VISUAL COMFORT UNDER REAL AND THEORETICAL, OVERCAST AND CLEAR SKY CONDITIONS

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ABSTRACT

The presented work is devoted to the analysis of visual comfort indexes under theoretical and real sky conditions: clear and overcast. For the selected period of the year, the sky luminance distribution was estimated using standard sky model and measurement data. Measurements were conducted through the whole year from March 2011 to March 2012. Illuminance distribution inside a room was estimated by way of computer simulation using Ray Tracing Techniques. Based on simulation results, Daylight Glare Index and Vertical Illuminance at Eye were determined at 1/3 and 2/3 depth of the room. The main goal of the presented study was to estimate the difference between theoretical and real daylight conditions and its effect on the value of comfort indexes. Both parameters (DGI and VIE) were estimated numerically and experimentally using scale model of the room.

The second purpose of the presented analysis was to find the best possible solution for transparent façades considering different spectral properties of glazing systems. Four glazing systems differring in total visual transmittance were considered and analysed both numerically and experimentally. Taking into account the minimum level of illuminance at a working plane, the recommended solution was proposed. Finally, general remarks for highly glazed buildings were formulated with some recommendation depending on the façade's orientation.

INTRODUCTION

Luminous distribution in a building space is usually analysed as virtual models using advanced numerical techniques (*Radiosity* and *Ray-Tracing*) (Tsangrassoulis & Bourdakis 2003). A variety of daylight simulation programmes have been developed in the last decade based on the calculation methods listed above. For daylight calculations, lighting sources are described by hemispherical luminance distribution – sky models. Sky models are always characterized by an ideal, continuous luminance pattern which differs from the distribution of light over the sky dome (Kittler at al. 1997). There are many sky models but the most common is an overcast sky, frequently used in problems of illuminance distribution. The most popular standardized sky models are recommended by *the International Commission on Illumination CIE* (CIE 1995). The purpose of this paper is to compare illuminance distribution in a scale model of a building under measured and theoretical (CIE models) luminance conditions. Two types of skies have been selected: clear and overcast.

The experiment was conducted using an original measurement station *Heliobox* exposed to external weather conditions. *Heliobox* is a model of a rectangular room (3×3×9 m) built in a scale of 1:6. External daylight conditions were monitored by photometric techniques, on the stand installed on the roof above the *Heliobox*. High Dynamic Range images of the sky were taken every hour. Sky luminance distributions were calculated based on the digital images (Jacobs 2007). The *Backward Ray-Tracing method* was selected for the simulation as it can be used to solve the rendering equation under any kind of reflection or transmission, also in geometrically complicated environments. The computer simulation software Radiance was used for calculations of illuminance distribution (Larson & Shakespeare 1998).

PROBLEM DEFINITION

The problem of visual comfort usually occurs in highly glazed buildings exposed to direct solar radiation. In constructions without solar protection systems, comfort indexes, e.g. DGI, VIE can be improved by different or even changeable solar transmittance ("intelligent materials"), including the character of light (direct or diffuse). The required transparent properties can be obtained by using unusual type of glass: coloured, frozen, etc. Such solutions can eliminate the luminance contrast in building interiors, but on the other hand decrease the illuminance level at a working plane.

Numerical analysis of glare discomfort caused by daylight source is determined by sky luminance distribution. Over the last decades, Kittler and Darula have done a lot of research to formulate more realistic sky models describing external conditions (Darula & Kittler 2009), (Darula et al. 2000). However, differences between real and theoretical sky luminance distribution are still significant, even the proposed number of basic sky types was increased to 15. Therefore, individual model adaptation to local climatic conditions is usually necessary.

VISUAL COMFORT

VCP (Visual Comfort Probability) (IESNA 1984), UGR (Unified Glare Rating) (CIE 1995) and DGI (Daylight Glare Index) (Hopkinson 1972) are well known approaches to the evaluation of discomfort glare. Among others, UGR is the assessment method that the International Commission on Illumination (CIE) defined as the standard to evaluate discomfort glare. For the purpose of current work, two methods were selected and taken to assess visual comfort.

