PREDICTING OF DAYLIGHT ON VERTICAL PLANE IN REAL OFFICE ENVIRONMENT FOR VISUAL AND BIOLOGICAL EFFECTS

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1. Introduction

The effects of natural light on health, welfare and productivity of employees have been known for a long time, but only recently scientists discovered the mechanism through which natural light triggers these effects (Berson et.al., 2002, Brainard and Hanifin, 2005, Lockley et.al., 2003). The human eye is sensitive to the part of sunlight spectrum between 380 and 780 nm. Photoreceptors responsible for spectral sensitivity of eye (vision) have the peak at other wavelengths than receptors responsible for regulation of circadian rhythms (secretion of melatonin and regulation of other hormones) (Brainard et.al., 2001). Recent studies of office environments confirm the connection between the quality of environmental factors (especially lighting), productivity and health of employees. A study conducted by Heschong (2003) showed that the impact of well-lit workspaces directly reflects in the performance of employees. Dogrusoy and Tureyen (2007) in his field study demonstrated that most employees prefer natural lighting and that the employees define the three most important factors of pleasant working environment as daylight, exposure to sun and natural ventilation. Mills et al. (2007) found that blue light improves productivity, Hoffmann et.al. (2008) discovered that variable light potentially improves the mood of employees in an office environment. The above mentioned studies show that circadian rhythms in addition to light also affect the productivity and mood. Existing regulations, standards, guidelines and recommendations in the field of daylighting refer to the entire visible spectrum and deal with lighting suitable for visual tasks, thus illuminances at workplane are controlled. Triggering of biological (non-visual) effects of daylight involves a different light intensity and spectral composition, and requires illumination at the eye.

People on average spent 80-90% of the time in indoor working and living environment (Evans and McCoy, 1998). As a consequence exposure to strong and direct daylight is short, and this has negative psychological and physiological consequences (Boubekri, 2004). This information is crucial for the evaluation of workplaces, especially because according to the study by Aries (2005) only at one fifth of the existing workplaces the values at which the light has a positive impact on the biological responses of the organism were reached. In the following study we examined an existing office environment and compared the level of illumination at workplane and at the eye level. Rea et al. (2002) have also found that the level of electric lighting at the eye is three to five times lower than levels measured at the working plane. The aim of the study was to define how the hitherto known criteria are reflected in the real time situation and whether it is possible to obtain relevant information for vertical illuminance at eye level with simple simulation tools usually used in architectural praxis. We compared the results measured in real time office environment during various periods of year to the calculated values (both horizontal and vertical illuminances) and determined the extent of certainty with which the conditions in an office can be predicted with computer tools.

2. Daylight study of an office space

2.1 Background

The most obvious and commonly known effect of light on people is influence of illumination on the visual perception. Sufficient amount of light in the room is treated at two levels. The first level is the general room lighting and the second level refers to the illumination of the workplace, which strongly influences work efficiency (Goodman et.al., 2006, Juslen et.al., 2007). Although the human eye is very flexible, an optimal performance of visual function can be expected only in the range of certain illumination levels. Illumination requirements for office work (writing, reading, work on computer, etc.) are defined at workplane and must be in the range of 300 – 750 lx (EN 12464-1, 2004).

