figure 72 shows the situation in the three rooms with very low sun position. The sun patches fall on the sidewall and the back wall. In this case the lighting level is significantly higher with the vertical window than with the dormer window and the roof window. The Scale of Shadows can not easily be determined, but it can be seen that the while the light near the window is almost purely directional, is quickly changes with the distance from the window, so that it is almost purely diffuse at the back of room (outside the sunrays).

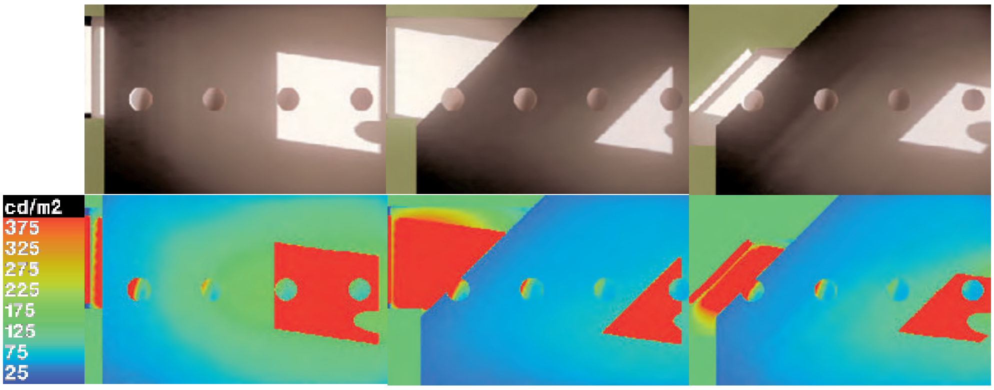
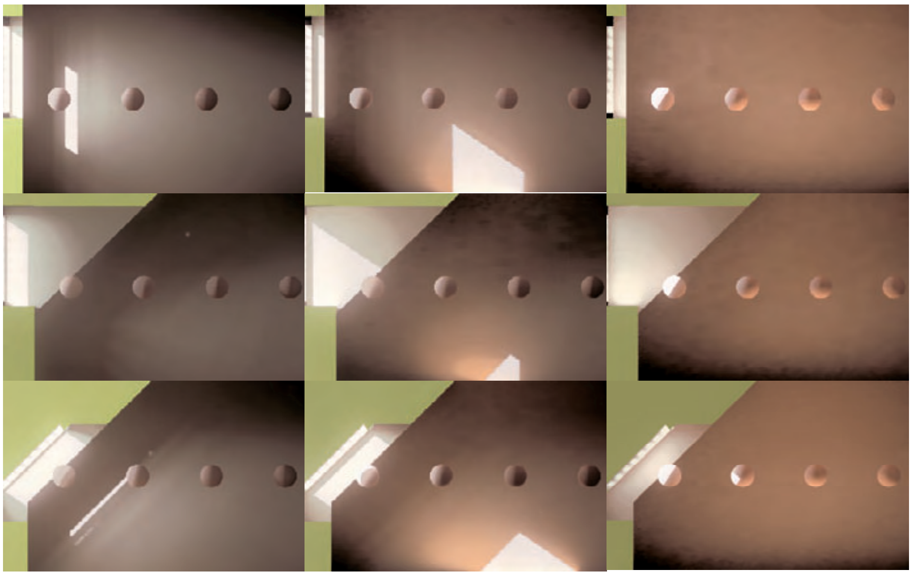


Figure 72. Sunny sky conditions. South facing in December at 10:0. With the sun at this low position the sunlight hits the back wall, and therefore the diffuse interreflected light dominates in the depth of the rooms.

Figure 74 shows how the lighting level and the distribution changes over the morning, from 8:00 hours till noon. One can observe that the level in general is significantly higher under the roof window. One can also get the impression that the perception of the form of a small object would be somewhat more difficult in the room with the roof window because of the high level of diffuse interreflected light. Since a major part of the diffuse light is reflected from the floor (South facing window), one way to “adjust the balance” between directional light and diffuse light would be to decrease the light reflectance of the floor.



South, March at 08:00 | South, March at 10:00 | South, March at 12:00

Figure 73. Radiance pcond images of three rooms over the morning on a sunny day in March. The images clearly show that the lighting level increases significantly with the solar height (solar altitude angel).

Figure 73 illustrates the changes of the light distribution in the morning of a sunny day in March with the three window configurations.

Figure 74 shows the situation with low sun position and sun patch on the back wall, similar to the images of the South facing windows in December at 10:00 hours (Figure 72).

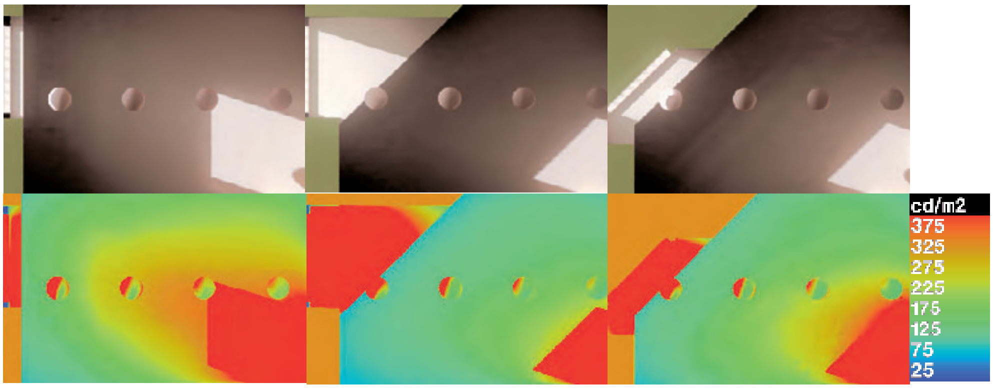


Figure 74. West facing in March at 16:00: The sunlight hits the back wall, and therefore the diffuse inter-reflected light dominates in the depth of the rooms.

Conclusion regarding the use of the Scale of Shadows

Although the Scale of Shadows does not cover situations with several light sources, like in a small room with light coloured surfaces, the concept proved to be very useful for the prediction of an immediate impression of the luminous environment of the room. The practical use of the concept by introducing a number of spheres in the Radiance simulations added to the understanding of the importance of the light's components (directional and diffuse) to the perception of objects in the room.

However, it was not a question of correct determination of the type of shadow on the scale. The images themselves as well as the false colour renderings gave good impression of how the rooms would be perceived in reality and how the form of objects would be recognised.

Use of 3-layer glazing unit

For a few cases analyses were made with a 3-layer glazing instead of the double-glazing otherwise used. The main difference in the analyses was, as expected, that the illuminance and luminance levels were reduced according to the lower light transmittance of the glazing. Figure 75 shows the optical properties of the 3-layer glazing, which had 3 coatings. The total light transmittance was 0.52 compared with the double-glazing where it was 0.78.

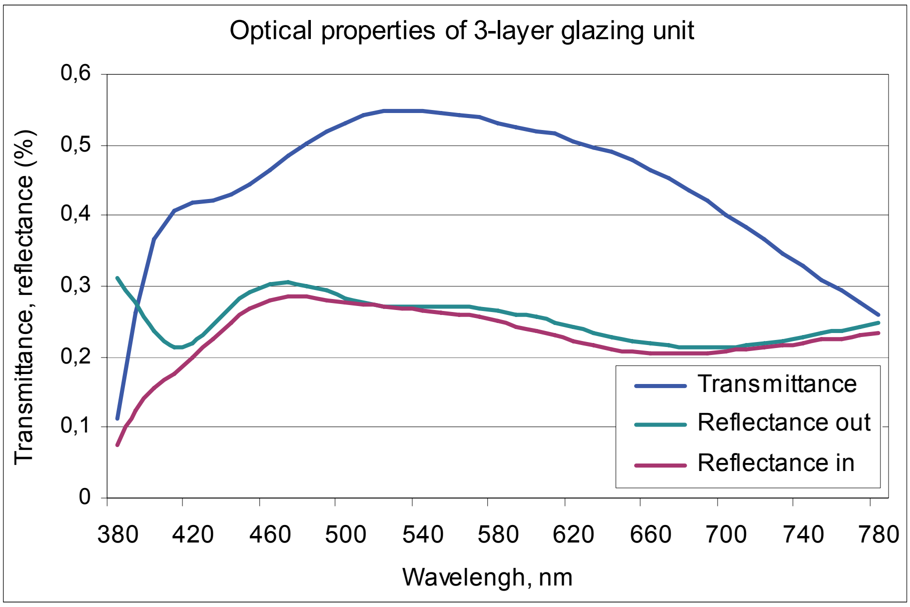


Figure 75. Optical properties of the 3-layer glazing unit used in a few of the analyses.