From the human perception, the glare effect can be divided into five degrees: perceptible, acceptable, borderline between, uncomfortable, and intolerable. Classification to one of the following groups depends on the value of Daylight Glare Index (DGI). The highest luminance in the building interior is caused by the light source, e.g. window and other elements of the transparent envelope (direct glare). The first expression of DGI was based on an analytic relation to the so-called Cornell'a formula (Hopkinson & Bradley 1960), by modification of Chauvel et al. (1982). For n light sources of glare index is expressed as follows:

$$DGI = 10\log\sum_{i=1}^{n} G_i \qquad (1)$$

where:

$$G_i = 0{,}478 \cdot \left(\frac{L_{vs}^{1,6} \cdot \Omega_i^{0,8}}{L_{vb} + \left(0{,}07\omega^{0,5} \cdot L_{vw}\right)} \right) \qquad (2)$$

where:

L_{vs} is the luminance of each part of the source [cd/m^2],

L_{vb} is the average luminance of the surface in the environment, within the field of view [cd/m^2],

L_{vw} is the weighted average luminance of the window, in function of the relative areas of sky, obstruction and ground [cd/m^2],

ω is the solid angle of the window [sr],

Ω is the solid angle of the source, modified in function of the line of sight [sr].

The second glare index analysed in this work is Vertical Illuminance at Eye (VIE) directly calculated by RADIANCE model.

MODELLING AND MEASUREMENTS

Model set up and measurement installation

The simulation analysis and the experiment were conducted for the selected, fully cloudy (overcast sky), and sunny (clear sky) days of the year 2011÷2012. The experiment was conducted for a scale model of rectangular building space (3×3×9 m) *Heliobox* (Figure 1). Location of the installation is Central Europe, latitude 52 degrees north. Reflectance, expressed in *RGB* format of all internal surfaces are presented in Table 1.

Table 1
Physical properties of opaque and transparent

DATE	INTERIOR				GLASS	
	NAME	R	G	B	NAME	τ
27-01-2012 12:14	90	55	55	55	0	0,84
10-02-2012 12:07					1	0,66
27-04-2011 12:10					2	0,45
01-02-2012 13:05					3	0,20
27-04-2012 12:30	0	227	228	226	0	0,84
20-04-2011 12:17					1	0,66
19-06-2012 12:25					2	0,45
29-06-2012 08:35					3	0,20
07-02-2012 11:14	90	55	55	55	0	0,84
13-02-2012 14:11					2	0,45
20-02-2012 14:06					3	0,20
04-01-2012 12:16	0	227	228	226	0	0,84
18-01-2012 12:01					1	0,66
06-04-2011 12:10					2	0,45
11-04-2011 12:08					3	0,20

The transparent part of the external wall was oriented to the south. The daylight source for the building space was a solar radiation transmitted through glass pane with a thickness of 4 mm and different visual transmittance τ_{vis} presented in Table 1. All optical parameters for opaque and transparent surfaces were obtained using spectroscopy measurements (VIS). A set of nine luxmeters for simultaneous illuminance measurement was installed inside the *Heliobox* at the height corresponding to the height of the working plane (Figure 2). The last, tenth luxmeter was installed outside *Heliobox* on a horizontal plane to measure total horizontal illuminance. The same model was defined in Desktop Radiance for daylight simulation. Materials properties were assumed to be the same as for the experiment. Transparent elements were described as a glass with visual transmissivity and opaque material was defined using RGB values, with specularity equal 0.