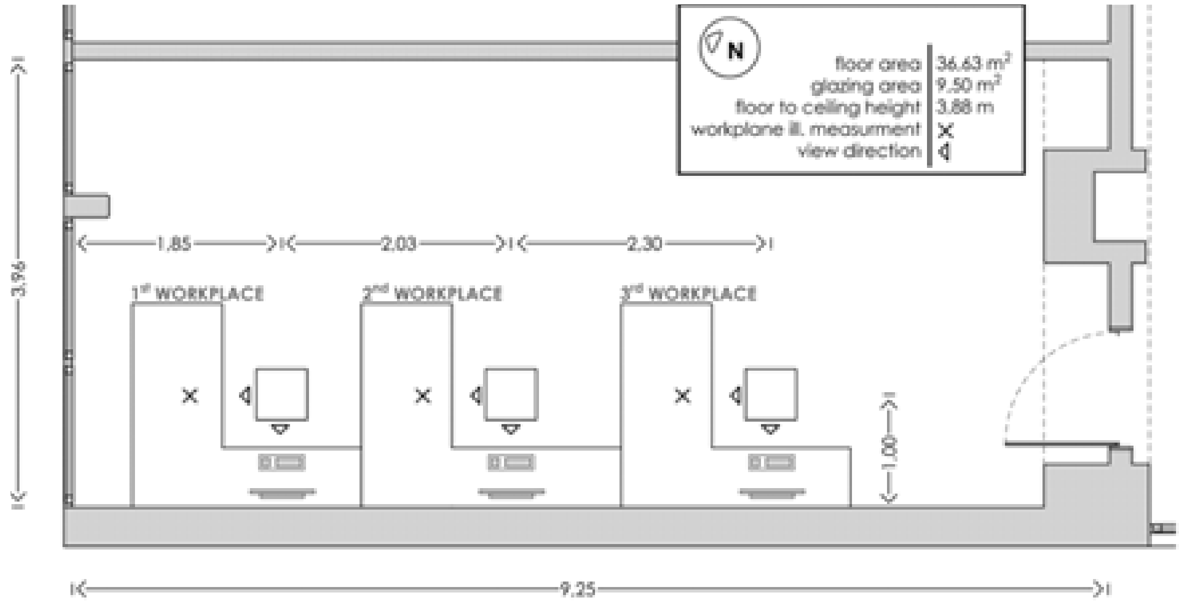


Fig. 1: Plan of the office space

The influence of light on the psychological and physiological functioning of the organism requires higher levels of illumination, especially incidence of short wavelengths directly into the eye. Intensity and the exact composition of the spectrum are presently not precisely defined, but the existing studies suggest that light has to contain the blue part of the visible spectrum and reach the value over 1000 lx at the eye (Boivin et.al., 1996, Zeitzer et.al., 2000, Cajochen et.al., 2000, Schierz 2002). At most existing work spaces spectrum of artificial light significantly differs from the spectrum of natural light. The commonly used glazing (for instance combined plain and low-E glass) transmits light that contains a high portion of visible light and thus also the blue part of the spectrum. Knowing this, the obvious solution is that most of the needs for biological effects can be provided by well designed windows, while the light for visual functions can be provided by means of daylight, artificial light or a combination of both. We have to bear in mind that doses of blue light are needed during certain time periods (eg. morning and early afternoon) and the person may receive them at the workplace, while moving about the room or in the external environment. The light for performing of visual tasks must be fairy constant and is required at the workplace.

2.2 Measurements of the real time office environment

The daylight measurements were carried out in office situated on the 3rd floor of the Faculty of Civil and Geodetic Engineering building in Ljubljana (46.03°N). The dimensions of the office are: length: 9.25 m, width: 3.96 m and a height 3.88 m. The thickness of the external wall is 0.41 m Window is positioned on the north wall and covers the entire wall (3.4 m / 2.8 m) with exception of the sill with height of 0.85 m. Glazed area of 9.5 m^2 thus amounts to 26 % of the floor area and 49% of the window wall. The window is glazed with double 6 mm glass, with low-E coating, gap of 16 mm and Argon filling. The window frames are 8 cm wide Aluminium profiles. The measured light transmittance (τv) is 0.66 (dirt on glass was taken into account). The window is not shaded.

The room is equipped with standard office furniture. Surface reflectance is: floor 35%, walls average 65%, and ceiling 80%. The 1st working place is positioned 1.85 m from the window, the 2nd 3.88 m and the 3rd 6.18 m. The detailed setup of the office is presented in Fig. 1. Measurements were executed in overcast and clear sky conditions. As a reference value 500 lx was set for task illuminance and 1000 lx for vertical illuminance at the eye.

North oriented window was chosen because in this phase of experiments the window was not shaded. Any other orientation would therefore cause direct sunshine onto the vertical measurement plane and sun patches on workplane which would cause glare in real-time conditions. Under these circumstances the employees would probably use shading and the measured values would not be realistic. As shown at the end of the paper on the case of real-time west oriented office, the use of shading completely changes the conditions in the room compared to the free-run state or simulations. This approach however enabled us to evaluate only diffuse light. It can be expected that the illuminance values at other orientations would be at least such as these or higher.