Horizontal illuminance

Figure 76 shows the calculated illuminances along the depth on a horizontal plane of the room with the roof window for a sunny sky in March at 12:00 hours. The illuminance dropped with the 3-layer glazing to 66 % of that found with the double-glazing, in accordance with the transmittance ratio.

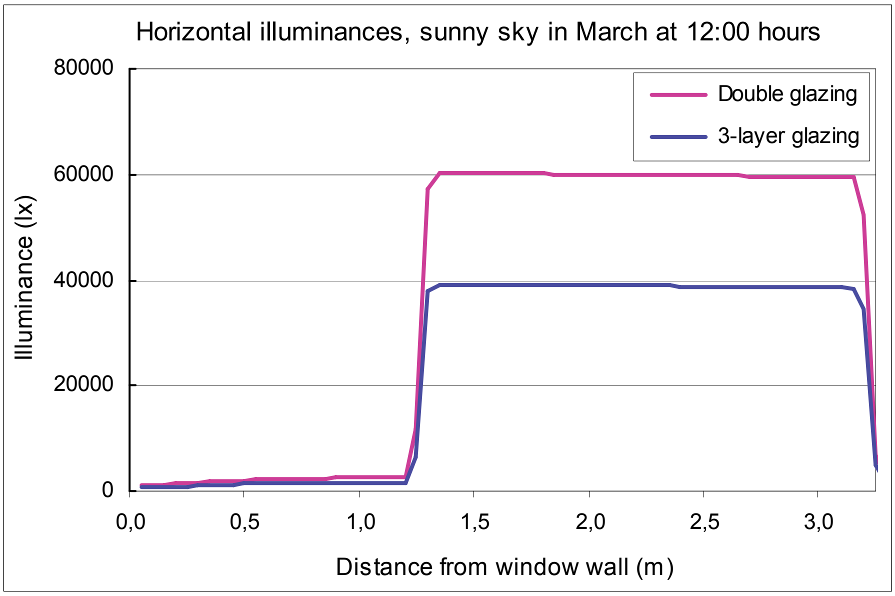


Figure 76. Calculated illuminances along the depth of the room on a horizontal plane with the roof window for a sunny sky in March at 12:00 hours using 2-layer and 3-layer glazing , respectively.

Luminance distribution and DGI

Figure 77 shows the Radiance renderings with the roof window with 2-layer glazing (left) and 3-layer glazing (right) and the corresponding iso-luminance contours. As expected, all the luminances dropped to about 66 % with the 3-layer glazing, corresponding to the ratio of the glazing light tranmittances: 0.52 / 0.79 = 0.66. The peak luminance, for instance dropped from 15,000 cd/m² to 9,000 cd/m².

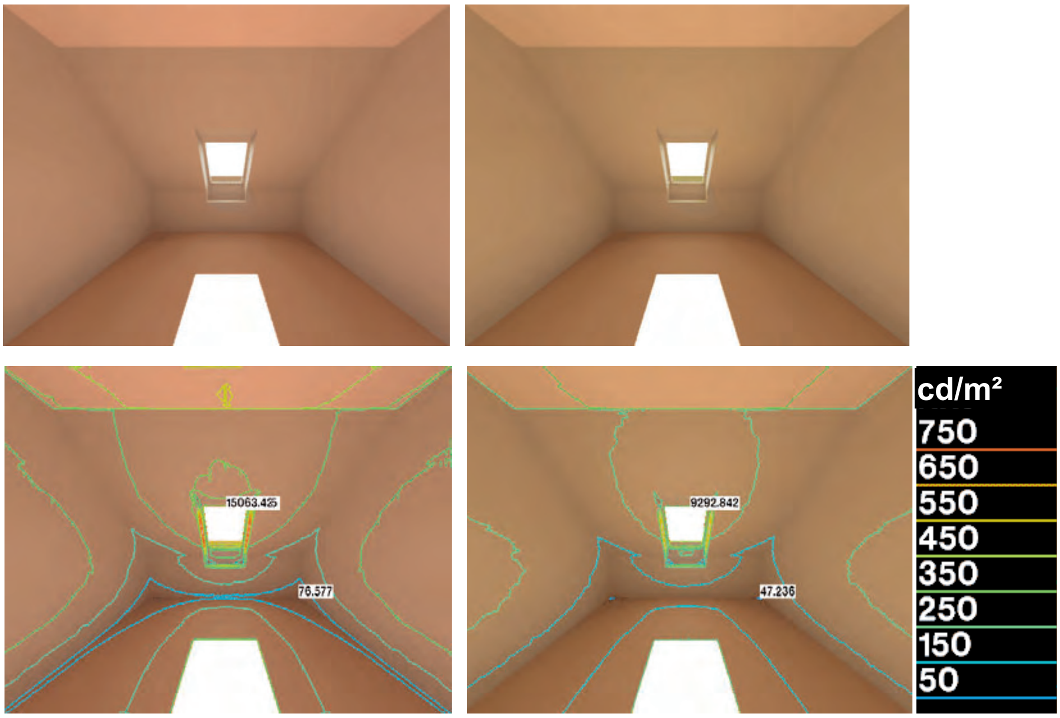


Figure 77. Radiance renderings of the room with 2-layer and 3-layer glazing units in the roof window. Calculations were made for March at 123:00 hours.

The Daylight Glare Index, DGI, was calculated by Radiance for the 3 window configurations and the two glazing types. Figure 78 shows that the DGI in all cases dropped to a "just uncomfortable" level for the vertical and dormer windows, and to an "acceptable" level for the roof window. The drop in DGI was to be expected since by definition of the index, the luminance of the "light source" (the window) is raised to the power 1.6 in the nominator, while the value of the background luminance is used directly in the numerator.

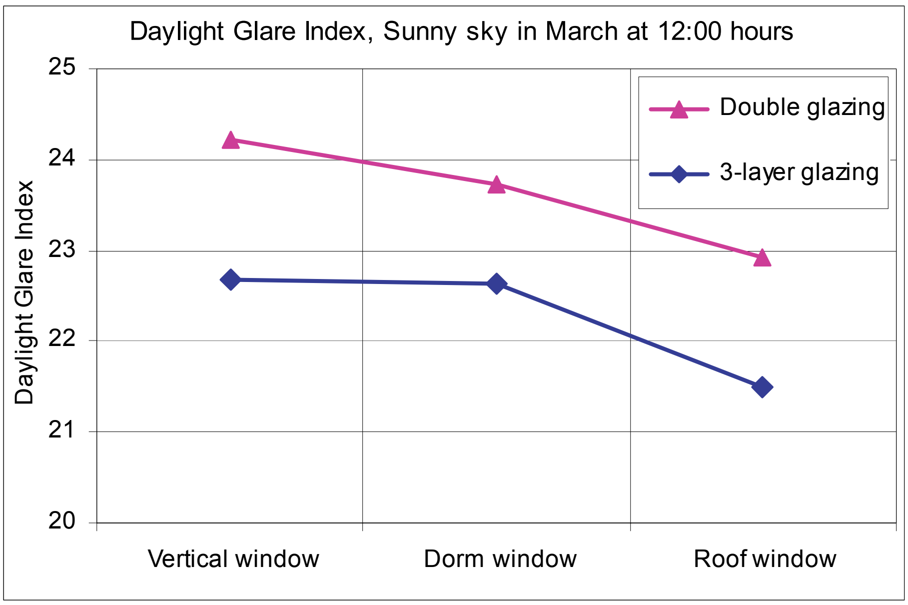


Figure 78. Calculated DGI for the three windows with 2-layer and 3-layer glazing units. The DGI dropped with the 3-layer glazing.

Assessment of the need for solar shading

Luminance is the only visually perceptible unit of photometric measurement. When surfaces with large differences in luminance occur side-by-side, as is often the case in daylit environments, our eyes may have difficulty in adapting to the wide field of luminances, leading to possible visual discomfort and a potential reduction in visual performance. If appropriately selected and controlled, shading devices can significantly reduce luminance differences.

While it would make sense to use luminance as the basis for lighting recommendations or code requirements and their assessment in terms of lighting quality, its dependence on observer position and daylight variability makes it difficult to judge compliance with a simple set of numbers. Luminance and luminance ratios (and contrast) can perhaps be seen as a subset of glare, but they have implications beyond glare. The likely impact of a particular luminance ratio between surfaces is judged by whether or not it exceeds a recommended maximum (van Ooyen et al., 1987). The general rule is to avoid bright light patches in the visual field, which can cause disability and discomfort glare. According to Veitch (2000), direct glare and excessive luminance contrast can create undesired arousal and stress. The typical recommended maximum luminance value is 1,000 cd/m², which is often related to office work and to the luminance of an average (old type CRT) computer screen of 85 cd/m². Little research has been conducted specifically for daylit interiors. However, surveys appear to indicate that ratios of up to 1000:1 are frequently tolerated in daylit offices if views and other amenities compensate for possible glare experiences (Osterhaus, 2001). For residential buildings it can therefore be expected that significantly higher maximum luminance values would be accepted by most people.