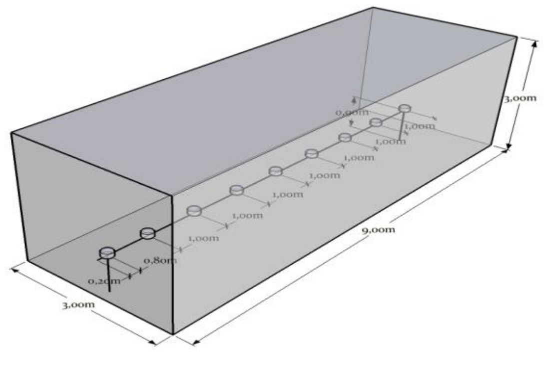

Figure 1 Scheme of head distribution in Heliobox

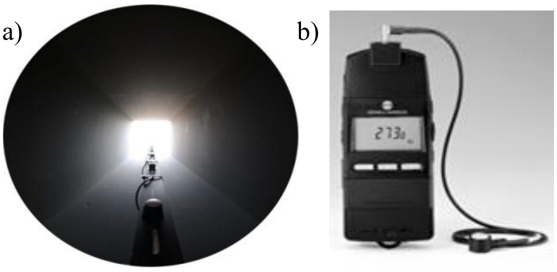

Figure 2 a) Interior of Heliobox, b) meter T-10 with measurement head

Monitoring of the sky luminance

Boundary conditions for the simulation were defined separatelly for each hour, according to theoretical and measured sky luminance distribution (Tables 2 & 3). Weather conditions during measurements were classified as a clear and fully cloudy sky. Cloudiness was at the level of 0% or 100%. For 0% of cloudiness, the sky was completely clear, while for 100% it became regularly covered by clouds with an invisible sun disc. Sky area with different lumination was defined based on HDR images (Table 2). Obtained quantities were verified by comparing HDR results and mesurements of zenith luminance by a high precision luminance meter (with a small view angle 1 sr).

Additionally, for the purpose of simulations, all overcast sky models were adopted to the measured conditions by comparison of horizontal illuminance. The corrected values are presented in Table 3 (last column). Due to the lack of separate, direct, and diffuse light measurements data, it was impossible to adapt this information for simulation.

RESULTS & ANALYSES

The results are presented in the following form:

- 2D distribution along building depth (Figures 3÷8):
- spatial distribution from camera toward the window (Table 6), and
- as comfort indexes: horizontal illuminance (Table 2), DGI (Table 4), and VIE (Table 5).

Results of analyses performed for clear skies are presented in Figures 3 & 4. For 2D illuminance distribution, the highest differences were noticed for light colour of interior (Figure 3). Differences are in both the boundary of lighted area and local illuminance value. For heavy dark skies, daylight distribution is more regular. This effect is also confirmed on a spatial distribution (Table 6).

Results of analyses conducted for overcast skies are presented in Figures 5÷8. Based on the results presented in Figures 6 & 8, the effect of luminance adaptation was noticed. For glass “1” and “0”, the total agreement was obtained, while for glass “3”, the differences increased. For glass “2”, the measured and simulation results are inverted, however in this case the sky condition was relatively bright. It was also noticed from the previous work that for very bright cloudy skies, the overcast model is inappropriate. Comparison of figures 5 & 7 confirm the effect of adaptation for glasses “0” and “3”. For glass “2” the effect is worst again but this time the sky is very foggy.

The spatial distribution of the light in an analysed room (Table 6) was used for estimation of DGI index (Table 4). Based on the general criteria, the visual environment can be classified in 8 class from "just perceptible" (DGI<16) to "intolerable" (DGI>28). For all cases under cloudy sky, the indoor visual condition can be classified as comfortable, with highest DGI at 6 m from the window. The highest values were obtained for four types of clear skies, while the visual conditions are classified as uncomfortable. For one moment daylight conditions were even intolerable, DGI above 28.

While evaluating results of Vertical Illuminance at Eye, it is necessary to consider the visual and non-visual effects of light on human body. While for the visual effect the required value is 50-150 lx, the non-visual in the morning is even 2000 lx. Based on the results presented in Table 5, the most required values were recorded for overcast sky at 3 m from the window. For clear skies these values are much than few times higher. Additionally, the differences between theoretical and adapted skies are still even double.

SUMMARY

This paper is the first step in an extensive project related to the validation of visual comfort parameters obtained by numerical techniques.

