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Empirical Lighting Performance Assessment of a Light Emitting Glass Product

unter der Leitung von

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I dedicate this work to the memory of my mother, to whom I owe every success.

ABSTRACT

The purpose of this research is to assess the visual performance of a light emitting glass product and evaluate its potential use in the building sector. There are several uncertainties which prevent one from fully understanding whether an emerging technology will actually work and deliver the intended benefits in the real world. In this research, an empirical test is performed in order to clarify issues related to the product performance. A scale model served as a test bed to collect product-related data under real sky conditions during different illumination states of the product. Recorded data from the test bed was used to generate performance indices and to construct virtual building components. The reliability of virtual models was verified against the conducted measurements aiming to ensure that it would closely predict real world conditions. A series of building simulations was performed in order to generate product related performance indices and to analyse them in the view of lighting requirements proposed in building standards and scientific literature. Parallel experimental investigation into the visibility through the product in the illuminated state was performed. Visibility dependency on the viewer's distance and the visual target positions, together with surrounding lighting condition were examined. Empirical test results showed that indoor light penetration through the product is highly related to outdoor sky conditions and it can reach acceptable levels even under the worst conditions. Once illuminated, the product did not show a major reduction in visible daylight transmission to indoors. Concerning the usage as office glazing, the product ensures adequate levels of light in the perimeter close to its mounting wall. For this reason, the combination with other light sources would assist in order to reach required visual satisfaction. Finally, visual clarity through the product is found to be highly dependent to the viewer and visual target position. More precisely, the product covers more details the further they are located from the viewer, and hides fewer details for close viewers and visual targets. Surrounding lighting conditions have a reduced impact on visual clarity. In the end, the study summarizes the benefits and deficits of the examined product, concluding that in the current stage of development it is not advisable to use the product as the only source of light in office buildings environment.

Keywords

Photometric measurement; Performance assessment; Illuminance; Visual acuity; Lighting simulation

ZUSAMMENFASSUNG

Die vorliegende Diplom-Arbeit befasst sich mit Aspekten der visuellen Performance sowie der zukünftigen architektonischen Anwendung eines innovativen, neuen Glasprodukts, welches aktiv Licht emittieren kann (ein mit LED-Leuchten im Randverbund sowie einer Funktionsschicht im Scheibenzwischenraum versehenes Isolierglaselement). Gerade in der Produktentwicklung von neuen, wenig etablierten Technologien zeigen sich oft große Unsicherheiten, die es schwierig machen vorherzusagen, ob und wie ein neuwertiges Produkt funktionieren wird und auch vom Markt angenommen wird. In dieser spezifischen Arbeit wird die Performance des genannten Glasproduktes empirisch untersucht um entsprechende Indikatoren ableiten zu können. Dazu wurde ein maßstäbliches Modell einer Einbausituation gebaut, welches im Freien, das heisst unter realen Außenlichtbedingungen, aufgestellt wurde, sowie anschließend verschiedenen Testszenarien unterworfen wurde (unterschiedliche Tageszeiten, verschiedene Beleuchtungsfälle). Während der Testläufe wurden laufend verschiedene Parameter innerhalb und außerhalb des Modells aufgezeichnet, so dass aus diesen Monitoring-Daten virtuelle Modellierungen des Glaselements erstellt und rudimentär kalibriert werden konnten. Diese solcherart verifizierten, virtuellen Modelle konnten anschließend dazu verwendet werden eine ganze Reihe von weiteren experimentellen Anwendungsfällen zu testen und zu dokumentieren. Parallel zu diesen Bemühungen wurden mittels ausführlicher Literaturrecherche die für verschiedene Anwendungen erforderlichen Beleuchtungserfordernisse aus Richtlinien und Normen extrahiert und diese dann mit den Mess- und Simulationsergebnissen verglichen um festzustellen für welche Anwendungsfälle das Produkt sinnvoll eingesetzt werden kann. Da das untersuchte Isolier-Glaselement über die Funktionsschicht im Scheibenzwischenraum auch die Durchsicht-Möglichkeit durch das Glas beeinflussen kann, wurden in einem weiteren Schritt empirische Experimente angestellt um herauszufinden, wie gut das Glaselement sich als lichtdurchlässige, aber weitgehend blickdichte Durchsichtsbarriere eignet. Die Sichtbarkeit von verschiedenen Gegenständen für Probanden auf der anderen Seite wurde unter verschiedenen Settings (Position des Probanden, Position von Sehaufgaben auf der anderen Seite des Glases) untersucht.

Zusammenfassend kann festgehalten werden:

- Die Beleuchtungsstärke im Innenraum hinter dem Glaselement ist stark abhängig von den Außenbedingungen, allerdings können auch unter

"schlechten" Außenbedingungen akzeptable Beleuchtungszustände erreicht werden.

- Im Betriebszustand (d.h. LED-Leuchten angeschalten) kann keine signifikante Abnahme der Tageslichtdurchlässigkeit nach innen festgestellt werden.
- Als alleiniger Beleuchtungskörper kann das Element adäquate Ausleuchtung nur in unmittelbarer Nähe gewährleisten, demzufolge ist hier eine Kombination mit anderen Beleuchtungskörpern anzudenken.
- Die Durchsicht durch das Element ist stark von der Position des Betrachters und der betrachtetenen Sehaufgabe in Relation zu dem Glaselement abhängig. Kurz gesagt, je weiter betrachtete Gegenstände von dem Glaselement entfernt werden, desto weniger Details dieser Gegenstände können erkannt werden. Die Kombination von Betrachtern und betrachteten Gegenständen, die jeweils sehr nahe an dem Glaselement positioniert sind, kann als "gute und deutliche Wahrnehmung" charakterisiert werden.

Aus der Diskussion der Resultate können zahlreiche Vor- und Nachteile des untersuchten Glaselements abgeleitet werden. Im aktuellen Entwicklungsstand ist das Element als alleinige Beleuchtungsquelle für Innenräume jedoch noch nicht hinreichend geeignet.

Keywords

Photometrsche Messungen, Performance Evaluierung, Beleuchtungsstärke, Lichtsimulation, Sehschärfe

CONTENTS

1 INTRODUCTION

1.1 Overview

Illumination of architectural spaces is achieved through transparent glazing and/or artificial light sources. Lighting development has been focusing both on improving architectural glazing types to offer the desired access to natural daylight and also conceptualizing artificial lighting systems aiding visual comfort. Recent industrial research efforts achieved to combine these two fields and produced products that can act as both daylight and artificial light sources.

The innovative technology of LightGlass ALED enables illumination of a glass across its entire surface by applying a voltage, changing its function from a transparent glazing surface to a light source (LightGlass 2016). When applied in the building sector, such technology can add the light source function to an architectural glazing. This research addresses the product visual performance when used in buildings. The architectural use of glass that is considered involves office facades' glazing and interior partitioning systems.

When used in buildings, the product has to satisfy both functions of a natural daylight source and an artificial light source; however, the building sector is subject to regulations and standards defining visual performance. To this end, this research will assess the ability of product to meet lighting requirements at office work places.

For the purpose of the research, a test bed is constructed to represent the indoor climate and the product is mounted on one of its sides. The test bed is placed on the terrace roof of the *TU Vienna*. A series of physical measurements is performed. The data collection strategy allows recordings under various situations related to the product illuminated state, sky condition and day time. Recorded data is used to calculate performance indices, as well as to construct virtual window and luminaire which reproduce the product characteristics.

A validation of virtual models is achieved through the modelling of an identical test bed equipped with virtual product models and comparing simulation results with physical measurement. Virtual models are transferred to a hypothetical office room and series of simulation are run in order to assess results against lighting requirements proposed by building standards and scientific literature.

An assessment of visibility through the product is experimentally performed in the laboratory using visual acuity method. The product visual interaction with viewer and vision target and the interaction with lighting conditions of its surroundings are subjectively explored.

1.2 Motivation

The basic function of architectural glazing is transmission of daylight while offering a clear view to the outdoor environment (Piccolo et al. 2008), however, issues of overall building energy performance and the related glazing solar transmission led industry specialists to include cutting edge material technologies into glazing.

Functional films and coatings, phase changing materials, vacuum and aerogel insulation, light redirecting systems are all solutions to specific issues in the building performance. The previously mentioned measures and others are embedded in the terms of smart glazing and complex fenestration systems.

Any applied measures though can affect directly the light transmission and the visibility of the glazing (Jonson et al. 2010). The product analysed in this research is introducing a glazing technology additional to daylight transmission that provides also artificial light when needed. When used as architectural glazing, the innovative developed product will serve the new function of emitting light to its surroundings, thus an assessment of both functions, either separately or simultaneously will clarify to which extend the product is fulfilling its intended functions .The motivation of the current study is the assessment of the potential added-value of this innovation to the building sector. Furthermore, the performance assessment will serve as an efficient roadmap for further improvement of the product performance.

1.3 Background

1.3.1 Overview

Several experimental studies have been focusing on the performance of innovative glazing, mainly electrochromic windows. Jonson et al. (2010) investigated light scattering through a window glass with electrochromic foil and antireflective coatings. Other experimental investigations using scale test chambers aimed to assess the performance of electrochromic windows with respect to daylighting control in buildings (Piccolo et al. 2008). A similar study addressing daylight control of an electrochromic window with a focus on the films used was deployed at the Lawrence Berkeley National Laboratory, USA (Lee et al. 2005). Bjorn (2012) further investigated the solar radiation glazing factors for glass structures and electrochromic windows though experimental measurements and calculations.