Depending on whether a bright patch is directly in the field of view or not, the accepted luminance may be as high as 2,500 cd/m² or even up to 5,000 cd/m² at some angular displacement from the line of sight. In the following analysis of the need for a shading device for protection against glare, a luminance value of 2,500 is used for patches on the sidewalls while 5,000 cd/m² is used for patches on the floor as limits of acceptance.

The following pages show calculated luminances and areas of sun patches on the right wall (WR) and on the floor (FL) for the three rooms with South, respectively West facing windows. It should be noted that these figures show only the bright patches on selected surfaces in the room under sunny skies.

A sky of high luminance as viewed directly through the window will of course also be a potential glare source. The brighter the sky, and the greater the apparent size of the visible area of the sky at the observer's eyes, the more uncomfortable the condition will be. For the roof window the visible area of the sky will always be significantly greater than for the vertical window and the dormer window. Furthermore, under overcast and partly clouded skies, the illuminance of the visible area through the roof window will often be significantly higher than the areas that are visible through the vertical and dormer windows. This may certainly call for a more frequent use of a shading device with the roof window. However, since the position of a user of the room is not defined a comparison of potential glare from cloudy skies has not been included in the study.

Figure 79 shows the calculated luminances of sun patches for all hours from 8:00 to 17:00 hours on the right wall (WR) and on the floor (FL) for the three rooms with South facing windows. The "symmetrical" values will appear on the left wall at symmetrical hours, and in the symmetrical months, i.e. November as in January, October as in February, etc.

The results showed only small differences in the luminance levels of the sun patches on the floor. In the summer months May, June and July, the luminances were about 10 % higher under the roof window than with the other window types. Since the human perception is logarithmic, this difference is insignificant. For the sun patches on the right sidewall (when looking towards the window from the inside),WR, the differences were more significant in the summer. In April and August there were no sun patches with the dormer window, while there were two hours with sun patches of luminances above 5,000 cd/m² with the vertical window and the roof window. In the summer months May, June and July, there were only sun patches on the sidewall under the roof window, cf. Figure 79.

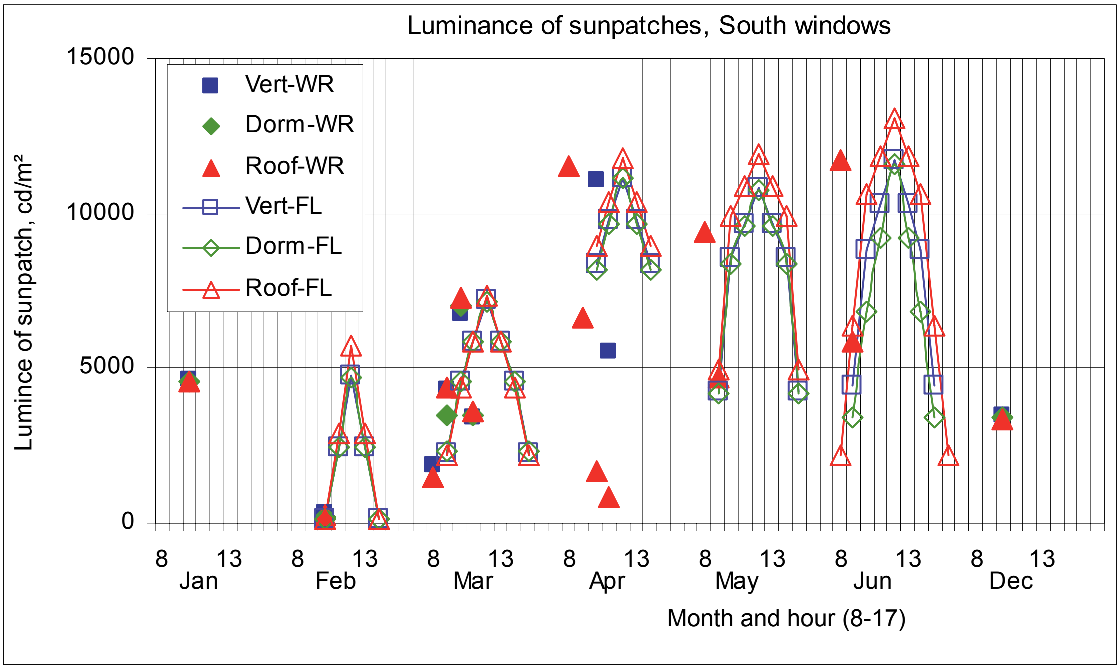


Figure 79. Luminances of sun patches on the side wall (WR) and on the floor (FL) with the three window configurations. All hours from 8:00 to 17:00 are included for the 7 months from December – June. The most significant difference was that in May, June and July there were only high luminance spots on the sidewall under the roof window, while no spots with the other two types.

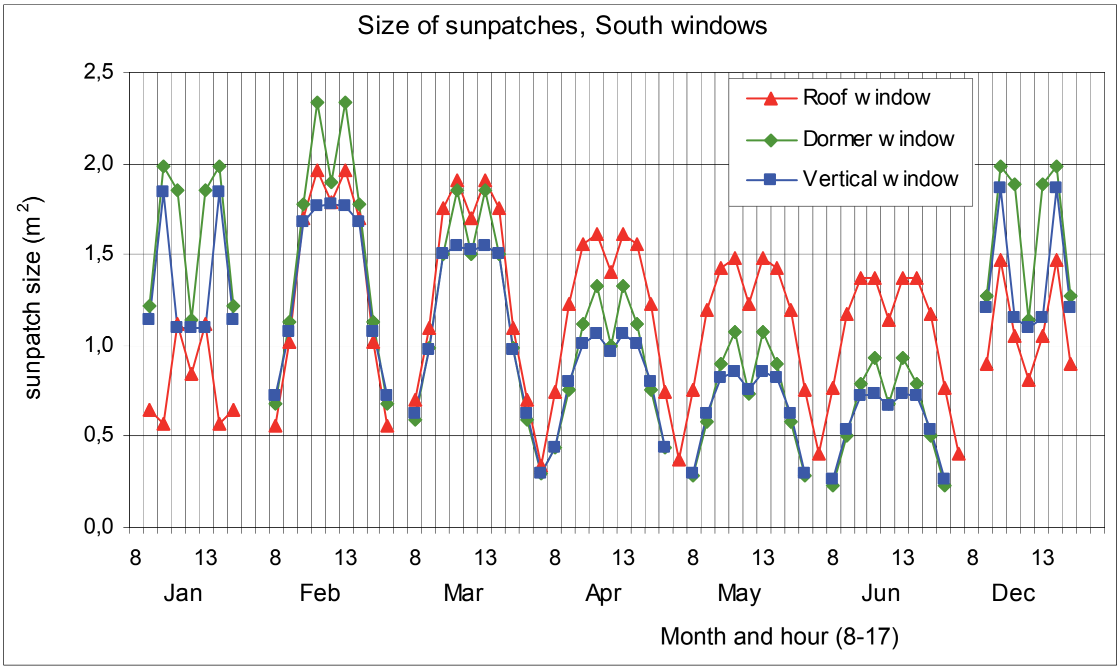


Figure 80. Size of *all* sun patches in the South facing rooms under direct sun in the months December-June and from 8:00 to 17:00 hours.

Figure 80 shows the size of *all* sun patches in the South facing rooms under direct sun from 8:00 hours to 17:00 hours. The figure shows that in the months April-August the greatest patches occur under the roof window. In combination with the high illuminance values, this clearly indicates that there is a strong need for a shading device on the roof window to avoid glary sun patches on the walls. In the months September-March the illuminances are about the same for the three windows and the size for patches are smallest for the roof window.

To get an estimate of how often the sun patches of high luminance will occur in each month, it is necessary to combine the "critical hours" with the probability of the given sky condition at this hour of the month in question. For example: The high luminance patches on the sidewalls (almost 5.000 cd/m²) with the South facing windows occur at 10:00 and 14:00 hours. From Figure 81 it can be seen that at these hours in January the solar altitude is about 10°. From Figure 82, the upper curve (yellow) shows that for SH = 10° the illuminance on a sunny day will typically be about 17,000 lux. Figure 83 then shows that in January 17,000 lux is reached about 10 % of the hours 8-18, i.e. about 30 hours.