ACKNOWLEDGEMENTS

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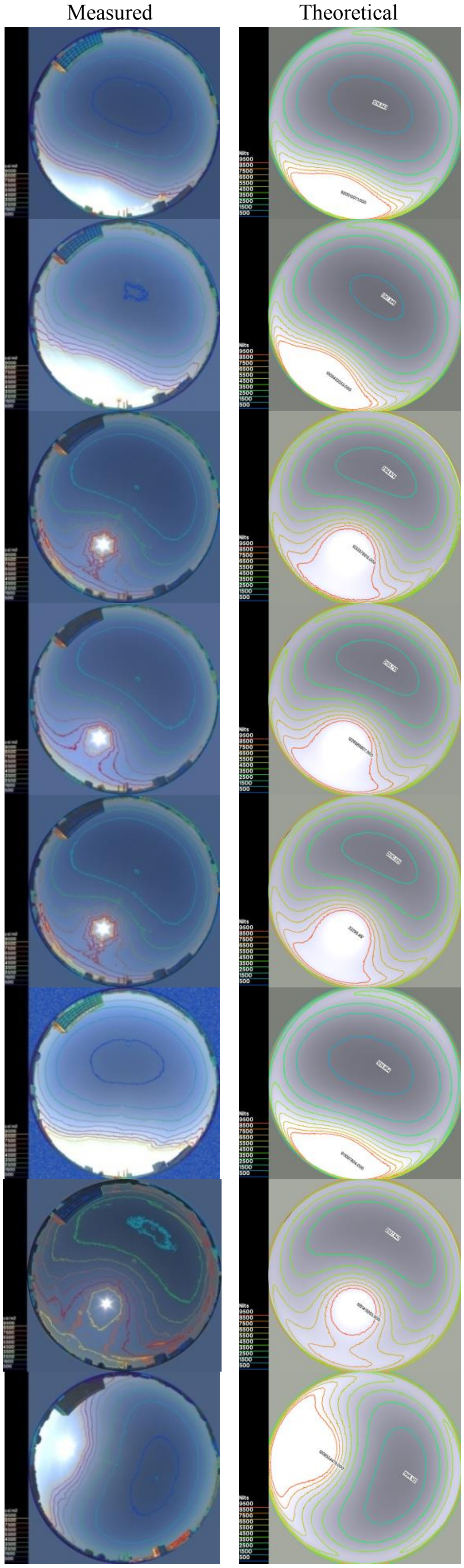
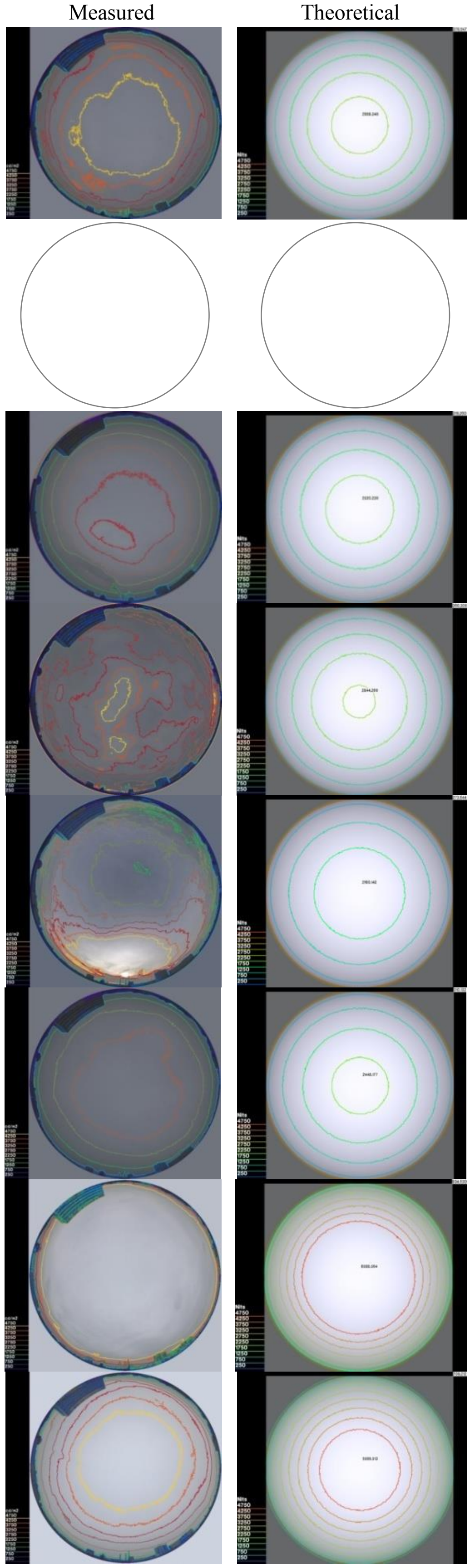
Table 2
Luminance distribution of measured and theoretical clear sky and overcast sky.





	Clear sky date/time (Measured, Theoretical)	Overcast sky date/time (Measured, Theoretical)
0	27-01-2012 12:14	07-02-2012 11:14
1	10-02-2012 12:07	
2	27-04-2012 12:30	13:02-2012 14:11
3	20-04-2011 12:17	20-02-2012 14:06
0	27-04-2011 12:10	04-01-2012 12:16
1	01-02-2012 13:05	18-01-2012 12:01
2	19-06-2012 12:25	06-04-2011 12:10
3	29-06-2012 08:35	11-04-2011 12:08

Table 2 (continuation)
Luminance distribution of measured and theoretical adapted overcast sky.