Measurements were taken at the:

- E_a: Horizontal working plane (measured at 0.76 m above the floor level).
- E_b: Eye looking at (directed towards) workplane, measured 1.20 m above the floor lever (45º inclination towards workplane, sitting laterally to the window).
- E_c: Eye looking at computer screen, measured 1.20 m above floor level (measured at vertical position, sitting laterally at the window).
- E_d: Eye looking towards window, measured 1.30 m above floor level (measured at vertical position, sitting laterally at the window).

With these parameters were covered typical positions of a person performing office work. The measured values were obtained by manual lux meter (LX-101, Lutron). The aim was to present typical conditions on the location, two of them are presented in the tables below (December and April/May). Measurements were carried out under overcast and clear sky the time of measurements was from 11 a.m. to 1 p.m.

2.3 Illuminance measurements overcast sky

The calculated E_{av} reached sufficient level regarding task lighting, but E_{min} was very low (lower than 300 lx). Consequently, spatial distribution was inadequate (uniformity ratio E_{min} / E_{av} was 0.13).

Tab. 1: Illuminance under overcast sky at three specific workplaces and at four specific positions

Sky: overcast	**1st workplace** E_{in} (lx)		**2nd workplace** E_{in} (lx)		**3rd workplace** E_{in} (lx)	
Position of measurement	April/May	December	April/May	December	April/May	December
Horizontal exterior	9450	18000	9450	18000	9450	18000
Horizontal workplane	795	1045	215	460	117	210
Looking at workplane	361	650	102	181	62	98
Looking at computer screen	332	600	77	150	57	90
Looking toward window	1483	1990	668	950	341	450

During the measurements in April and May sufficient daylighting of workplane was achieved only on the 1st workplace which is nearest to the window. There the level reached almost 800 lx. On the 2nd and 3rd workplace the levels were 215 lx and 117 lx, respectively. These levels were too low to be adequate for performing of the expected visual tasks, and additional electrical lighting was necessary. From the aspect of biological effects the value over 1000 lx at the eye was achieved on the 1st workplace with the eye oriented toward the window. On the 2nd and 3rd workplaces the levels were 668 lx and 341 lx, respectively. Daylight levels in positions of the eye looking at the workplane and at the computer screen were all much lower than required. During the measurements in December sufficient daylighting of workplane was achieved only on the 1st workplace which is nearest to the window. There the illuminance exceeded 1000 lx. On the 2nd workplace the level was 460 lx and was acceptable. The 3rd workplace was not adequately daylighted. Similar situation occurred when vertical illuminances in the direction of window were measured. The eye at the 1st workplace received 1990 lx, which is well over 1000 lx and at the 2nd workplace 950 lx, which is nearly adequate. The 3rd workplace received 450 lx, approximately half of the required value. Illuminance levels in positions of the eye looking at the workplane and at the computer screen were all much lower than required. We can conclude that the 1st workplace is sufficiently daylighted, the 2nd workplace is on the limit of acceptable values and the 3rd workplace is inadequate (Tab. 1).

Even though the absolute illuminance values deeper in the room did not reach the reference levels, it is interesting to know that the ratios between the horizontal and the vertical illuminance were quite constant. The measured illuminance values depended on the external conditions and the objects in the person's visual field. In our case a large portion of the window opening appeared in the visual field. For instance the ratio between vertical illuminance and horizontal workplane illuminance measured in April and May was 1.9 at the 1st workplace and 3.0 at the 2nd and 3rd workplaces.

2.4 Illuminance measurements clear sky

The measurements were performed during May and December around midday. External horizontal illuminance under clear sky (H_{ex}) was 31500 lx in December and 35400 lx in April-May. Average horizontal illuminance of the office space calculated on the basis of the spring measurements (E_{av} = 637 lx) was adequate for office work. Minimum measured illuminance value (E_{min} = 131 lx) does no reach the recommended value (300 lx) (EN 12464-1; 2004) and the uniformity ratio is not adequate (E_{min}/E_{av} = 0.20).