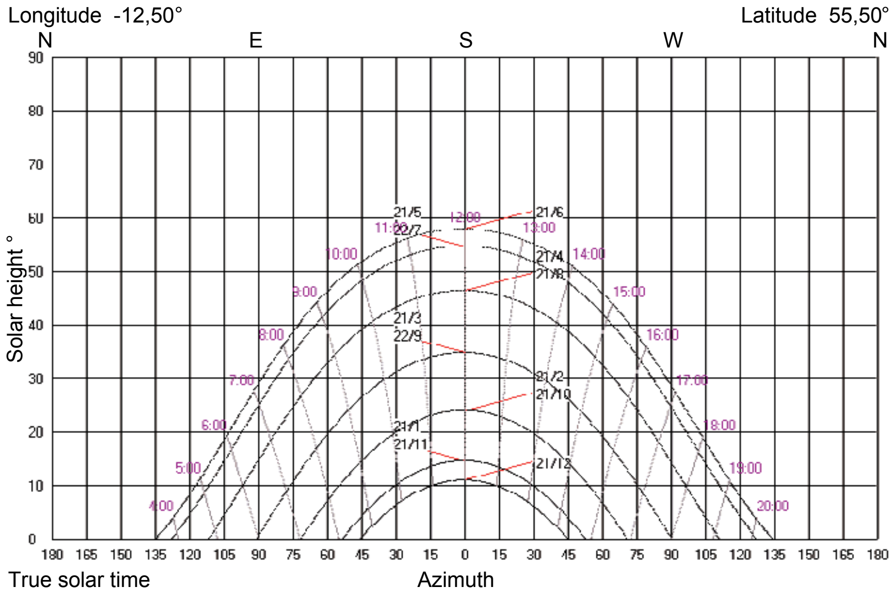


Figure 81. Solar diagram showing the sun position (Azimuth, Solar Height) as function of month and hour for Denmark.

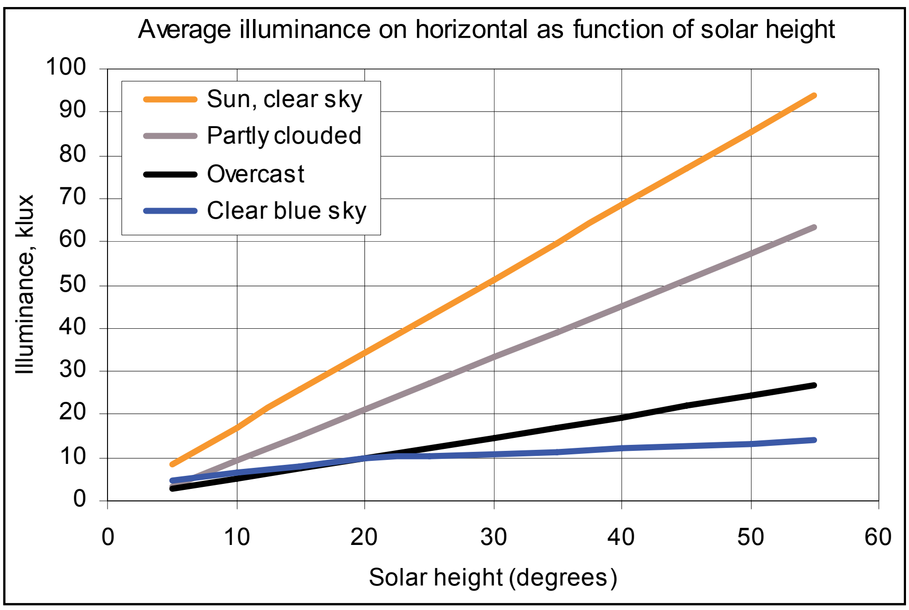


Figure 82. Typical global illuminance under different sky conditions as a function of the solar height.

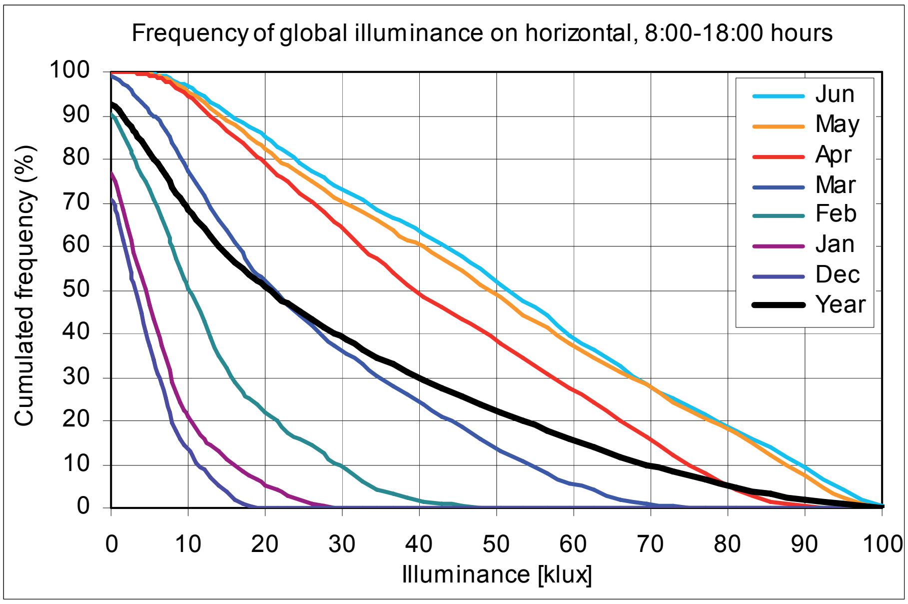


Figure 83. Cumulated frequency of global illuminance on horizontal for the months December – June.

This is of course only a crude estimate of how many hours in January that there may be sun patches in the rooms with critical high luminances. Analyses of the “critical hours” and corresponding illuminance levels for all months are given in Table 9. All hours where the luminance spot on one of the side-walls exceeded 2.500 cd/m² or the luminance spot on the floor exceeded 5,000 cd/m² were included. The estimated hours when a shading device would be required was about 520 hours with the vertical and the dormer windows, while about 840 under the roof window. If the limits were chosen at different values, e.g. 2,000 cd/m² on the sidewalls and 3,000 cd/m² on the floor, the numbers of critical hours would be higher. But the figures can be used as a relative measure and for comparison of the three window configurations. Since the position and the view direction of an occupant was not defined, the estimated hours did not include hours where high luminances of the sky seen directly through the windows would cause visual discomfort.

Table 9. Estimated hours in each month and for the whole year where a solar shading device would be required to reduce visual discomfort in the room from high luminance sun patches in the rooms with South facing windows. The critical hours has been determined as hours when the luminance on the side walls exceeded 2.500 cd/m² or the luminance on the floor exceeded 5.000 cd/m².

	Critical hours Vertical	**Illuminance limit**	**%**	**Hours**	**Critical hours Dormer**	**Illuminance limit**	**%**	**Hours**	**Critical hours Roof**	**Illuminance limit**	**%**	**Hours**
Jan	10, 14	17,000	10%	30	10, 14	17,000	10%	30	10, 14	17,000	10%	30
Feb				0				0	12		2%	5
Mar	9-15	43,000	20%	60	9-15	43,000	20%	60	9-15	43,000	20%	60
Apr	10-14	68,000	17%	50	10-14	68,000	17%	50	8-16	45,000	44%	130
May	9-15	71,000	27%	80	9-15	71,000	27%	80	8-16	58,000	40%	120
Jun	10-14	82,000	18%	50	10-14	82,000	18%	50	8-16	59,000	40%	120
Jul	9-15	71,000	27%	80	9-15	71,000	27%	80	8-16	58,000	40%	120
Aug	10-14	68,000	17%	50	10-14	68,000	17%	50	8-16	45,000	44%	130
Sep	9-15	43,000	20%	60	9-15	43,000	20%	60	9-15	43,000	20%	60
Oct				0				0	12		2%	5
Nov	10, 14	17,000	10%	30	10, 14	17,000	10%	30	10, 14	17,000	10%	30
Dec	10, 14	12,000	10%	30	10, 14	12,000	10%	30	10, 14	12,000	10%	30
Year				**520**				**520**				**840**

Figure 84 shows the calculated luminances of sun patches for all hours from 8:00 to 17:00 hours on the right wall (WR) and on the floor (FL) for the three rooms with West facing windows. The figure shows that in the months October-April the vertical window and the roof window gave very high illuminance patches (5 – 15,000 cd/m²) on the sidewall, while there were no patches on the sidewall in the summer.