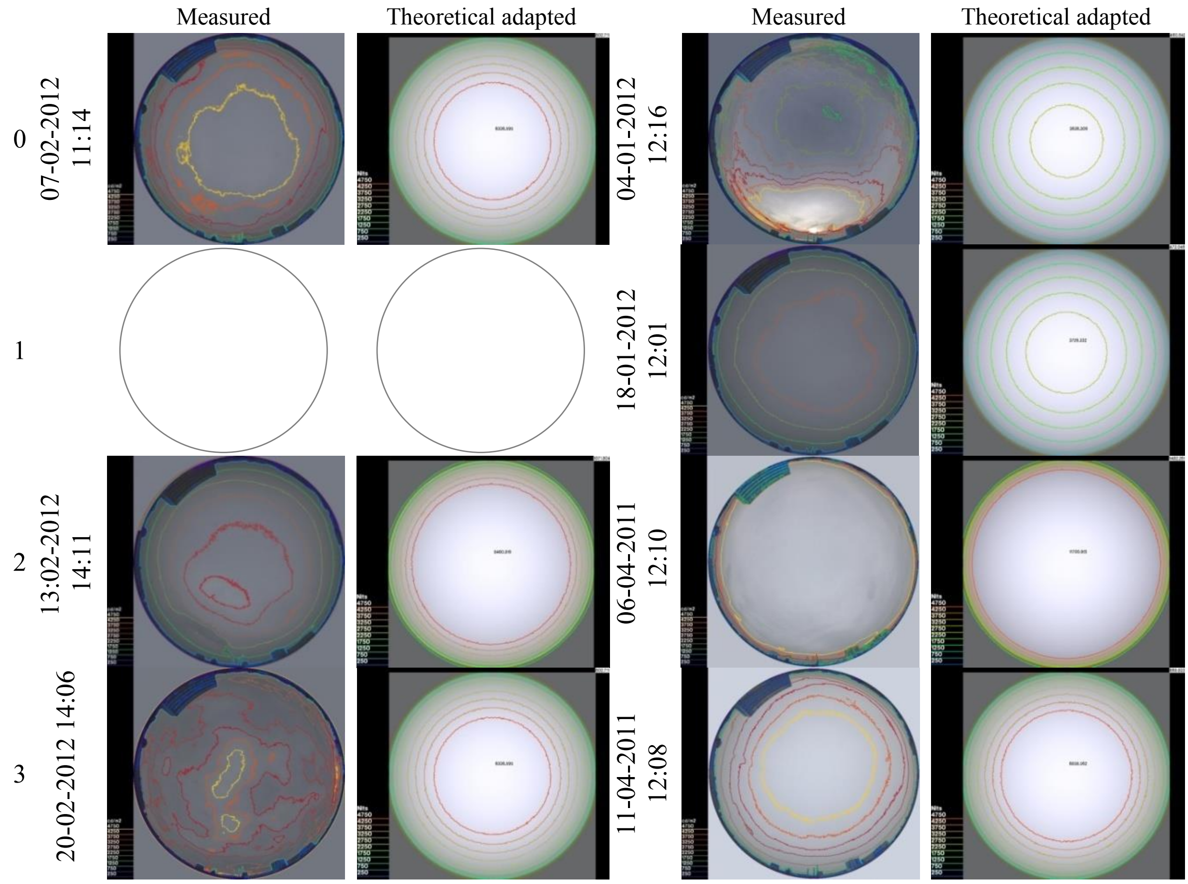


Table 3
Comparison of boundary conditions

	DATE	HORIZONTAL ILLUMINANCE		
		MEASURED	THEOR.	THEOR. ADAPT.
0	27-01-2012 12:14	31920	28299	-
1	10-02-2012 12:07	38800	35329	-
2	27-04-2011 12:10	91450	74679	-
3	01-02-2012 13:05	37740	30726	-
0	27-04-2012 12:30	96750	73767	-
1	20-04-2011 12:17	92550	71917	-
2	19-06-2012 12:25	105850	83427	-
3	29-06-2012 08:35	6485	69046	-
0	07-02-2012 11:14	15405	7258	15391
1	-	-	-	-
2	13-02-2012 14:11	20565	6122	20541
3	20-02-2012 14:06	12360	6909	12368
0	04-01-2012 12:16	8815	5246	8828
1	18-01-2012 12:01	9050	5944	9047
2	06-04-2011 12:10	28400	13155	28408
3	11-04-2011 12:08	16650	13592	16651