Tab. 2: Illuminance under clear sky at three specific workplaces and at four specific positions

Sky: clear	**1st workplace** E_{in} (lx)		**2nd workplace** E_{in} (lx)		**3rd workplace** E_{in} (lx)	
Position of measurement	April/May	December	April/May	December	April/May	December
Horizontal exterior	35400	31500	35400	31500	35400	31500
Horizontal workplane	857	580	360	260	218	200
Looking at workplane	437	280	210	142	116	106
Looking at computer screen	412	260	189	125	105	100
Looking toward window	1811	1330	1183	765	732	405

During the measurements in April and May sufficient daylighting of working plane achieved only at the 1st workplace, which is nearest to the window. There horizontal illuminance level reached 857 lx. At the 2nd workplace the level was 360 lx and exceeded the minimum criterion, at the 3rd workplace the level was 280 lx. From the aspect of biological effects the value over 1000 lx was achieved at the 1st workplace and the 2nd workplace at the eye looking toward the window. At the 3rd workplace the level was 732 lx and was therefore too low. Daylight levels in positions of the eye looking at the working plane and at the computer screen were all much lower than the reference. We can conclude that the 1st workplace was sufficiently daylighted, the 2nd workplace was somewhat adequate and the 3rd workplace was inadequate. Ratio between vertical illuminance and horizontal working plane illuminance was 2.2 at the 1st workplace, 3.4 at the 2nd and 3.5 at the 3rd workplace. The calculated average illuminance (E_{av} 668 lx) was quite high but the distribution of light was very uneven (uniformity ratio $E_{c\ min}$ / $E_{c\ av}$ is 0.20) (Tab. 2). During the December measurements sufficient daylighting of workplane was as expected achieved only on the 1st workplace. There the illuminance reached 580 lx. On the 2nd and 3rd workplace the level was 260 lx and 200 lx, respectively. Similar situation occurred when vertical illuminances in the direction of window were measured. The eye at the 1st workplace received 1330 lx, which is over 1000 lx and at the 2nd workplace 950 lx, which is nearly adequate. The 3rd workplace received 450 lx, approximately half of the required value. Illuminance levels in positions of the eye looking at the workplane and at the computer screen were all much lower than required. We can conclude that the 1st workplace is sufficiently daylighted, the 2nd workplace is on the limit of acceptable values and the 3rd workplace is inadequate.

The results of the on-site measurements showed that illuminance at different directions of view are the highest when directed toward the window and exceed 1000 lx at the 1st workplace for clear and overcast sky conditions and in some cases at the 2nd workplace under clear sky conditions. The illuminance values at the eye looking at the working plane and computer screen at all workplaces reach a quarter or less of the value at the eye looking toward the window, both under overcast and clear sky conditions and did not reach the reference values. The differences of illuminance levels are not just seasonal but strongly vary with weather conditions.

Tab.3: Illuminance at three workplaces (vertical at eye level and horizontal at workplane) in specific office space for three reference days

Sky: CIE overcast						
	21st December		**21st March/September**		**21st June**	
	Illuminance (lx)	**V_n/H_n**	**Illuminance (lx)**	**V_n/H_n**	**Illuminance (lx)**	**V_n/H_n**
H_{ex}	6687,03		15340,27		17350,71	
$V_{1\ III/1-2}$	576	1,28	658	1,15	716	1,22
$H_{1\ III/1-2}$	449		574		586	
$V_{2\ III/1-2}$	280	1,47	343	1,60	336	1,43
$H_{2\ III/1-2}$	191		215		236	
$V_{3\ III/1-2}$	133	1,58	164	1,77	169	1,61
$H_{3\ III/1-2}$	84		93		105	
Sky: CIE clear						
	21st December		**21st March/September**		**21st June**	
	Illuminance (lx)	**V_n/H_n**	**Illuminance (lx)**	**V_n/H_n**	**Illuminance (lx)**	**V_n/H_n**
H_{ex}	26300		59479,36		81413,50	
$V_{1\ III/1-2}$	640	1,91	684	1,74	802	1,65
$H_{1\ III/1-2}$	336		393		487	
$V_{2\ III/1-2}$	403	1,99	396	1,67	480	1,71
$H_{2\ III/1-2}$	202		236		281	
$V_{3\ III/1-2}$	223	1,94	224	1,74	254	1,82
$H_{3\ III/1-2}$	115		129		139	