Other studies focused on windows powered by integrated photovoltaic films and their daylight transmission and colour rendering properties. The performance was tested by physical experiments and simulation results (Lynn et al. 2012),(Deb et al. 2000).

Energy efficiency of light sources (luminaries) in regard to the degree of visual comfort they deliver in office buildings was addressed by Linhart and Scartezzini (2010)

However, since the combination of glazing and light source is a new technology, a lack of research is identified as no available study has yet explored the potential of a product combining both these functions.

1.3.2 Architectural glazing

Glass is an old building material, which facilitated penetration of light into buildings. Regardless of its use for windows, facade or interior partition, glass connects the spaces, transmits light and the contemporary types of glass can even contribute to energy savings (Savic et al. 2013).

One of the most insistent contemporary building challenges is the energy saving while maintaining the comfort. Glazed parts of the building envelope are regarded as the less energy efficient building component because of their solar and thermal transmission properties (Ruben et al. 2009). Glass development researches made an important step in improving these properties by applying active solutions like coatings, films and vacuums.

The properties of architectural glazing that affect directly the building indoor environment as defined Lawrence Berkeley National laboratory (LBNL 2013) are:

Visible transmittance: The percentage of visible light falling on the window glazing that will pass through.

Visible reflectance: Indicates to what degree the glazing appears like a mirror, it is the percentage of light falling on the window that is reflected back.

Solar Heat Gain Coefficient or Shading Coefficient: The ratio of total transmitted solar heat to incident solar energy.

U-Value: The measure of heat transfer through the glazing due to temperature difference between the indoors and outdoors.

Ultraviolet Transmittance: Indicates the percentage of ultraviolet radiation falling on the glazing that passes through.

Colour rendering index: A common performance criterion for architectural glazing. It assesses the colour rendering that is defined as effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their appearance under a reference illuminant. The index is directly related to the spectral transmission properties of the glass (Lynn et al. 2012).

Sound Transmission: Outdoor-to-indoor transmission class (OITC) is the property used to express sound attenuation characteristics.

1.3.3 Daylight in buildings

Physically, daylight is the part of solar irradiance with spectral power distribution in the visible range of 380 nm to 780 nm. Daylight is considered the best source of light, as an alternative of artificial light. Daylight in building designs is a useful strategy to reach the human visual comfort, to reduce energy consumption and to augment productivity (Alrubaih et al. 2013). The use of natural light is a key solution in modern architecture; it provides an attractive indoor environment and gives a sense of cheeriness and brightness that can have a significant positive impact on people (Danny 2010)

For building daylight applications, diffuse light is more important and widely considered. The use of direct sunlight for providing a natural light source in buildings is often excluded. Problems of glare, excessive brightness ratios and visual discomfort support the exclusion. In addition, diffuse illuminance is more energy-efficient in terms of luminous efficacy (Danny 2010)

In designing daylight, two strategies are common. First and most used is side lighting; it consists of using building walls apertures to admit daylight and offers views to the outside. Inconvenience is that it might cause discomfort glare. The second one is top lighting; it consists of using the upper parts of the building structure to place windows. Its inconvenience is that it does not offer a direct view to the outside. (Ander and Greg. 2003)

Methods for predicting daylight in buildings during the early design stages are fenestration prototype physical measurements, scale model measurements and computer daylight simulation.

1.3.4 Artificial light in building:

Electrical artificial lighting for indoor environments is a recent practice. For thousands of years people relied on daylight and fire, until the beginning of the 20th century when the use of incandescent lamps reached a large scale.

Artificial light sources have been in a constant development since they were first introduced. Research efforts to enhance their performance and improve the luminous efficacy which means reducing their energy consumption while maintaining high luminous flux were successful. Some light sources with low luminous efficacy like incandescent lamps were totally banned in Europe.

Architectural lighting is applied on illuminating buildings and other architectural elements. Functional indoor lighting intends to cover a specific space with a defined level of illumination that is judged to be adequate to perform various tasks, while decorative light tries to focus on parts on the indoors or the building facades to offer a pleasant view or to attract attention to a specific object.

Some strategies used in light planning in order to efficiently illuminate indoor architectural surroundings are:

Ambient lighting**:** It consists of the general lighting of the space with the purpose of illuminating objects and spaces to adequate levels wish permit occupant to perform their visual tasks.

Task lighting**:** A method used with ambient lighting to illuminate a specific area known as the task area. Task lighting solution combined with ambient lighting offers direct control to users over the illuminated space.

Dimming strategies: Manual and electronic light dimming enables the building's occupants to adjust the level of light depending on their preferences or by setting an illuminance level as reference under which light lumen output is adjusted

Control groups**:** Control groups consist of organizing luminaire in a switch groups based on possible combinations with daylight and in order to offer the possibility to change the lighting mood.

1.3.5 Building glass and light standards

Standards are important tools in conducting scientific research. The main organizations responsible of issuing building lighting standards and codes are: CIE (International Commission on Illumination), IES (Illumination Engendering Society), EN (European Standard), ISO (International Standards Organization). DIN (German Institute for Standardization). Standards used in the current research are:

1) DIN EN 410 .Glass in buildings-Determination of luminous and solar characteristics of glazin:

The standard describes luminous and solar properties of glazing and methods for their calculation for different glazing types. However, the standard doesn't specify threshold values or preferred performance ranges. The norm applies both to conventional glazing and the absorbing or reflecting solar control glazing, used as vertical or horizontal glazed apertures. The appropriate formulae for single, double and triple glazing are given. The program Optic 5, includes the standard method on its glass assemblies properties calculations. (DIN EN 410:2011)

2) *DIN 5034-1. Daylight in interior:*

The standard simplifies the determination of appropriate window size for working spaces. It also defines metrics for assessing daylight conditions in interiors. The standard (DIN 5034-1:2011) states that *'Workspaces must have a sufficient daylight to create a pleasant brightness and assure a visual contact between indoors and outdoors. Therefore, it is necessary to equip spaces with transparent, distortion-free and if possible colour-neutral glazing*'. In DIN 5034-1, clause 4.3.2.2 titled 'Required Illuminance' explains the difference of human perception of daylight and artificial light and argues that a task performed under artificial light needs more illuminance than the same task under natural daylight. For this reason, it suggests a reduction of 0.6 of illuminance values required by EN 12461. It also suggests a daylight factor of at least 2% in the centre of the room for sufficient lighting of interiors with daylight. The next figure and table show how the standard suggests window size in relation to the work room dimensions and optimal windows positioning in the walls.

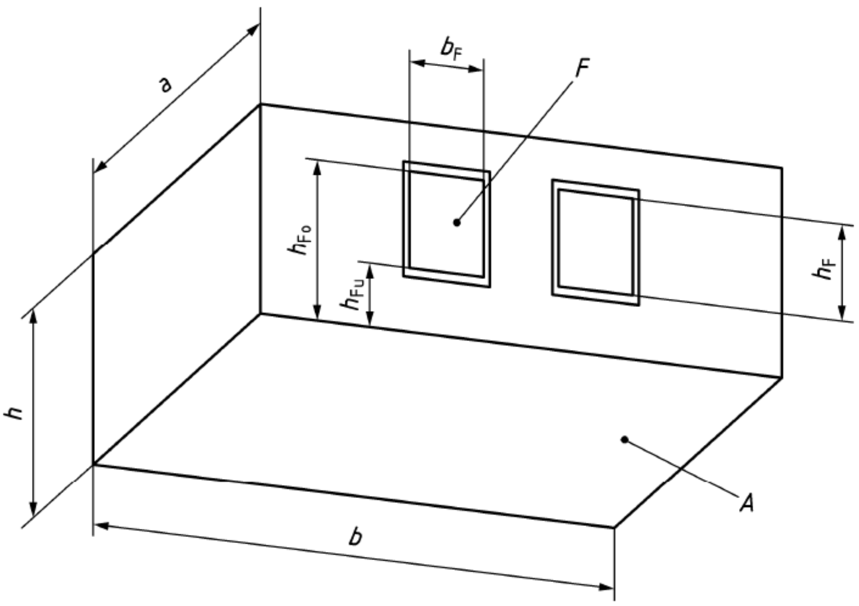


Figure 1. Dimensions of transparent window surfaces of work spaces. (DIN 5034-1:2011).

Table 1. Relation of window size to room dimension (DIN 5034-1:2011)

Work room dimensions	Window dimensions
For $a \leq 5.0$ m	$F \geq 1.25$ m²
For $a > 5.0$ m	$F \geq 1.50$ m²
For $A \leq 600$ m²	$\Sigma F \geq 0.1 * A$
For 600 m²< $A \leq 2000$ m²	$\Sigma F \geq 60$ m² + $0.01 * A$
For $h > 3.5$ m	$\Sigma F \geq 0.3 * b * h$

Requirements for the window position are like the following:

- bF ≥ 1.00 m
- hF ≥ 1.25 m for sitting activities; 1.00 m for predominantly standing activities
- hFu ≤ 0.95 m for predominately sitting activities
- hFu ≤ 1.20 m for predominantly standing activities
- hFo ≥ 2.20 m

Previously stated suggestions are according to DIN 5034-1 (2011)

3) DIN EN 12665 (Basic terms and criteria for specifying lighting requirements)

This standard gives a definition of lighting related terminology, starting from terms of eye and vision, to physical and technical definitions, the standard covers also lighting equipment and installation. (DIN EN 12665:2011)

4) EN 12464-1 (Light an lighting – lighting of work place)

This European norm specifies lighting requirements in a wide range of working spaces. Requirements are based on the type of the working place and tasks performed. The standard doesn't describe the type of light, so it is assumed to be daylight, artificial light or the combination of both (EN 12464-1:2002). Office work places requirement in the current research is based on values described in this standard. Further explanation of this code will follow in section 2.5.1.