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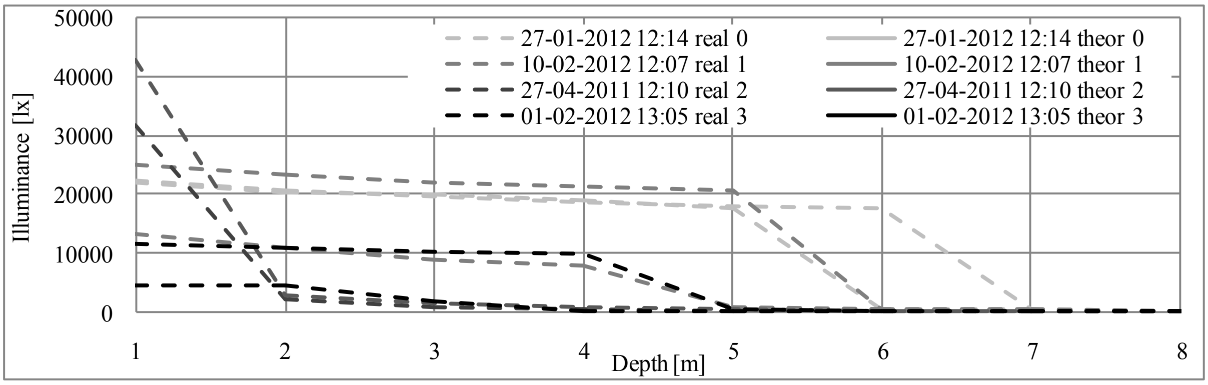

Figure 3 Illuminance distribution for Clear Sky in Heliobox with black surfaces – measured vs. simulation (theoretical)

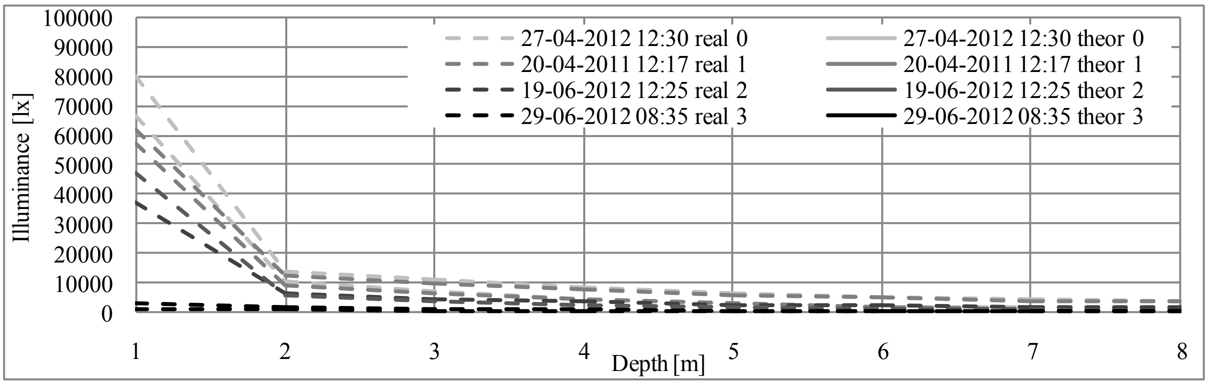

Figure 4 Illuminance distribution for Clear Sky in Heliobox with white surfaces – measured vs. simulation (theoretical)