Real time measurements showed that the vertical illuminance levels greatly differ depending on the direction of view. Eye looking at window received approximately four times larger portion of light than eye looking at workplane or computer screen (Tab. 5, Tab. 6). We know that most of the working time the view is directed downward and in this position the eye does not receive enough light to trigger strong biological effects. Horizontal workplane under both sky conditions reached approximately half of the illuminance compared to the level at eye looking toward window. The ratio between vertical illuminance at eye in direction of window and horizontal illuminance at workplane (V / H) is 1.0 near the window and gradually limitates toward 2.0

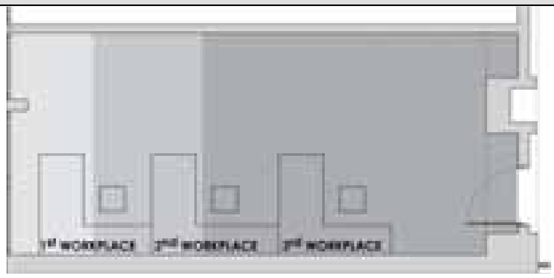
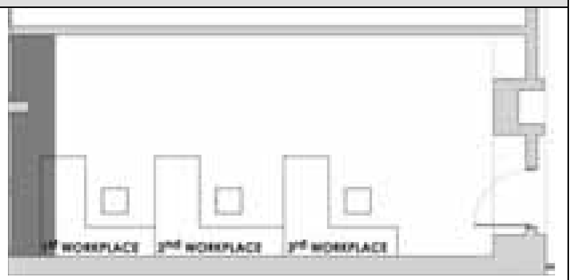
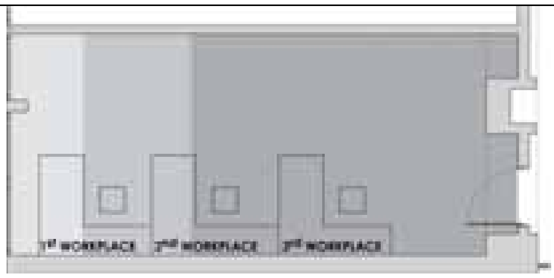
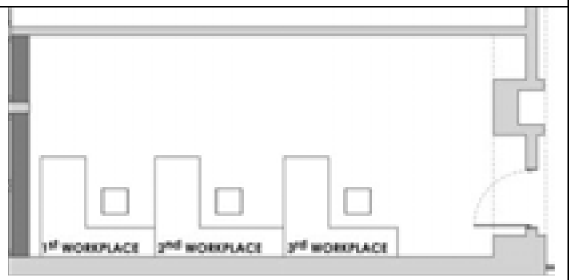
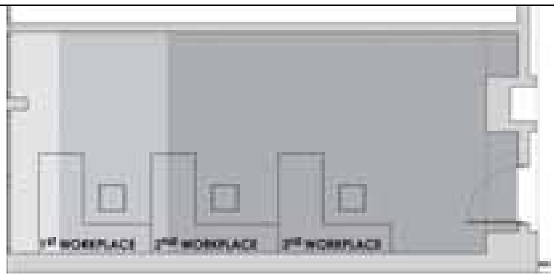
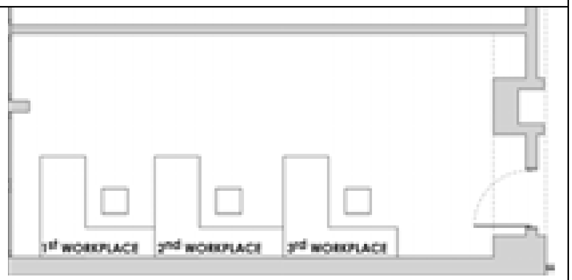
deeper in the room. The reason for this change is the fact that horizontal illuminance on workplane deeper in the room greatly depends on the light reflected form internal surfaces while vertical illuminance in the direction of window is mainly a function of portion of bright sky in the visual field.