5) DIN EN IS0 8596 (Ophthalmic optics- Visual acuity testing- Standard and optical optotypes and their presentation)

This standard is used in this study to design the charts used in acuity tests. It sets the rules for the relation between optotypes presented in the chart and the viewer distance. (DIN EN ISO 8596:2016)

2 METHOD

2.1 Overview

The aim of the research is to assess a light emitting glass product performance when used in buildings. In order to collect light related data of the product, a test bed was constructed and placed on the top roof of *TU Vienna* . The test bed was equipped with illuminance sensors distributed on various locations inside and outside. Measurements procedures started by collecting data related only to daylight, and then On/Off switch strategy was launched to permit the collection of both artificial light and daylight data. A statistical analysis was performed on the collected data based on the scope of the research question. Parallel measurements aiming to investigate the glass diffuse light transmissivity were performed.

For further use in lighting simulation, a virtual model identical to the test bed was constructed in the lighting simulation program DIALux evo 7 (DIAL 2017). Virtual sensors in the model were placed in the same positions as physical sensors in the test bed. The product related luminous intensities distribution file was adjusted to the product being tested. A window glass was modelled matching physical characteristics of the product. Measurement and simulation results were compared in order to validate the simulation.

A hypothetical model of a simple office room was modelled in DIALux evo 7 and a series of calculations was made using the luminaire and glass models validated on the test beds. Performance metrics were generated and compared with building standards values in order to assess the product performance.

The final assessment method was a subjective experiment of the visibility through the product in the illuminated state using visual acuity method. The product was installed between two laboratory rooms where light levels were adjusted to represent common lighting situations in office surroundings. Participants were invited perform a visual task consisting of reading from vision charts from different distances.

2.2 Hypothesis

This research is based on the suggestion that the product can be used as an effective light source in buildings.

2.2.1 Research questions

The present experimental study seeks to address the following performance inquiries:

a) *What is the amount of daylight transmitted?*

- Daylight level entering indoors through the product glass under real sky conditions and the relation between outdoor daylight and indoor daylight at various positions.

b) *What is the daylight transmission behaviour of the product in the illuminated state?*

- Behaviour of the product glass surface towards daylight permeability when it is illuminated.

c) *How the product performs in office work places?*

- The usage of the product as office window glazing and its performance according to building codes requirements for office work spaces.

d) *To which extend does the product cover details in the illuminated state?*

- Level of details the product covers when illuminated and its relation to the viewer and vision target position together with the lighting condition of the surroundings.

2.3 Measurements

In order to collect realistic data related to the product, a system combining the product prototype with a test bed and sensors was constructed. Various light related physical measurements under actual weather and daylight conditions were made inside and outside. Detailed explanation of the measurement procedure will be explained in further clauses.

2.3.1 Test bed

In order to perform the monitoring and to collect the desired data, a scale test bed was constructed. According to Thanachareonkit et al. 2005. *„Physical models mock* *up buildings at different scales, placed within a sun and/or sky simulator allow performance assessment in a sound and reproducible way"*

The test bed is 800 mm wide, 800 mm high and 150 mm long. It consists of an assembly of three wooden boxes of 500x800 mm each. An inclined roof was constructed and covered with a waterproof material in order to prevent rain and snow water leakage into interiors. A door opening was made to allow access to the interiors.

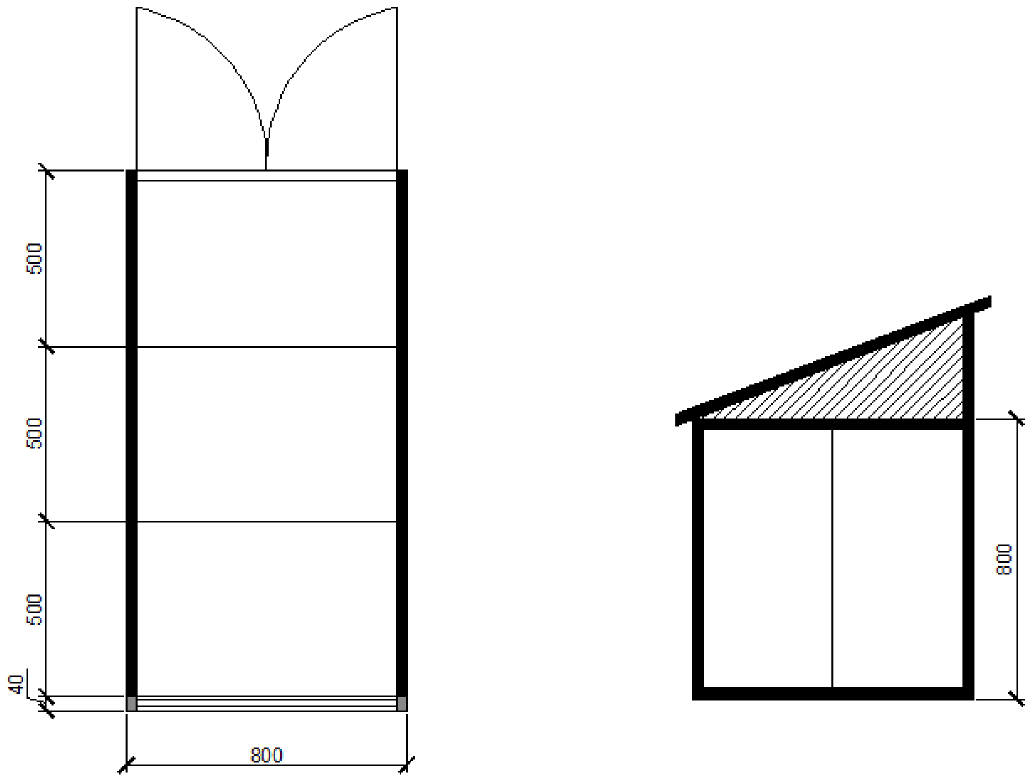


Figure 2. Left: Test bed plan. Right: test bed section. (dimensions in mm).

One of the main physical factors contributing to experimental errors with scale models is the surface reflectance of internal walls and partitions (Thanachareonkit et al. 2005) .For this reason the interior of the test model was painted black as shown in figure 4.

Figure 3. Test bed interior (product Illuminated).

Since the black paint was still reflective, the interiors were completely covered with matte black paper to avoid reflections interaction during measurements and therefore discrepancy in measurements. Light distribution inside the test bed is not restricted.

2.3.2 The product prototype

The product used for testing is named: LightGlass Aled FixedWhite. (LightGlass 2016).It has the following characteristics according to measurements and delivered datasheet:

Table 2. Product details.

Product prototype details	
Length	0.8 m
Height	0.8 m
Width	0.04 m
Length of luminous/transparent area	0.726 m
Width of luminous area/transparent area	0.726 m
Dimmable	No
Colour temperature variation	Fixed white
Colour temperature	6500 K
Product weight	~ 19 kg
Light emission	Both sides
Colour Rendering Index (CRI)	>90

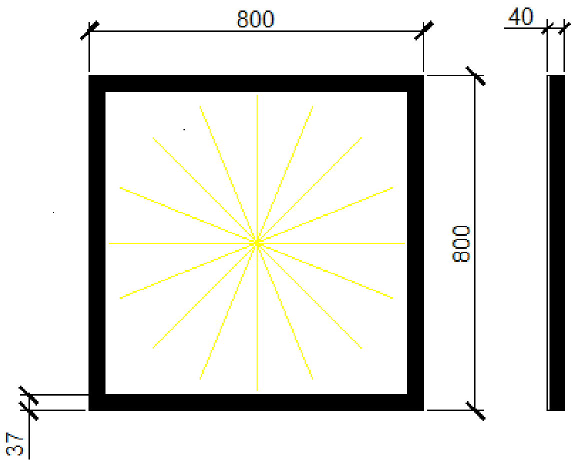
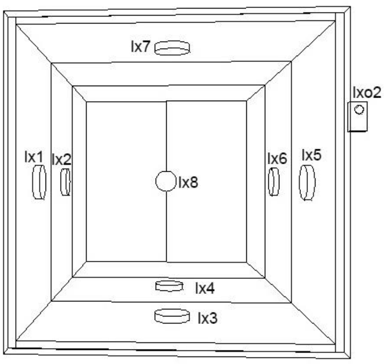


Figure 4. Left: Product image. Right: Product dimensions (mm).

The product consists of an assembly of two glass panes and a light guiding transparent foil. The foil helps the propagation of light uniformly across the product surfaces. The product frame is equipped with a number of LED‘s which are responsible of emitting light.

2.3.3 Sensors

The combination of the test bed and the product was equipped with a number of sensors measuring illuminance. Eight luxmeters were placed inside the test bed and one vertical sensor outside. Sensors were distributed in a way that permits the monitoring of Illuminance on all surfaces of the structure and on different depths.