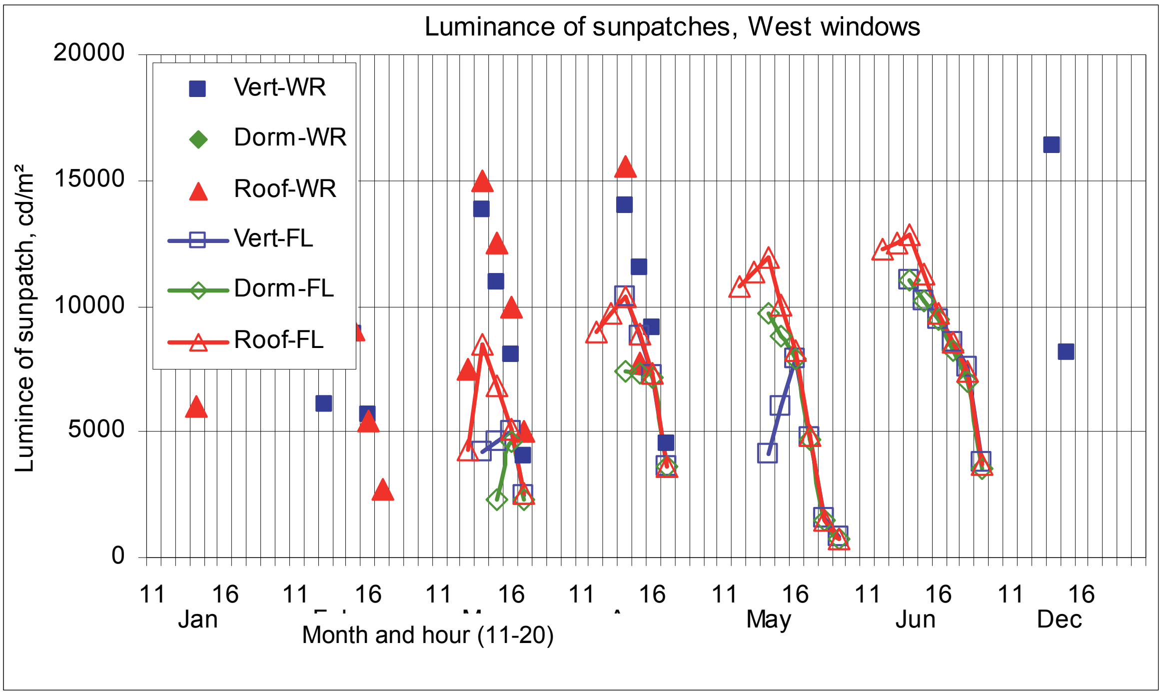


Figure 84. Calculated luminances of sun patches on the right wall (WR) and on the floor (FL) for the three rooms with West facing windows for the hours 08:00 – 17:00. The figure shows that in the months October-April the roof window and the vertical window give higher illuminance on the sidewalls than the dormer window.

Figure 85 shows the size of all sun patches in the West facing rooms under direct sun from 12:00 hours to 20:00 hours. It can be seen that there are no big difference in the sizes of patches with the three different windows.

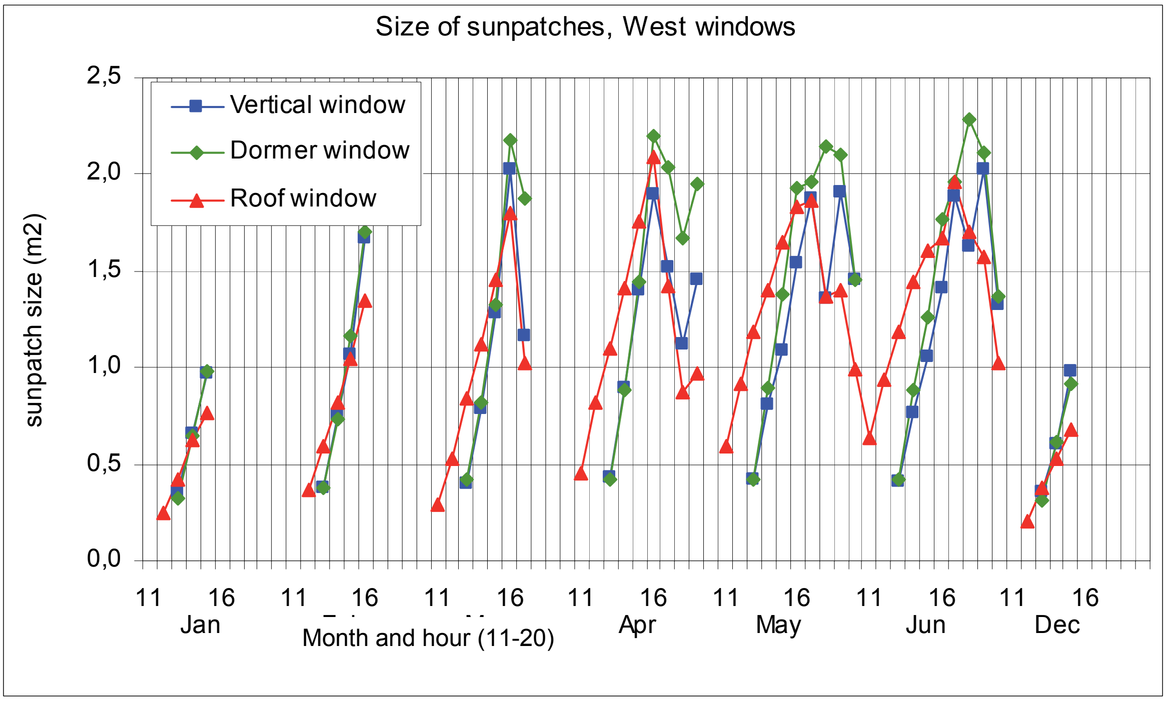


Figure 85. Size of *all* sun patches in the West facing rooms under direct sun in the months December-June and from 12:00 hours till 20:00 hours.

Table 10. Estimated hours in each month and for the whole year when a solar shading device would be required to reduce visual discomfort in the room from high luminance sun patches in the rooms with West facing windows. The critical hours has been determined as hours where the luminance on the side walls exceeded 2,500 cd/m² or the luminance on the floor exceeded 5,000 cd/m².

	Critical hours Vertical	**Illuminance limit**	**%**	**Hours**	**Critical hours Dormer**	**Illuminance limit**	**%**	**Hours**	**Critical hours Roof**	**Illuminance limit**	**%**	**Hours**
Jan									14	17.000	2%	5
Feb	13-16	12,000	15%	45				0	14-16	12,000	10%	15
Mar	14-17	16,000	18%	60	15-17	43,000	15%	60	13-17	16,000	24%	60
Apr	14-16	26,000	14%	40	14-16	26,000	14%	40	12-16	26,000	30%	90
May	15-16	34,000	12%	35	14-16	34,000	16%	50	12-16	34,000	45%	140
Jun	14-16	60,000	7%	20	14-16	60,000	7%	20	12-16	60,000	25%	75
Jul	15-16	34,000	12%	35	14-16	34,000	16%	50	12-16	34,000	45%	140
Aug	14-16	26,000	14%	40	14-16	26,000	14%	40	12-16	26,000	30%	90
Sep	14-17	16,000	18%	60	15-17	43,000	15%	60	13-17	16,000	24%	60
Oct	13-16	12,000	15%	45				0	14-16	12,000	10%	15
Nov									14	17,000	2%	5
Dec	15	7,000	3%	10								
Year				**390**				**320**				**695**

Conclusion regarding the need for solar protection

From the analyses of sun patches in the South and West facing windows combined with the cumulated frequency of global illuminance the relative need for the use of solar shading were estimated. For the windows facing South the vertical windows and the dormer window had about the same number of hours, 520 hours with the chosen criteria, when solar shading would be needed. The room with the roof window needed shading in about 60 % more hours, or 840 hours over the whole year.

For the West facing windows, the situation was about the same. Shading was needed 390 hours with the vertical window, 320 hours with the dormer window, and about twice the number of hours, about 700 hours, with the roof window.

Impact of screen and Venetian blinds

Radiance simulations were made for two types of shading devices, an exterior fabric (screen type) and an interior Venetian blind.

The exterior shading was a dark grey textile with small holes mounted parallel to the glazing. The fabric causes almost no scattering of the transmitted light but have a direct transmittance of 18 %.

Luminances in the field of view with the screen

The screen type reduced the illuminance and luminance levels significantly. Figure 86 shows the luminances in the field of view when looking towards the window, in March at 12:00 hours. For all three window types the average luminance (40° band) dropped from around 5,000 cd/m² to around 1,000 cd/m². The luminance ratio between the window and the surroundings remained about the same, namely 10:1. The maximum luminance at the centre of the windows dropped from 15,000 to 2,800 cd/m², i.e. a reduction to 18 %, as expected.