The in-situ measurements indicated the trends that were later proven with the computer simulations and automatically logged real-time measurements over longer period of time. The illuminance differences under clear and overcast sky conditions near the window were not large, but increased when moving deeper into the room. Without the influence of direct sun the ratio between the vertical illuminance at the eye and the horizontal illuminance at the working plane was almost constant both under clear and overcast sky conditions; we have to add that the manually measured ratios were somewhat higher (2.0 near the window and 3.0 deeper in the room) than the later measured and simulated values. Very important for high illuminance level at the eye was large area of bright sky in the visual field.

2.5 Simulation of the office environment

For calculations was used software tool Radiance (2010). The real-time office environment was simulated under the standard CIE overcast sky (type 1) and the standard CIE clear sky (type 12) (ISO 15469:2004 (E)) for three days during the reference year (December 21, March 21, and June 21). We calculated two parameters, the illuminance at the workplane and vertical illuminance at eye level looking in the direction of the window (Fig. 1). The simulated points correspond to the previously measured position of a person's eyes performing office work. The calculations were carried out on a grid of 0.15 m / 0.15 m (for each cell average luminance was calculated).

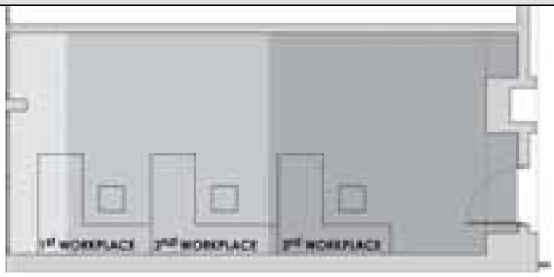
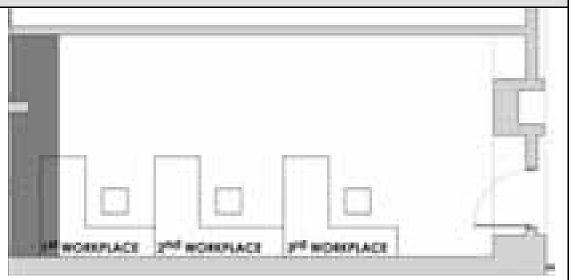
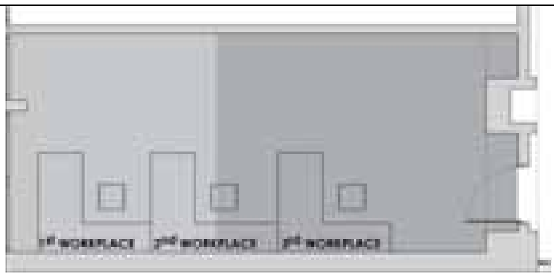
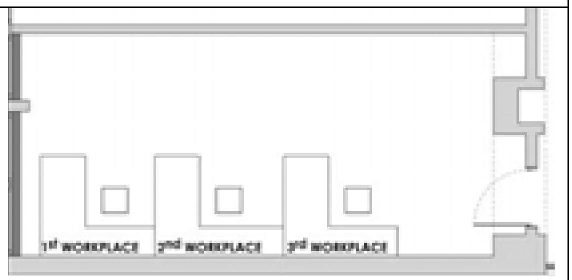
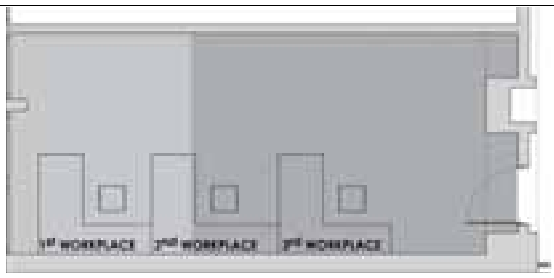
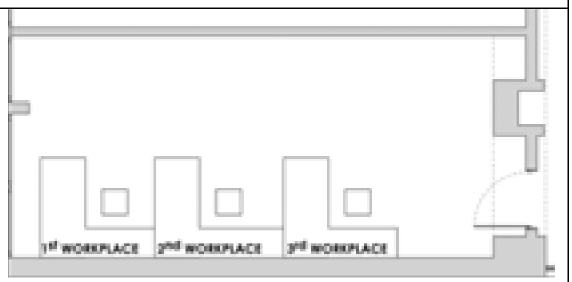
Tab. 4: Seasonal illuminance levels at three workplaces in the specific office space under standard CIE overcast sky