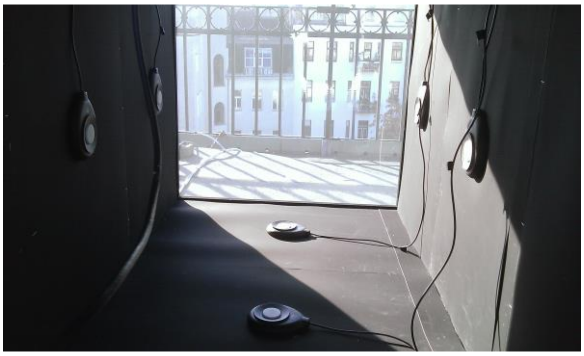


Figure 5. Left: 3D illustration of sensors distribution. Right: Image of sensors inside the test bed.

The type of sensors used for recording interior Illuminance is manufactured by Chauvin Arnoux, model number is CA808. The connected data logger is from a manufacturer named Almemo and the model number is 2890-9.

Table 3. Instruments used to collect and record Illuminance.

Illuminance Sensor	**Data logger**
	

In the end of the measurements, the sensors reliability was verified using a desk task light on the *Building Physics and Building Ecology* laboratory. Results did not reveal any anomalies.

2.3.4 Test bed location

The test bed was placed on the top floor of the *Building Physics and Building Ecology Institute* (BPI) at *TU Vienna*. The location is few meters away from BPI weather station where various other measurements are constantly made. The test bed was oriented in a way that the product glass was facing south, the choice of the orientation permits to have light inside the test bed for longer time. The location benefits from the fact that there are no other high rise buildings or vegetation in the surroundings; this helped to avoid any daylight obstruction or other light sources interfering in the measurement results. Location latitude is: 48.1986°; longitude: 16.3694° and height above sea level of 193 meters.

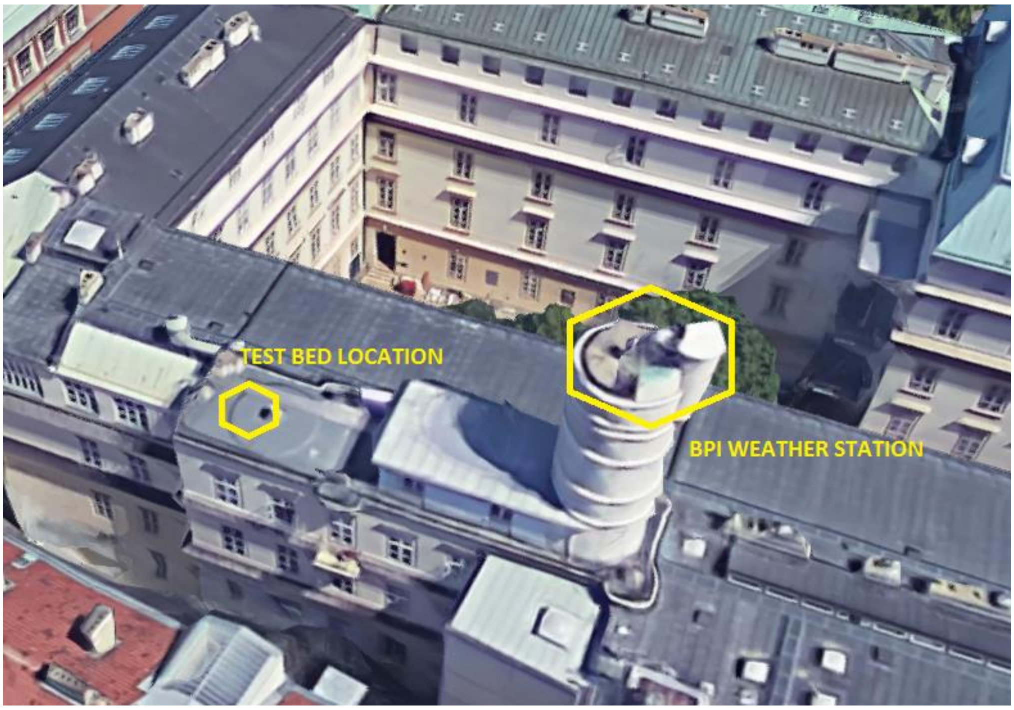


Figure 6. View of test bed location.

Figure 7. Test bed location.

2.3.5 Measurement Procedures

Referring to Danny (2010), long-term data measurement is the most effective and accurate method of setting up reliable daylight illuminance databases. The measurement period started on 01.11.2016 and ended on 04.04.2017. The system was recording data twenty four hours. From 01.11.2016 until 22.11.2016 the product was constantly switched off, which means that the system was recording data related only to daylight.

Starting from 23.11.2016 until the end, an On/Off timer strategy was installed. The control strategy was that the product is illuminated for 30 minutes seven times a day with an interval of 90 minutes from 07:00 to 19:30. The switch was always set to 100% dim value. The procedure repeated every day. A detailed On/Off switch control strategy is shown in the Figure.

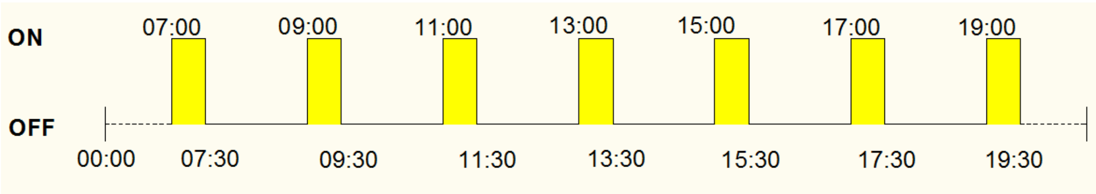


Figure 8. Product On/Off switches strategy.

Having the product illuminated seven times a day allows the recording of illuminance values under various daylight conditions. This procedure permitted the collection of illuminance data of daylight, artificial light and the combination of both.

a) **Daylight:** In addition to the first part of the measurement, daylight illuminance data was recorded during times when the product was switched off.

b) **Artificial light**: Since a portion of the experiment time was during winter where daylight time is short, the switch strategy helped to collect Illuminance data related only to artificial light. Data recorded from 17:00 to 17:30 and 19:00 to 19:30 was already at night time, since the exterior sensors lxo2 was recording a value of 0. This allows having measurements of only artificial light emitted by the product.

c) **Daylight and artificial light combination**: The strategy permits to record the combination of both since the product was illuminated during daytime and under various daylight conditions.

Since the product is a source of both daylight and artificial light, the switch strategy had a considerable benefit in assessing its performance and analysing the data in order to answer research questions.

2.3.6 Data

Internal and external sensors were collecting data with 5 minutes interval. Collected data was acceded via a dashboard system. Recorded illuminance data was simultaneously displayed on graphs. Data can be downloaded on a .csv files based on 5 minutes, 15 minutes or 1 hour interval. Output files of measured illuminance were opened and analysed using Microsoft Office Excel. The dashboard was constantly consulted in order to check the good functioning of the system. Data reliability was checked using the linearity correction chart.

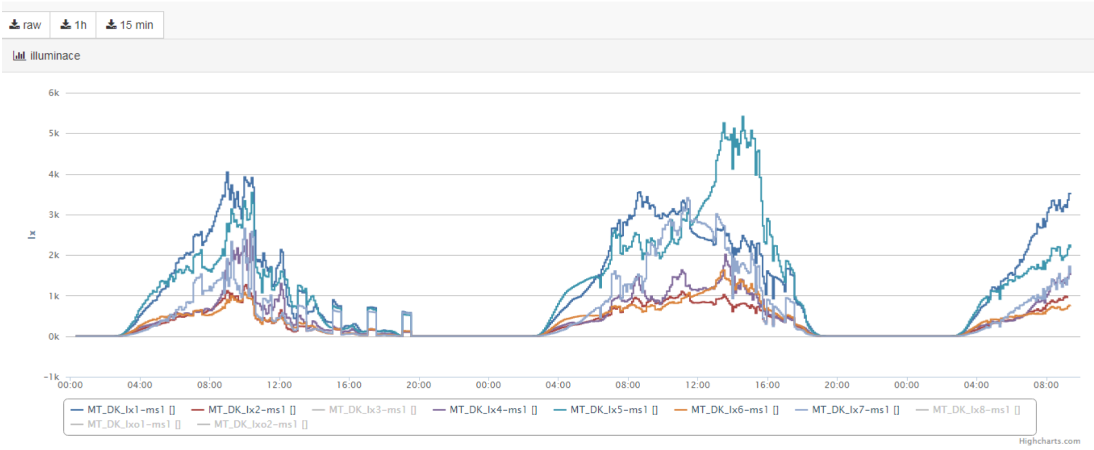


Figure 9.Illuminance data displayed on graphs.

Output files contain a time reference number joined by the Illuminance value. Reference numbers represent the time of the measurement in a way that the subtraction of two successive reference numbers gives the time interval between the two measurements in seconds. Based on this method reference numbers were converted to the exact time when the measurement was recorded.