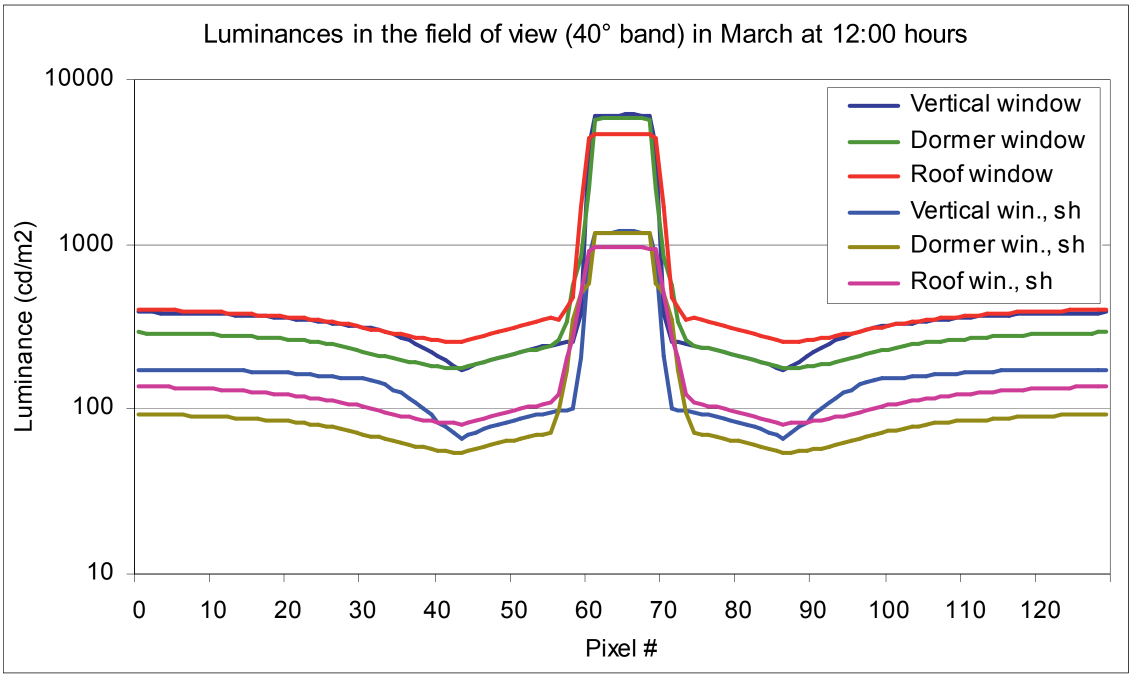


Figure 86. Luminances in the field of view, when looking towards the window, in March at 12:00 hours with South facing windows. The lower 3 curves (SH) show the average luminances with the dark grey fabric screen. All average luminances were reduced to about one third when the screen was used.

Figure 87 shows the corresponding Radiance fish-eye rendition of the room with the roof window, in March at 12:00 hours, facing South. The screen significantly reduced the luminances of the window and the sensation of direct glare from the "light source". It was most obvious that the extreme luminance of the sun patch on the partly specular floor did not show when the screen was used. This can be seen from the iso-luminance contours of Figure 87.

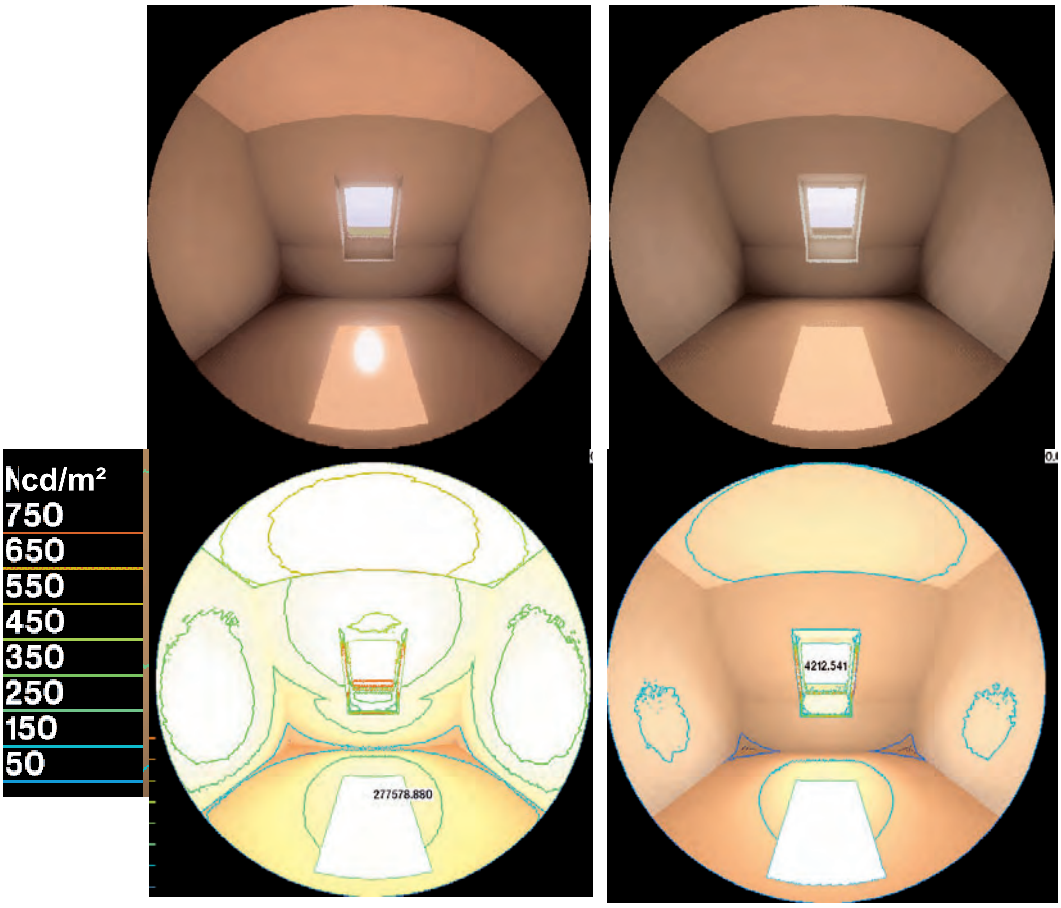


Figure 87. Radiance pcond rendering of iso-luminance contours for the roof window in March at 12:00 hours, without (left) and with (right) the dark grey screen.

Luminances in the field of view with the Venetian blinds

The venetian blinds were the same for the the vertical and the dormer windows, while the slats were smaller for the roof window, see Figure 88.

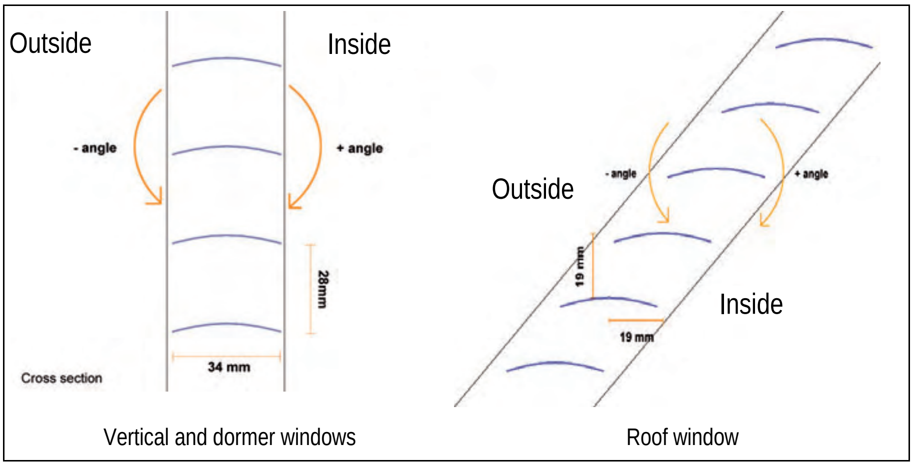


Figure 88. Definition of slat angle for the Venetian blinds for the vertical, the dormer and the roof window.

The Venetian blinds reduced the illuminance and luminance level in the room significantly more than the screen. Figure 89 the average (40° band) luminance in the field of view when looking towards the window, without blinds and with Venetian blinds (vb). The average peak values were somewhat higher than with the screen, while the general luminance levels were significantly lower.