	Horizontal illuminance	**Vertical illuminance**
21st June		
21st March/September		
21st December		
	≥ 500 lx 499 - 201 lx ≤ 200 lx	≥ 1000 lx

Standard CIE overcast sky model covers situations with very uniform distribution of light in the hemisphere and also throughout the year. It should be noted that the second and the third workplace are not adequately daylighted over the year and the first workplace is not sufficiently daylighted during the winter. The vertical illuminances at the eye are low and do not reach the value of 1000 lx at any of the workplaces during the year. Ratios between vertical illuminance at the eye and horizontal illuminance at the workplane (V_n/H_n) are at all three positions relatively uniform and amount to the value of 1.5 (Tab. 3, Tab. 4).

Compared to CIE overcast sky, under CIE clear sky horizontal illuminance near the window is lower but deeper in the room more uniformly distributed. The calculations showed that the ratio V/H in a specific position does not change significantly during the year. In the zone near the window the V/H is close to 1.0 and deeper in the room limits toward 2.0 (Tab. 3, Tab. 5). Because the orientation of the room in North and the window is not under influence of direct sunshine, the differences of illuminance levels under clear and overcast sky are relatively small.

Tab. 5: Seasonal illuminance levels at three workplaces in the specific office space under standard CIE clear sky

	Horizontal illuminance	**Vertical illuminance**
21st June		
21st March/September		
21st December		
	≥ 500 lx 499 - 201 lx ≤ 200 lx	≥ 1000 lx

Tab. 4 which refers to conditions under overcast sky shows that 500 lx on the workplane are reached only on the first workplace (shaded area) during spring, summer and autumn. During winter the conditions are not satisfactory on any of the workplaces. The illuminances at the eye that would trigger strong biological response (≥ 1000 lx) (shaded area) are not reached on any of the workplaces during the year. Zones of good visual conditions and of bright light at the eye overlap most of the year only on the first workplace. This means that the first wokplace is satisfactory regarding visual conditions and partly regarding significant biological influences. The reason for relatively bad result is spatial distribution of workplaces in the office. In spite of large window openings relatively small amount of light reaches zone deeper in the room.

Tab. 5 which refers to conditions under clear sky shows that the 500 lx on the workplane are reached only on the first workplace (shaded area) during summer. During the rest of the year the conditions are not satisfactory on any of the workplaces. The illuminances at the eye that would trigger strong biological response (≥ 1000 lx) (shaded area) are not reached on any of the workplaces during the year. Lower illuminance in the room compared to overcast sky is the consequence of the sky models, and the influence of direct light versus uniformly diffused light. Zones of good visual conditions and of bright light at the eye overlap during summer only on the first workplace. This means that the first wokplace is satisfactory regarding visual conditions and partly regarding significant biological influences only during short period of year. Results with such a bad outcome were not expected since the window area of the room is quite large and cover most of the most oriented wall.

3. Conclusion

The real-time measurements showed, that average horizontal illuminance in the room during the year was mostly adequate. Problematic was horizontal illuminance of specific workplaces measured at workplane, which (with exception of the 1st workplace) did not reach the recommended values. Due to the depth of the room the light was distributed unevenly. The intensity of light falling into the eye on all workplaces was largest when eye was turned toward window. The value exceeded ≥ 1000 lx on 1st workplace under overcast sky (Tab. 1) and on the 1st and 2nd workplace under clear sky (Tab. 2). Illuminance values measured vertically (simulating eye looking toward workplane and toward computer screen) reach approximately one forth of the vertical illuminance in the direction of the window. In spite of the fact that the window extended over 26% of the room area and 49% of the window wall area the measured horizontal illuminance under overcast sky was adequate only in the zone near the window (up to 2 m from the window). The ratio between vertical illuminance at the eye directed toward window and horizontal illuminance at workplane (V / H) was approximately 2.0. Similar values were measured under clear sky. The vertical illuminance value measured at the eye looking toward workplane and at the aye looking at computer screed reached 0.16 and 0.25 of value for eye looking at the window, respectively.