	A	B	C	D	E
1	time	MT_DK_lx1-ms1--1	Interval	Interval	Exact time
97	1477987196	960	300	00:05:00	08:04:56
98	1477987496	1018	300	00:05:00	08:09:56
99	1477987796	1246	300	00:05:00	08:14:56
100	1477988096	1614	300	00:05:00	08:19:56
101	1477988396	2047	300	00:05:00	08:24:56
102	1477988696	2121	300	00:05:00	08:29:56
103	1477988996	3155	300	00:05:00	08:34:56
104	1477989296	4630	300	00:05:00	08:39:56
105	1477989596	4972	299	00:04:59	08:44:55
106	1477989895	5186	301	00:05:01	08:49:56
107	1477990196	5486	300	00:05:00	08:54:56
108	1477990496	6583	299	00:04:59	08:59:55
109	1477990795	7868	301	00:05:01	09:04:56
110	1477991096	11054	299	00:04:59	09:09:55
111	1477991395	10146	301	00:05:01	09:14:56
112	1477991696	9621	299	00:04:59	09:19:55
113	1477991995	9716	300	00:05:00	09:24:55

Figure 10. Conversion from time reference number to exact time.

The dashboard has also access to measured data from BPI weather station; access to this data and especially to Global Horizontal Irradiance (GHI) helped in categorising the sky type.

Throughout the present research, a special focus was given to overcast sky conditions for multiple reasons, among which are:

- No shading strategy was installed on the test bed
- Direct sun light shouldn't be used in illuminating indoor spaces because of glare related discomfort.
- Daylight in overcast skies is independent from sun position and orientation.

- Overcast sky conditions represent the worst lighting scenes, thus, they serve as reference for assessment.
- Multiple daylight metrics are meaningful only under overcast skies.
- Overcast sky distribution patterns are well defined.

2.4 Simulation

Early assessment of interiors lighting conditions in building is performed either by measurements on scale models or using lighting performance simulation tools. This research involves both methods. Measurement results are used to validate simulation. Test bed geometry and collected data are used to generate an authentic virtual test bed. Comparing results of physical and virtual test environments helps to construct a view to which extend the simulation results are matching physical results. Validated product virtual models are used to perform assessment investigations in a hypothetical office room virtual environment.

2.4.1 Virtual test bed

The lighting calculation tool used to generate the model and to run simulation of the test bed is DIALux evo 7. The software is developed by the company DIAL GmbH. It allows calculation of artificial light and daylight in outdoors or indoor spaces. Virtual sensors inside the box are distributed at exactly the same position as the physical sensors; details of the virtual test bed are shown in the next table:

Table 4. Virtual test bed input parameters.

Virtual Test bed parameters	
Location	Vienna
Longitude	16.3694 °
Latitude	48.1986°
North alignment	180°
Geometry (L*H*W)	1500*800*800 (mm)
Sensors	lx1 to lx8
Calculation surfaces	All surfaces
Interior material	Black paint
Reflection of interior surfaces	0
Reflections from exterior	30

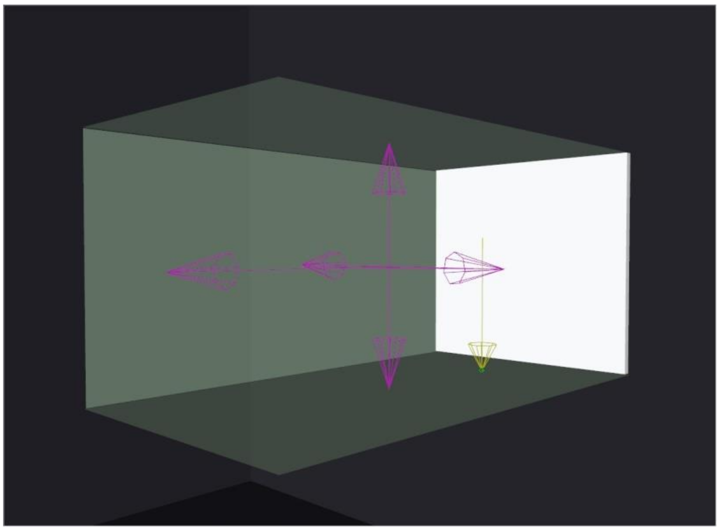


Figure 11. Virtual test bed 3D view.

2.4.2 Photometric file

Light distribution from the artificial light sources is defined by the spatial luminous intensity data presented in photometric files. There are two photometric data types used in lighting simulation: the first is called IES; it was proposed by the Illuminating Engineering Society of North America (IESNA). The second and most used one in European countries is called Eulumdat, it is a lighting industry standards format. It has an .ldt file extension. Most of lighting simulation programs support both file formats. Some applications are used for conversion between the two types.

Photometric data files are measured by using goniophotometer. Measurement requirements and procedures are explained in the standard *EN 13032-1(Light and lighting-Measurement and presentation of photometric data of lamps and luminaires-Part1: Measurement and file format.)*

The product has an Eulumdat file representing the emitted light intensities distribution. The file contains authentic directional distribution of luminous intensity (LID) to the delivered porotype. However, product geometry and related values are to be adjusted.

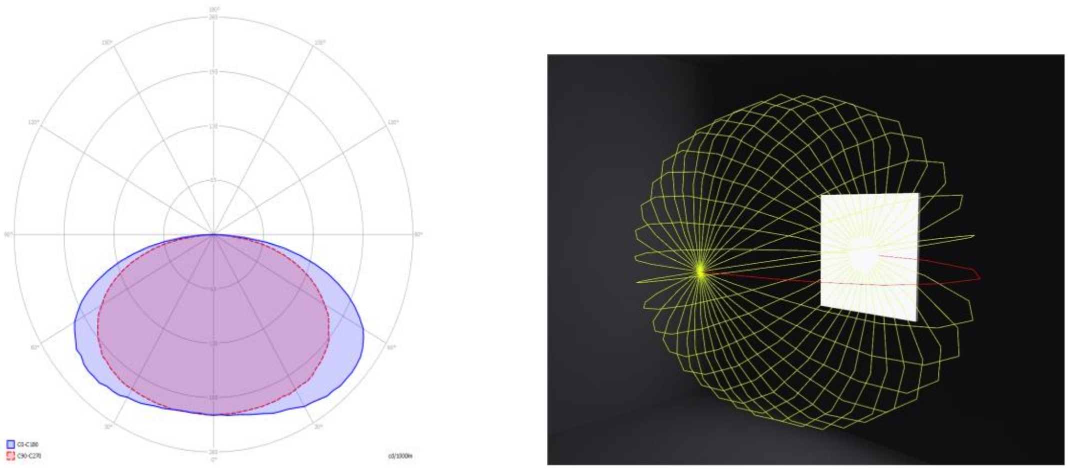


Figure 12. Left: 2D product luminous intensity diagram. Right: 3D luminous intensity distribution.

The Eulumdat file provided by the LightGlass representatives was adjusted using an application called QlumEdit. The size and the dimensions of the frame and luminous areas were edited to match the measured values performed on the product being tested.

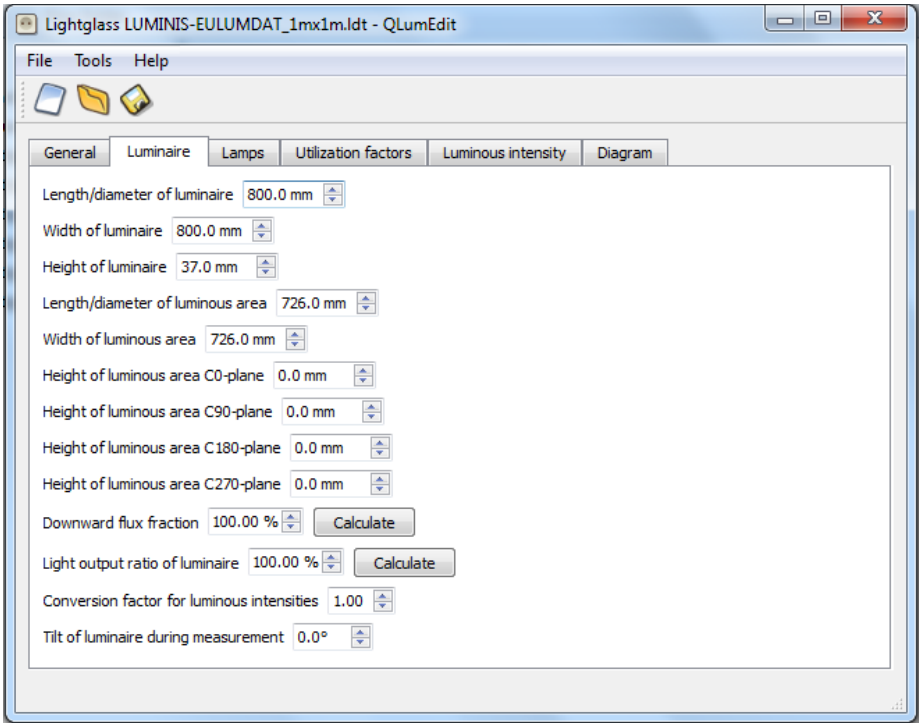


Figure 13. Eulumdat editing tool.

2.4.3 Glass modelling

Light scattering inside the test bed occurs through the product glass, thus an accurate modelling of the glass properties for further use in simulation was carried. DIALux evo requires the light transmission coefficient as an input. Delivered product datasheets did not contain information concerning the optical properties of the glass. In order to estimate the value, a series of simultaneous illuminance measurements on internal and external surfaces of the product as shown in the next figure was performed.

Figure 14. Image of daylight transmission measurements.

2.4.4 Sky models

Sky models reproduce sky luminance distribution patterns. They help to model the sky conditions and therefore predict indoor lighting conditions. There have been considerable efforts to create sky models which cover all possible sky luminous distributions. However, standardized and most used sky models in daylighting simulation are CIE standard sky models and Perez all-weather sky models.