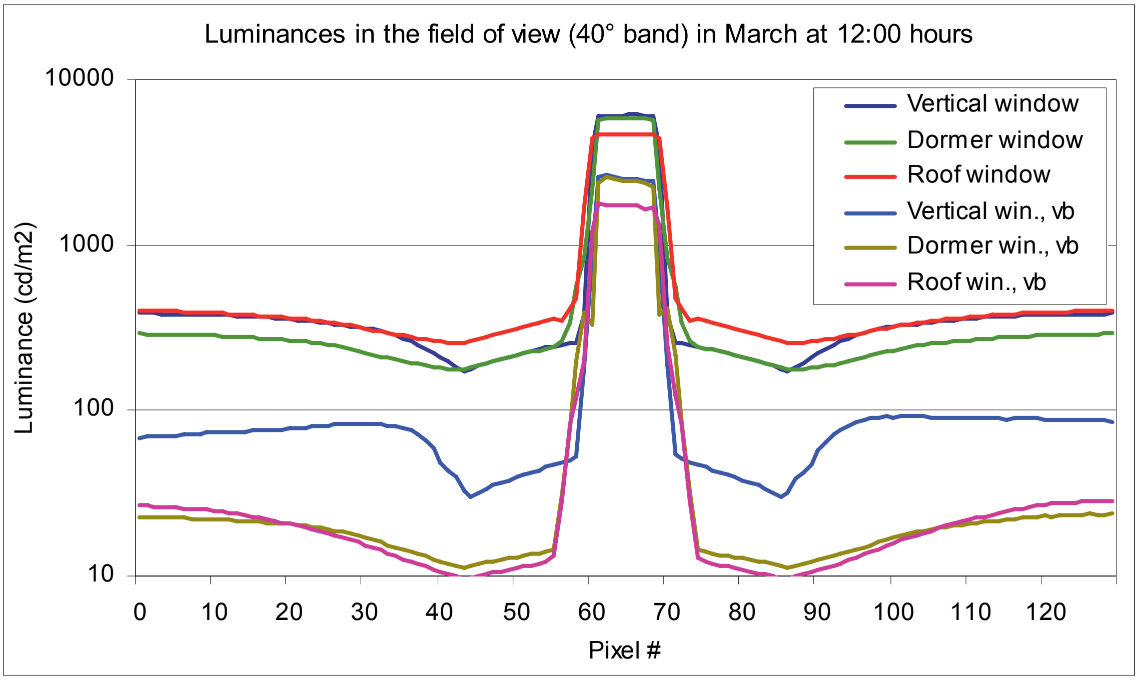


Figure 89. Luminances in the field of view, when looking towards the window, in March at 12:00 hours with South facing windows. The lower 3 curves (vb) show the average luminances with the Venetian blinds with the slats moved to direct-sun cut-off position, see Figure 91. Except for the peak of the window, the general level was reduced to less than 5 % when the blinds were used.

Figure 90 shows the Radiance fish-eye (pcond) rendering and the iso-luminance contours for the roof window without and with the Venetian blinds. It can be seen that there are some reflections from the slats causing very high luminances.

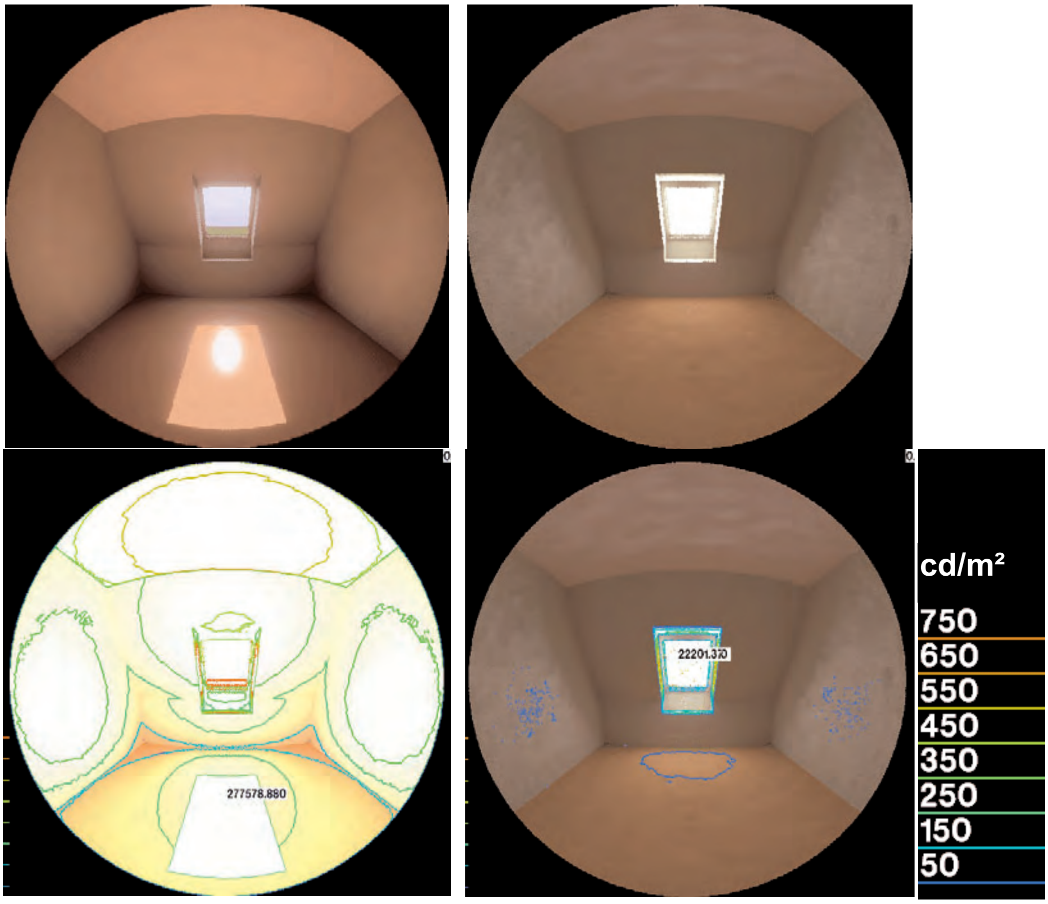


Figure 90. Radiance pcond rendering of iso-luminance contours for the roof window in March at 12:00 hours, without (left) and with (right) the Venetian blinds. The slats were white on the inside and silver specular on the outside.

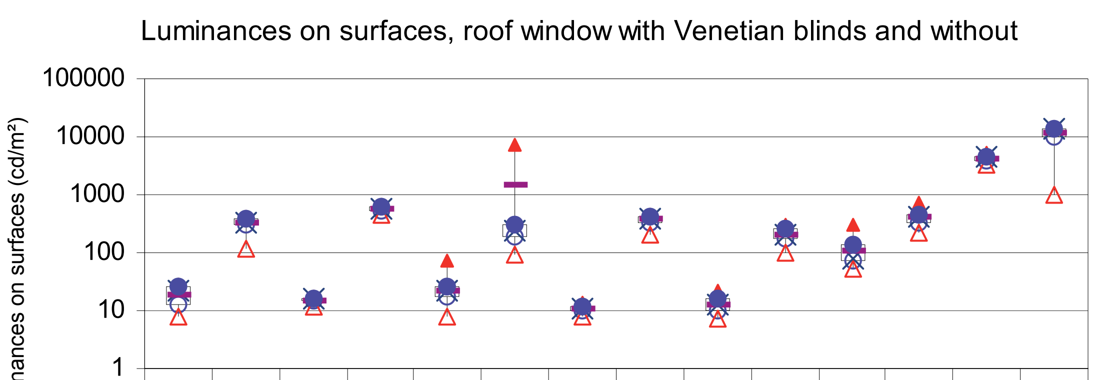
In the simulations the angle of the slats were tilted to the calculated cut-off angle, i.e. the minimum angle that prevent direct sun to penetrate. The angles for each of the simulated cases are shown in Figure 91, and the definition of the angle is illustrated in Figure 88.

Month.hour	Slat angle °	
	Vertical and dormer window	Roof window
Mar 08	-30	- 29
Mar 12	-19	- 25
Mar 16	-40	- 32
May 08	-10	- 22
Jun 10	+17	-6
Dec 12	-45	-34

Figure 91. Radiance rendering of the roof window with the Venetian blinds. The table shows the angles of the slats of the Venetian blinds as defined in Figure 88 for each of the simulation hours (cut off angle).

Luminance distribution on surfaces

Figure 92 show the luminance distribution on the room surfaces with the roof window in March at 12:00 hours with the Venetian blinds and without. The most significant luminance reduction with the blinds was on the floor, where the luminance was reduced to about 1 % of that without the blinds, see Figure 92.



	wall left, vb	wall left	ceiling, vb	ceiling	floor, vb	floor	slope, vb	slope	wind. wall, vb	wind. wall	linings, vb	linings	wind., vb	wind.
○ q1	12	301	15	518	18	182	10	334	10	172	71	335	3995	10373
△ min	8	118	11	443	8	93	8	197	7	102	53	224	3213	981
× median	22	337	16	585	22	238	11	378	12	211	78	421	4380	13434
▬ average	19	329	15	571	22	1526	11	372	13	211	112	407	4294	11682
▲ max	29	417	17	654	75	7362	13	461	22	304	294	709	5110	14798
● q3	25	371	16	627	25	292	11	414	16	250	142	459	4607	14232

Figure 92. Luminance distribution on surfaces in the room with roof window. Minimum, maximum, median, mean and interquartile range (q1, q3) for luminances (cd/m^2) of surfaces in the view towards the window wall, under sunny sky conditions in March at 12:00 hours.