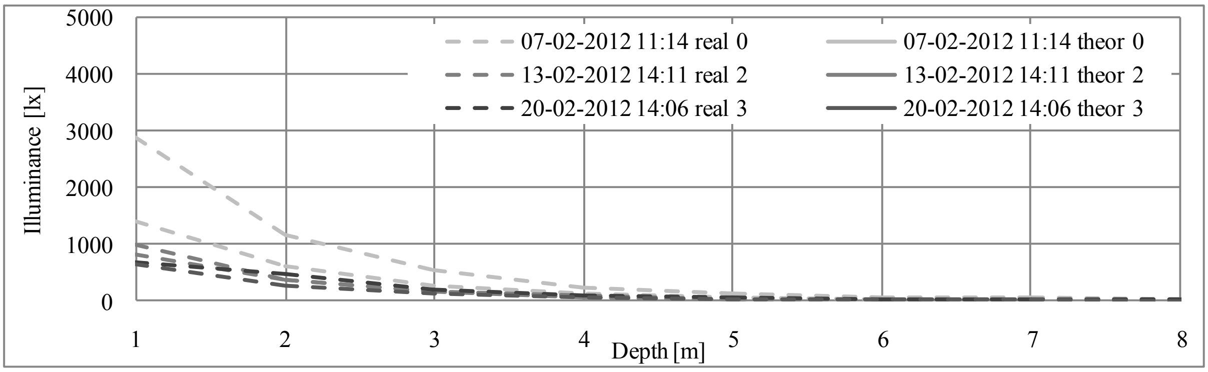

Figure 5 Illuminance distribution for Overcast Sky in Heliobox with black surfaces – measured vs. simulation (theoretical)

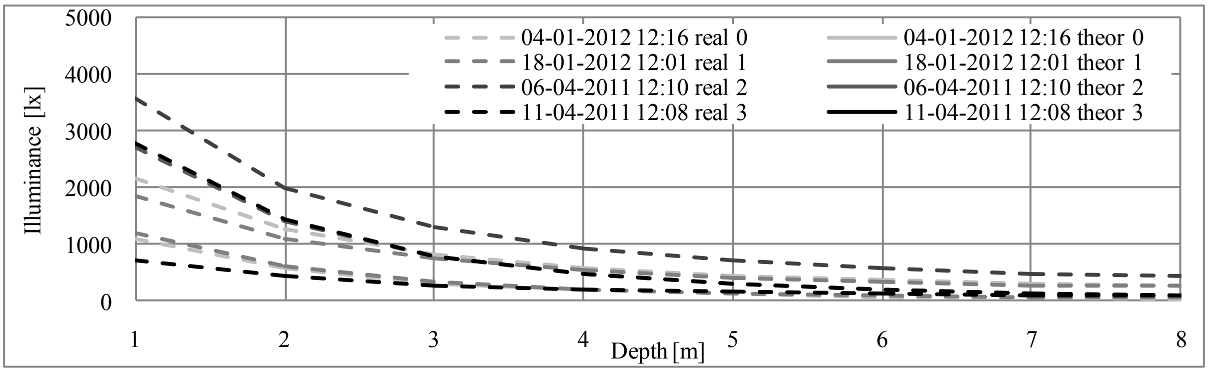

Figure 6 Illuminance distribution for Overcast Sky in Heliobox with white surfaces – measured vs. simulation (theoretical)

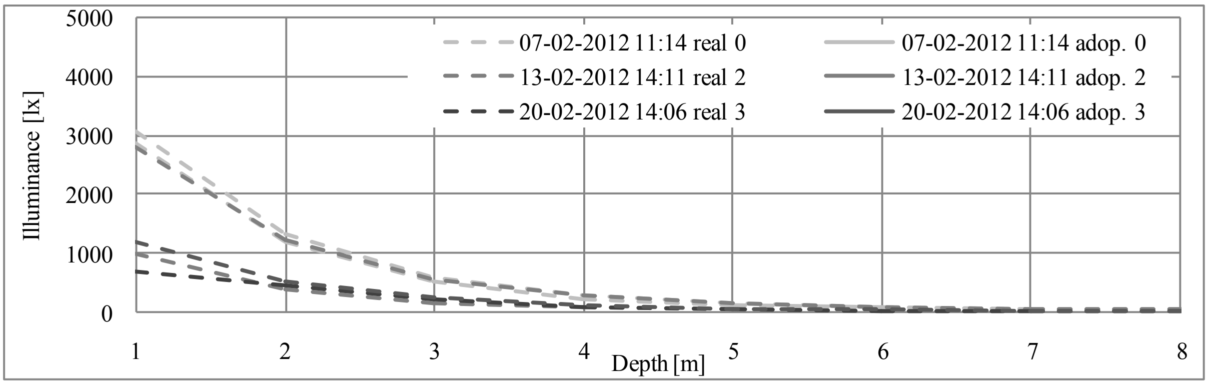

Figure 7 Illuminance distribution in Heliobox with black surfaces —measured vs. simulation (theoretical adapted Overcast Sky)