In conducting daylight analysis via simulation, the choice of the appropriate sky models is needed (Mahdavi and Dervishi 2010). This choice is one the main error sources when comparing daylight simulation with experimental measurement (Maamari et al. 2006).

For daylight simulation DIALux evo uses sky models described in *CIE-110 (1994) spatial Distribution of Daylight-Luminous distribution of Various Reference Skies* (DIAL 2017). In this research, only overcast sky conditions are relevant, since they reproduce the worst light scenarios and are independent from the sun position and orientation. A research made at the department of *Building Physics and Building*

Ecology at *TU Vienna* aimed to investigate the performance of sky models showed that the CIE sky model under overcast condition predicts better than other sky models.

2.4.5 Simulation room

In order to represent a realistic office room, a hypothetical rectangular individual office bureau was modelled in DIALux evo 7. The standard *DIN 5034-1(2011)* describes the optimal relation between the room geometry and the window sizes in work places with the aim to maximize daylight benefits (1.3.5). The simulation room model geometry and the usage of 5.8 m² of the product satisfy the standard requirements. The length of the room is 6 m; width 4 m and height 3.6 m. Window positions are also set according to DIN 5034-1(2011). The room is equipped only with a working desk of 2 m length, 1 m width and 0.8 m height to represent the task area during simulation. The model is oriented south although it is not supposed to have any impact because the assessment will be done only during CIE overcast sky. Room surface reflectance is set to the standard values expressed in the EN 12464-1(2002). The following table shows the material reflection values assigned to surfaces in the simulation room

Table 5. Reflection coefficient of simulation room materials.

Surface	Material	Reflection factor (%)
Walls	Default wall material	50
Floor	Oak wood grey	30
Ceiling	Ceiling panels	70
Door	White paint	50
Window frame	Metallic	50
Desk surface	Stained oak	24
Desk legs	Black metallic	0

2.5 Office lighting

2.5.1 EN 12464-1 Lighting of work places-Indoor work places

Users of a work space need to perform tasks for which comfortable visual conditions are needed, and lighting has been acknowledged many times as a key factor in work place satisfaction (Andersen 2014). The work space covered in this study is an office environment. Most of work performed by office workers consists of writing and reading papers, typing on keyboards and looking at screens. The standard EN

12464-1 (2002) gives specifications about the lighting requirements of office work spaces.

Table 6.Office lighting requirement. Reference: EN 12464-1:2002

3	Offices				
Ref. no.	Type of interior, task or activity	$\bar{E}_m$ lx	UGR_L -	R_a -	Remarks
3.1	Filing, copying, etc.	300	19	80	
3.2	Writing, typing, reading, data processing	500	19	80	DSE-work: see 4.11.
3.3	Technical drawing	750	16	80	
3.4	CAD work stations	500	19	80	DSE-work: see 4.11.
3.5	Conference and meeting rooms	500	19	80	Lighting should be controllable.
3.6	Reception desk	300	22	80	
3.7	Archives	200	25	80	

Requirements are expressed in three values to achieve on the work plane/task area. The notion of maintained Illuminance ($\bar{E}_m$) refers to the average illuminance value on a work plane. Illuminance on the task area should not fall under this value. The other values will be covered in 2.6.2.

The standard does not specify different values to daylight and artificial light. However, the standard *DIN 5034-1(2011)* recognizes the superiority of daylight over artificial light and allows the multiplication coefficient of 0.6 on the illuminance value expressed in EN 12464-1(2002).

2.5.2 Review of office lighting practices

Daylight:

Speaking about lighting condition in offices, various studies show the clear preference of office workers to daylight combined with wide opening over artificial light (Galasiu and Veitch. 2006). In the meantime, modern office architectural design tends to give building facades a large fenestration area. These practices often result in large heat gains and high heating and/or cooling loads. A solution to these issues has been the use of various solar and heat control methods like applying reflective or heat absorbing glazing and low emissivity coating on window panes to allow control over indoor conditions (Arsenault et al. 2011). The previous mentioned fenestration applications distort the colour on natural light; thereby it modifies the spectrum of natural light that reaches the building occupant. In other words, these changes alternate light and glass physical properties that have a direct impact on people's perception of lighting conditions like correlated colour temperature (CCT) and the perception of brightness (illuminance) and glass transmittance among others. Positive or negative effects on the visual conditions depend on the applied measures. (Arsenault et al, 2011)

The tested product has a thin plastic layer that helps to uniformly spread light emitted by the LED’s over the glass surface. In this study the impact of the layer is included in the measurement of the transmissivity ratio.

Artificial light:

The main design strategy for office artificial lighting is the ambient lighting system using ceiling mounted downlight luminaires. The reason is that ambient lighting is supposed to offer a uniform distribution which permits to see the surroundings and perform work related tasks. With an increasing aim to reduce energy consumption devoted to lighting, there was an increase in the usage of LED based luminaires in office lighting. Furthermore, methods have been used towards more energy efficient consumption related to light, among which is grouping luminaries in control groups and light control strategies based on motion and/or dimming sensors. In addition, several authors and researchers claim that the combination of ambient lighting with task lighting is an effective and efficient way to reduce energy and augment visual comfort. (Newsham et al. 2013).

In another study, Ngai (2016) suggests the addition of a third lighting layer called surround lighting to the ambient and task combination. The layers is oriented towards light the task area immediate surroundings. The author argued that it enhances the visual surroundings and leads to more energy savings.

2.6 Lighting performance metrics

Simulation and measurement results are used to generate lighting performance metrics. These metrics are proposed in building standards and scientific literature. They assess specified aspects of visual surroundings such as the amount of light, glare and the quality of light. In a review study Carlucci et al. (2015) collect and categorize available performance metrics based on common features. A detailed list of such indices and categorization features is shown in Table 1 in the appendix. A comprehensive analysis of such indicators was made in order to reveal the suitable and meaningful ones in assessing the visual performance of our case.

In this study and according to the feature of the subject being analysed, performance metrics are grouped under two sections namely daylight metrics and artificial light metrics. Although some metrics such as illuminance assess both lighting conditions, the target values differ.

2.6.1 Daylight metrics

Illuminance

DIN EN 12665 defined Illuminance at a point of a surface as '*the quotient of the luminous flux incident on an element of the surface containing the point, by the area of that element'* (DIN EN 12665:2016-09,p10). The unit of measurement is lux. It is the most used metric in assessing the amount of light. Mathematically it is like the following:

$$E=\frac{\emptyset}{A} \qquad (1)$$

Where:

$\emptyset$ is the incident luminous flux

A is the area of incidence

Target illuminance or threshold values refer to the maintained illuminance in the task area; these thresholds depend on light source and the performed visual task.

Regarding daylight, a number of studies concluded that 300 lux of daylight illuminance is considered adequate by the majority of building users and also correlates with the notion of a "well daylit space" (Mardaljevic and Christoffersen 2016). Moreover, the standard EN 5034 allows a reduction factor of 0.6 of the design values expressed in EN 12464-1(2002) when daylight is used.

Aiming to set a visual comfort range similar to the thermal comfort one, researchers propose an upper illuminance limit; it is meant to represent the level above which discomfort may occur because of daylight oversupply, thus, a shading device is needed. There is no agreement on the value, however ,value between 1800 lux and 2000 lux are used by various researchers (Nabil and Mardaljevic 2006, (Roche 2002).

A number of daylight performance metrics are based on assumptions on the upper and lower illuminance thresholds, for this reason, the outcome is relevant only to the input value. In this study, the daylight illuminance threshold values of 300 lux are considered the lower limit and 1800 lux as the upper limit.

Daylight factor:

The daylight factor is the ratio of internal horizontal illuminance to unobstructed external horizontal illuminance determined under sky illuminance distribution that conforms to the CIE standard overcast pattern; its calculation equation is as following:

$$\mathrm{DF}=\frac{\mathrm{E_{in}}}{\mathrm{E_{out}}}100\% \qquad (2)$$

Where:

$\mathrm{E_{in}}$ is the internal horizontal illuminance at a defined point in the room

$\mathrm{E_{out}}$ is the external horizontal illuminance due to an unobstructed sky under overcast sky conditions

This calculation measure takes into account three daylight components:

- Light reflected directly from the sky or sky component.
- Light reflected from an external surface.
- Light reflected from a surface within a room.

The threshold value of daylight factor is commonly expressed in Average Daylight Factor (DF_{AVE}); it depends on the intended usage of the architectural space. According to DIN 5034-1(2011), at least 2% daylight factor is recommended for work places. In addition the recommended minimum threshold value of 2% can be found in other standards and research papers (Alrubaih and al. 2012), (DIN 5034-1:2011).

In the current study simulation is used to generate daylight factors according to the product surface used. The aim is to find the optimal window-to-wall ratio (WWR) when using the product as daylight opening in order to reach the required daylight factor. The target DF_{AVE} is set to 2%.

Vertical daylight factor:

Danny (2010) states that in a side lit room the interior daylight is more dependent on the amount of daylight falling on the window than on the external horizontal daylight illuminance. According to this, the vertical daylight factor is introduced to the research. It is defined as the ratio of the illuminance at a point on a vertical surface due to the light directly or indirectly from the sky to the illuminance on a horizontal plane due to an unobstructed hemisphere of the same sky (J DU et al. 2011). As conventional daylight factor, VDF takes into account light that comes directly from the sky and reflected daylight from surrounding buildings and the ground.