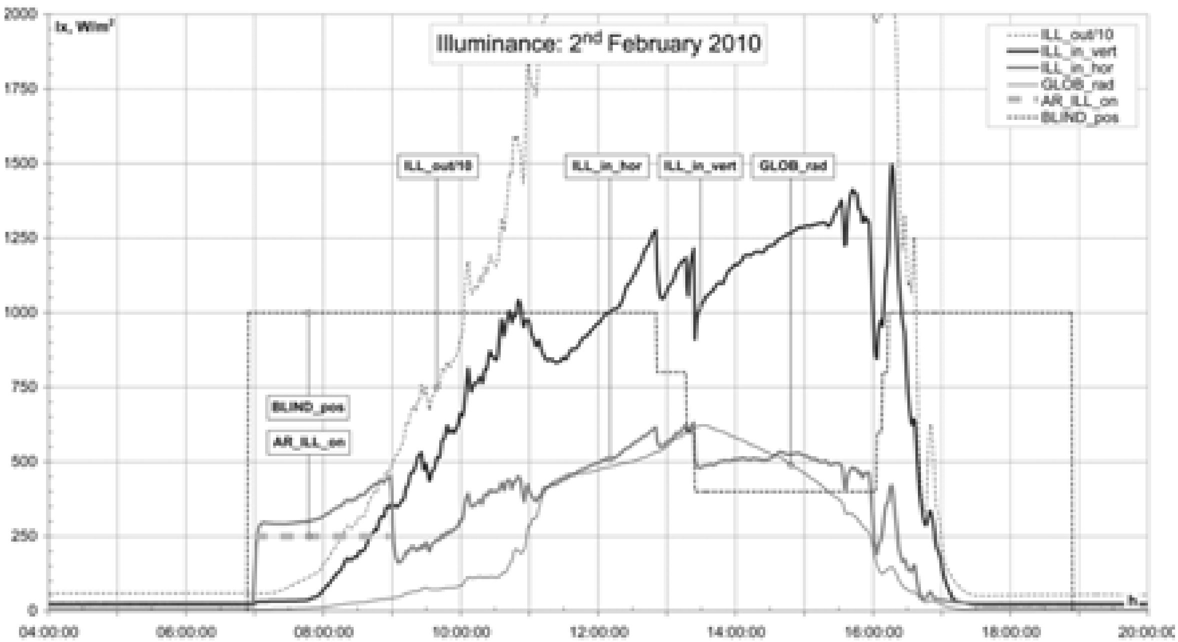


Fig. 2: Horizontal (ILL_in_hor) and vertical (ILL_in_vert) illuminance of the workplace in the western oriented office. The weather was sunny with morning fog. Additional presented values in the diagram are: external vertical illuminance divided by factor of 10 (ILL_out/10), global solar radiation (GLOB_rad), position of blinds (BLIND_pos) and duration of activated artificial illumination (AR_ILL_on).

The illuminance calculations with the program Radiance were used to control measurements and to compare standard and state-of-art conditions. They were executed for horizontal workplane and vertical plane parallel to window (simulating eye looking toward window). The illuminance values were calculated for four reference days during the year both under standard CIE overcast and clear sky. The conditions on the horizontal workplane under overcast sky were satisfactory at the 1st workplace during the whole year and too low at the 2nd and 3rd workplace. Vertical illuminance at the eye did not reach 1000 lx at any of the workplaces. Under clear sky horizontal and vertical illuminance did not reach the set criteria. The V / H ratio under overcast sky was in the range of 1.5 and under clear sky 2.0.

These results were confirmed by later continuous measurements of real time west oriented office. The results can not be directly compared due to changed orientation and different geometry of the office, but can be regarded as a guideline. Te Fig. 2 shows the example of measurement of a workplace positioned at a distance of 2 m from the window. The measured values are illuminance at horizontal workplane ((ILL_in_hor), vertical illuminance at the eye looking toward window ((ILL_in_vert) and external conditions. The V / H ratio in these specific conditions are between 1.2 in 3.5. The average V / H ratio during working hours is 1.8 to 2.1 even if the measurements were executed in very variable external conditions. Considering the measurements and calculations we can conclude, that in the presented situation we can define the vertical illuminance at the eye by a fair amount of certainty if we calculate the illuminance at the horizontal workplane. Further work for other orientations and various room geometries is needed.

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