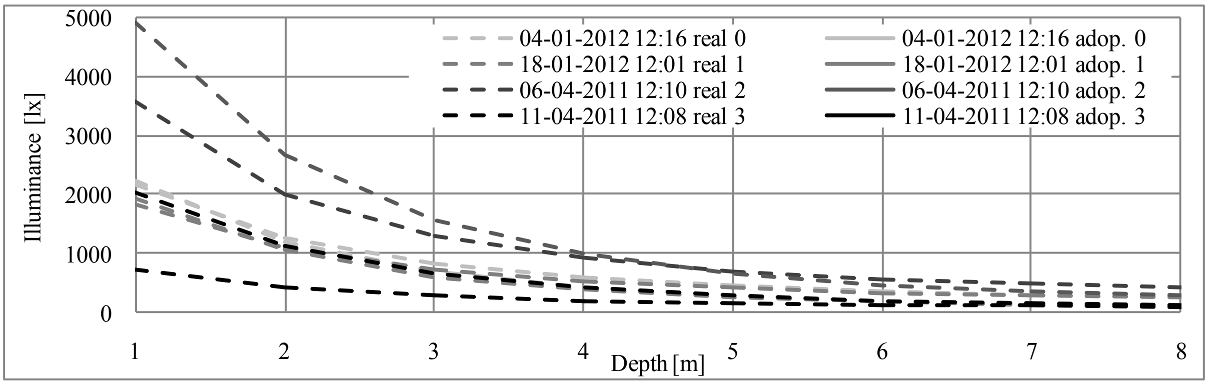

Figure 8 Luminance distribution in Heliobox with white surfaces —measured vs. simulation (theoretical adapted Overcast Sky)

Table 4
Daylight Glare Indexes for analysed time period

	DATE	DGI			
		1/3		2/3	
		THEOR.	THEOR. ADAPT.	THEOR.	THEOR. ADAPT.
0	27-01-2012 12:14	20,66	-	26,47	-
1	10-02-2012 12:07	18,35	-	25,57	-
2	27-04-2011 12:10	0	-	23,82	-
3	01-02-2012 13:05	38,29	-	23,91	-
0	27-04-2012 12:30	0	-	18,76	-
1	20-04-2011 12:17	0	-	16,00	-
2	19-06-2012 12:25	0	-	16,24	-
3	29-06-2012 08:35	0	-	15,88	-
0	07-02-2012 11:14	3,37	8,09	18,39	21,47
1	-	-	-	-	-
2	13-02-2012 14:11	5,89	7,05	17,93	21,95
3	20-02-2012 14:06	8,13	5,42	18,26	18,26
0	04-01-2012 12:16	0	0	15,15	12,66
1	18-01-2012 12:01	0	0	10,24	12,36
2	06-04-2011 12:10	0	0	13,45	15,99
3	11-04-2011 12:08	0	0	10,76	13,43

Table 5
Vertical Illuminance at Eye for analysed time period

	DATE	VIE			
		1/3		2/3	
		THEOR.	THEOR. ADAPT.	THEOR.	THEOR. ADAPT.
0	27-01-2012 12:14	8352	-	4357	-
1	10-02-2012 12:07	8918	-	4052	-
2	27-04-2011 12:10	7249	-	1425	-
3	01-02-2012 13:05		-	1923	-
0	27-04-2012 12:30	17645	-	6148	-
1	20-04-2011 12:17	18548	-	5788	-
2	19-06-2012 12:25	10202	-	3403	-
3	29-06-2012 08:35	3775	-	1460	-
0	07-02-2012 11:14	419	1722	123	520
1	-	-	-	-	-
2	13-02-2012 14:11	1202	1670	105	487
3	20-02-2012 14:06	763	1388	119	119
0	04-01-2012 12:16	2686	1462	1035	659
1	18-01-2012 12:01	2202	1441	399	589
2	06-04-2011 12:10	1104	3742	678	1442
3	11-04-2011 12:08	1272	1554	577	646

Table 6
Luminance distribution for theoretical Clear Sky and Overcast Sky