In the current study, ratio of daylight illuminance falling on indoor sensors to vertical illuminance falling on the product outer surface measured by luxmeters lxo2, is calculated under an overcast sky condition in order to estimate the ratio of daylight transmitted to interiors.

Frequency of occurrence:

Several illuminance based metrics use illuminance frequency of occurrence as input for periodic daylighting assessment. Grouping the occurred illuminance values into defined ranges serves as daylight indicators. Examples of these indicators proposed in scientific literature are *Daylight Autonomy* (Reinhart and walkenhost 2001), *Useful Daylight Illuminance* (Nabil and Mardaljevic 2006), *Frequency of Visual Comfort* (Sicurella and Evola 2012). These metrics differ in the scope of the assessment, however, they use similar assessment strategies of calculating the percentage of time within a certain period during which appropriate values of illuminance are accomplished only by daylight. Upper and lower illuminance threshold are a critical decision in the assessment method.

A similar method is used in the current research in order to perform a periodic assessment of Illuminance levels recorded by the test bed sensors. Comfort threshold values are based on literature research on similar assessments.

2.6.2 Artificial light metrics

Illuminance:

The same definition of daylight illuminance applies to artificial light illuminance, however, thresholds differ. Building standards rely on illuminance values since visual task performance is directly linked to the work plane illuminance values. Limits are defined with maintained illuminance $(\overline{\mathrm{E}}_{\mathrm{m}})$**.** Average illuminance values on work plane should not fall under this value. The artificial light or the daylight-artificial light combination design value of maintained illuminance for writing, reading, typing and viewing screens is assumed by the lighting codes to the value of 500 lux.

Illuminance uniformity:

The uniformity of light describes the light distribution on the task area. Since the human eye is sensible to contrasts, the standard EN 12464-1(2002) urges to illuminate task areas as uniform as possible. Illuminance uniformity (U_0) of a defined task plane is the simultaneous ratio between the minimum value of illuminance on a plane (E_{min}) and the average illuminance in the same plane ($E_{average}$). The formulation is:

$$U_0 = \frac{E_{min}}{E_{average}} \tag{3}$$

Illuminance uniformity required for office work places by EN 12464-1 shall not be less than 0.7 on the task area. $U_0 \geq 0.7$

2.6.3 Unified glare rate

EN 12464-1(2002) uses the unified glare rate method to evaluate glare impact on occupants. Rating discomfort glare from luminaires installation is based on limit values of UGR_L. A series of threshold limits depending on the work place and the visual task activities are defined in the standard. UGR scores range between lower values of 10 which means glare is imperceptible and upper value of 34 corresponding to intolerable glare situation (Carlucci and al. 2015). In office work places a value of 19 is considered as the border between comfortable lighting and situations where glare might cause discomfort. Formula for unified glare rate as explained in EN 12264-1 is:

$$UGR = 8 \log_{10}\left(\frac{0.25}{L_b}\sum\frac{L^2 w}{P^2}\right) \tag{4}$$

Where:

L_b is the background luminance in d/m^{-2}

L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye in $cd \times m\text{-}2$

w is the solid angle (Steradian) of the luminous parts of each luminaire at the observer's eye,

P is the Guth position index for each individual luminaire which relates to its displacement from the line of sight.

UGR calculation equation considers that luminaires emit light from a specified solid angle and inputs the corresponding solid angle when the light reaches the observer’s eye. Moreover, the position index assumes that the luminaire emits light above the observer’s field of sight. Researches took several initiatives to adapt the glare index with the type of light source and light emitting surfaces. An important number of indices are proposed in scientific literature. However, a reliable prediction of glare with indices is still a challenge because it depends to: a) the type of light source, b) luminaires installation, c) viewer position index, d) lighting emitting surfaces, e) surrounding reflections, f) viewer tolerance to contrast. Just to name a few.

Despite of the above mentioned limitations URG is still the most used and standardized glare index in assessing indoor conditions, and its formula is incorporated in several lighting assessment tools. It has also been noted that the formula would not be accurate for assessing complex light sources (Osterhaus 2004).

Because of the previously mentioned reasons, the present research uses the UGR method for general assessment; however, thresholds might not strictly apply.

2.7 Acuity experiment with people

2.7.1 Overview

One aspect of the product is its capability to cover details in the illuminated state. The present research aims to experimentally investigate this aspect. The method used is a visual acuity test using vision charts. The method involves participants trying to perform a visual task consisting of finding the orientation of Landolt's rings printed on charts at various distances and under various lighting scenes. Experimental results reveal to which extends the product can cover details and the product relation to viewer and vision target distance, and also to the surroundings light levels.

2.7.2 Visual acuity test

Visual acuity is described as capacity of seeing distinctly fine details that have small angular separation (DIN EN 12665:2016). Tests are used in ophthalmology and by vision specialists to assess the sharpness and thus, the capability of the human eye to distinguish optotypes plotted on charts at a defined distance. Different visual acuity charts have been in use; most common are Snellen chart, logMAR chart and Landolt's ring chart. Acuity grades references are assigned depending on the used chart; the references come from the assumption that a person with a normal vision is capable to see details that subtend a visual angle of 1 minute of arc from the sample viewing distance. An example is the Snellen fraction reference of 6/6 in the metric system or 20/20 feet. This assumption is valid for all optotypes. The equation is like the following:

$$\text{Visual Acuity (VA)} = \frac{\text{test reading distance}}{\text{Distance at which the width of the detail subtends 1 minute of arc}}$$

(5)

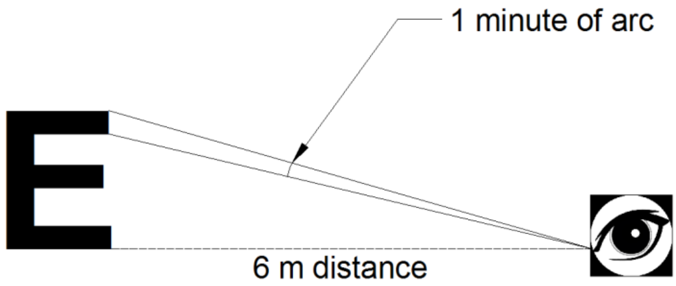


Figure 15. Visual acuity of 6/6 or (20/20).

The acuity chart used in the present research is the Landolt's ring chart, the reason of the choice is that the method is well described and standardized in European norm DIN EN 8596(2016*)*. Moreover, the chart is not based on the knowledge of Latin letters, so the linguistic backgrounds of the participants are not an obstacle.

Landolt's rings are also called Landolt C refering to the similarity of the used optotype with the letter C. The method has been used by a number of building related researches. In 2016, Konstantzos et al. used and adapted version of Landolt's C chart in a part of a series of subjective experiments in order to develop a new metric to measure the clarity of view through various window shadings. Methods derived from Landolt's ring chart were also used to compare visual performance under different lighting conditions (Linhart and Scartezzini 2010). Other research papers which used Landolt's ring to investigate vision through materials and to assess visual performance can be found in related literature (Arsenault et al. 2011), (Menozzi et al. 1998).

For the purpose of this research, a vision chart was designed using Landolt's rings and adapted to the nature of the research topic and the acuity test bed geometry.

2.7.3 Acuity chart design

The Landolt's ring chart used in the experiment is designed according to requirement expressed in the standard DIN EN ISO 8596. The chart consists of an assembly of rings with breaks on top, bottom, left or right and 45° position in between. Rings are presented in a number of sizes spread on lines (see figure 20). On each ring, the size of the break is the same as the width of the stroke. In the main time, the overall height of the prototype must be five times the break/stroke size.

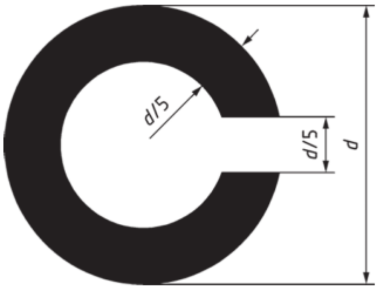


Figure 16. Landolt ring (DIN EN 8596).

In the current study the reference size of the optotype is designed in a way that its height subtends the angle of 5 minutes of arc at the distance of 3 meters using a simple right triangle equation and converting the angle from minute of arc to degree:

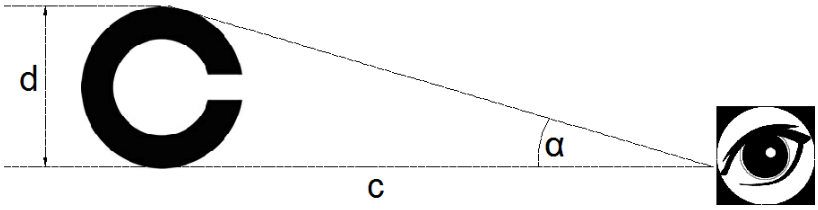


Figure 17. Landolt's rings size.

$$\mathrm{d} = \mathrm{c} * \tan\left(\alpha°\right) \tag{6}$$

Where:

d is the optotype height

c is the test distance from the optotype to the subject's eye

α is the angle of vision

The reference size is presented on the chart on line 9. The quotient of the optotype size increase is $\sqrt[10]{10} = 1.2589$. The quotient originates from the series of preferred numbers between 1 and 10 (DIN ISO 8596:2016). According to this quotient the size of the optotype doubles each three reading lines and it is 10 times each 10 reading lines. Dimeter of ring on each line in the chart is presented in next table

Table 7.Landolt's rings diameters

Line number	Ring diameter (mm)
1	341
2	271
3	215
4	136
5	108
6	86
7	68
8	54
9	43
10	34
11	27

The following measures were respected:

- Chart is printed black on A4 withe paper to have maximum colour contrast.
- On each line, 50% of the rings orientation is either horizontal or vertical.
- Enough space is left between optotypes.
- Number of optypes on each line is according to the standard.
- Line numbers are clear and in uniform size.
- 6 variations using random Landolt's rings orientation are prepared of the experiment

One of the used chart is presented in the next figure.