Daylight Glare Index

The daylight glare indices as perceived from the centre of the rooms were calculated for March at 12:00 hours for the three windows in the normal case with double-glazing, with triple glazing, and with the two shading devices. The results showed that the screen reduced the DGI value significantly, while the Venetian blind increased the DGI for all window types, see Figure 93. For the roof window, the DGI rose from “just uncomfortable” to “uncomfortable” on the perception scale, see Table 7 on page 53. The reason for this could be that the luminance of the window area was only reduced to about on third, while the luminance on all other surfaces dropped to 1-2 %.

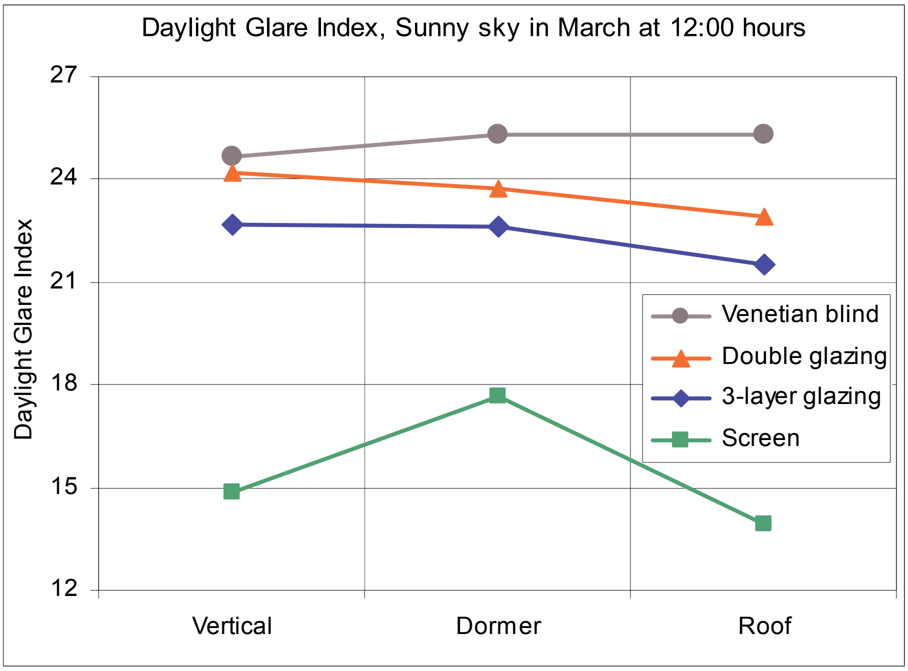


Figure 93. Radiance calculated values of the Daylight Glare Index, DGI, for the two types of glazing and for the double-glazing with the two shading devices.

Renderings for furnished rooms

In order to achieve a more realistic view of the three rooms and the window configurations, Radiance renderings were made with furniture. Figure 94 shows the pcond and false colour renderings for the three cases in May at 11:00 hours. The first impression was that the roof window gave a significantly brighter room, which were also confirmed by the false colour images.

Because of the chosen viewpoint in the images of Figure 94, the geometry of the rooms and the form of the furniture seemed somewhat disturbed. Therefore new images were made with a viewpoint in the symmetry line of the room, as shown in Figure 95. From these images the high luminance of the windows seemed to be more critical with the vertical and the dormer window than with the roof window, mainly because of the higher luminance level under the roof window.

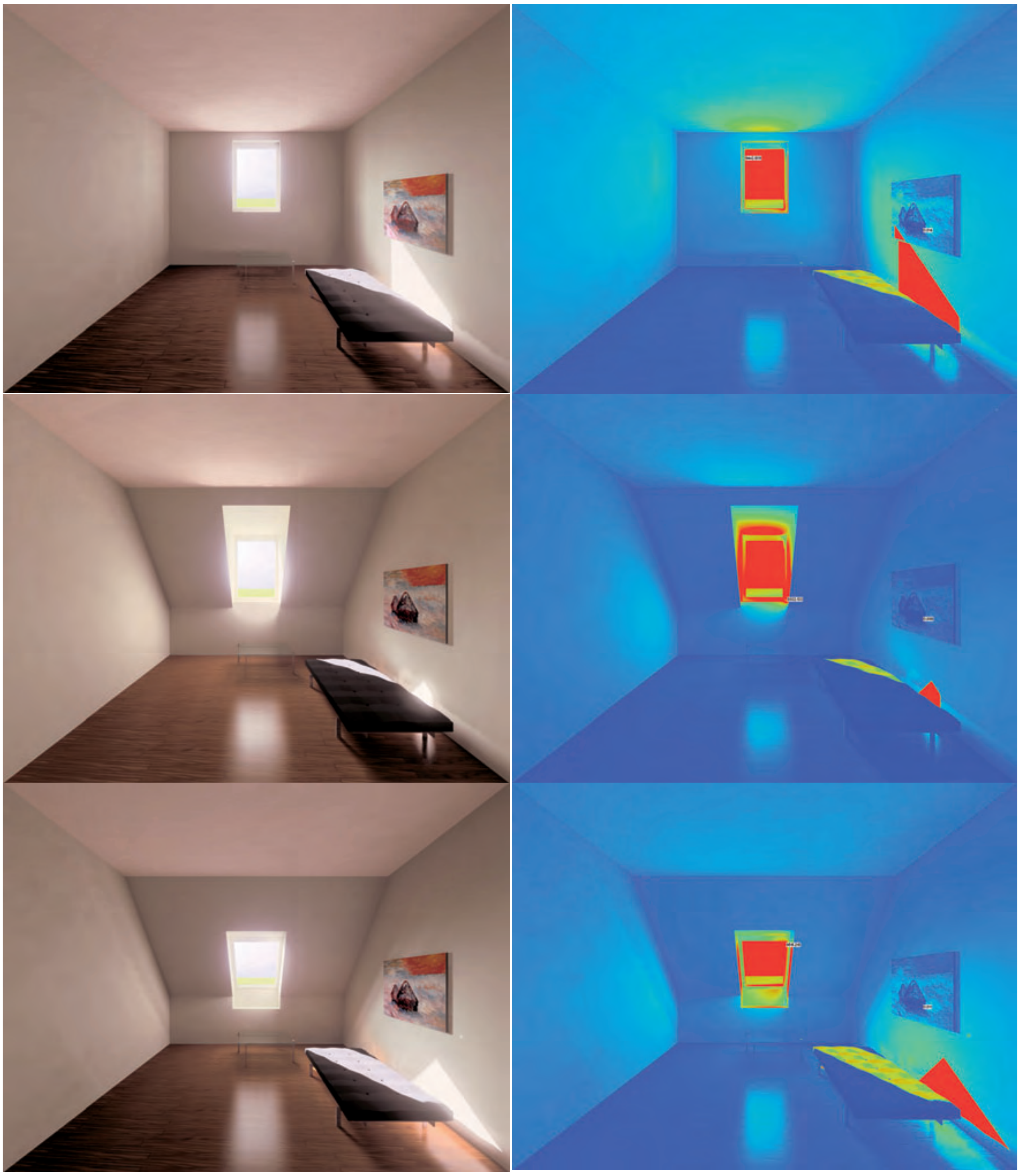


Figure 94. Radiance pcond and false colour renderings for the three rooms with furniture.

Figure 95. Radiance images of the three rooms seen from a viewpoint in the symmetry line. The high luminance of the windows seem to be more critical with the vertical and the dormer window than with the roof window, mainly because of the higher general luminance level under the roof window.

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The present report documents the results of a study on daylight conditions in simple rooms of residential buildings. The overall objective of the study was to develop a basis for a method for the assessment of daylight quality in a room with simple geometry and window configurations. As a tool for the analyses the Radiance Lighting Simulation System was used. A large number of simulations were performed for 3 rooms (window configurations) under overcast, intermediate, and 40-50 sunny sky conditions for each window (7 months, three orientations and for every other hour with direct sun penetration through the windows). A number of light indicators allowed understanding and describing the geometry of daylight in the space in a very detailed and thorough manner. The inclusion of the daylight factor, horizontal illuminance, luminance distribution, cylindrical illuminance, the Daylight Glare Index, vertical-to-horizontal illuminance ratio as well as scale of shadow gave valuable information allowing a detailed description of the three-dimensional geometry of daylight in the space. It should be mentioned however, that there is no universal definition of light quality. The approach in this study was to analyse differences in daylighting conditions for a number of lighting parameters. The results gave clear indications of, for instance, which room would be the brightest, under which conditions might glare be a problem and which type of window would yield the greatest luminous variation (or visual interest), etc.

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