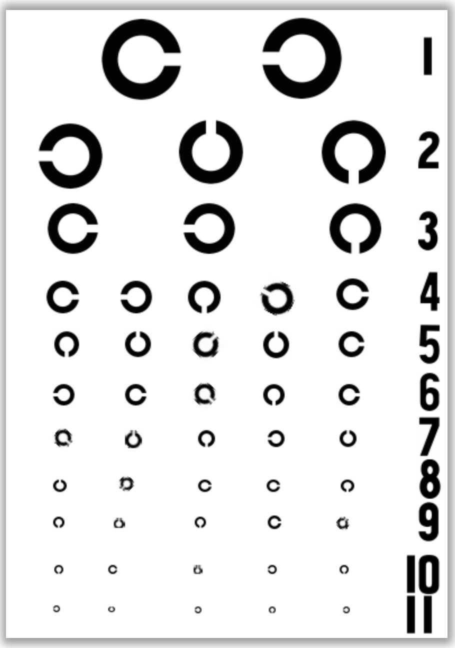


Figure 18. Experiment chart (no scale).

As the participants' sharpness of vision is out of the scope this research and the procedure requires looking to the chart from various distances. The visuals acuity grades described in DIN EN 8596(2016) are not relevant. Reference values and scores are generated based on the scope of the analysis.

2.7.4 Experimental set-up

The experiment was performed at the *Building Physics and Building Ecology* laboratory of *TU Vienna*. The acuity test bed consists of two juxtaposed similar rooms located in a bigger laboratory for general uses. The installed lighting system consists of two ceiling mounted luminaires in each room. The luminaires are connected to a building control system which permits to dim the level of luminous flux emitted by the luminaires using a reduction percentage of the maximum lumen output. The test bed has a side window and shading system, however, the shading system was fully operated to obstruct any light coming from outside and transparent parts of the doors were covered with an opaque paper material to avoid any external light interaction during the experiment. The first laboratory room was completely empty and the second one had a 0.8 m height desk table which was used as a support to mount the acuity chart.

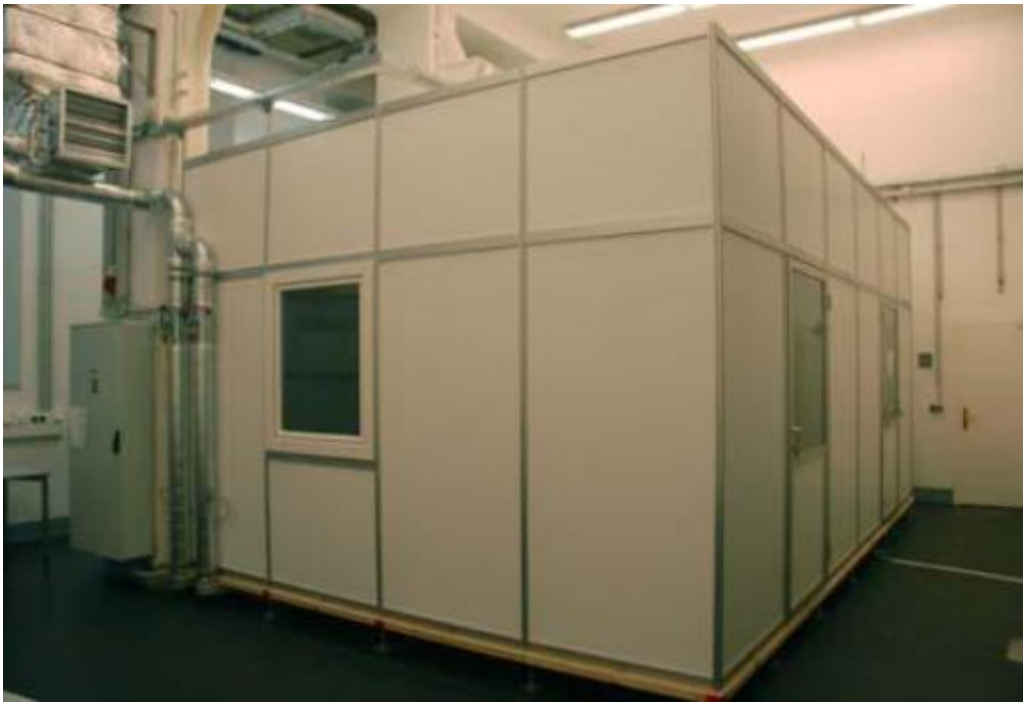


Figure 19. Acuity experiment laboratory from outside.

The product was installed on the door separating the two laboratory rooms, the upper edge the product was at a height 2 m from the floor. The first room is referred to as *Lab 1* for laboratory number one, it served as the location where participants are standing and looking towards the product at a distance of 1m and 2m. Lighting levels in *LAB 1* were adjusted to match the analysed lighting scenarios. Visual acuity charts were placed in *Lab 2,* the first chart was at 1 m distance from the product and the second one was hanged in the rear wall at approximately 3 m from the product.

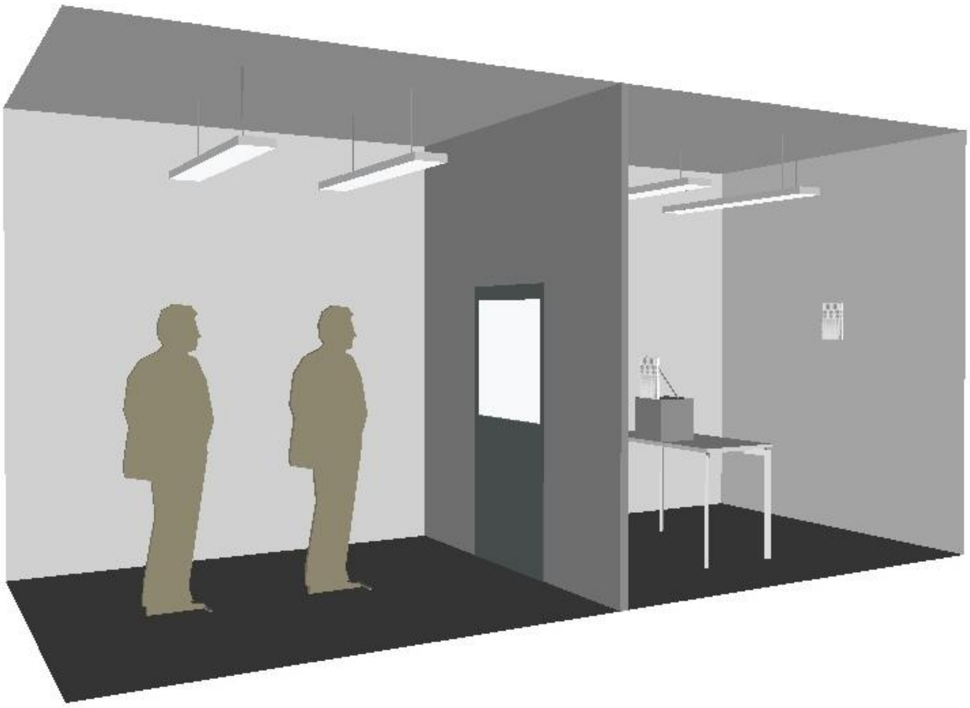


Figure 20. 3 D Illustration of the experiment laboratory.

The experiment took place in two days: 14.06.2017 and 15.06.2017. Three male and three female samples participated, they were all Building Physics and Building Ecology department members. At first, the participants got an explanation about the experiment and the task to perform. They were asked to mention on which line they can distinguish the Landolt's ring break, then to indicate the direction of the break verbally and with hand gestures. If a participant got more than 50% of the right orientation on the line, it was considered that she/he read the line successfully; otherwise they are asked to try with the upper line.

The duration of the experiment was approximately 20 minutes with each participant. A set of 6 charts with different rings orientations was prepared, and charts were replaced after each step in order to avoid participants remembering rings orientations from previous steps. Tests were performed when the glass was switched Off and repeated when it was switched ON. Experiment details are explained in the following table:

Table 8. Vison acuity experiment steps

Lighting Scene	Step	Viewer position	Glass switch
Office vision	Step 1	1m	Off
		2m	Off
	Step 2	1m	On
		2m	On
Corridor vision	Step 3	1m	Off
		2m	Off
	Step 4	1m	On
		2m	On
Outdoor vision	Step 5	1m	Off
		2m	Off
	Step 6	1m	On
		2m	On
Night vision	Step 7	1m	On
		2m	On

2.7.5 Lighting scenes:

Visibility through materials depends on capability of the surrounding light to reveal its details. The experiment was performed under four lighting scenes that represent common situations in the office environment and also refer to the various intended usages of the product:

1) **Office vision:** It refers to the usage of the product as an element in interior separation between two offices. The illuminance levels on Lab_1 and Lab_2 are adjusted to 500 lux on the work plane (0.8 m from the floor).

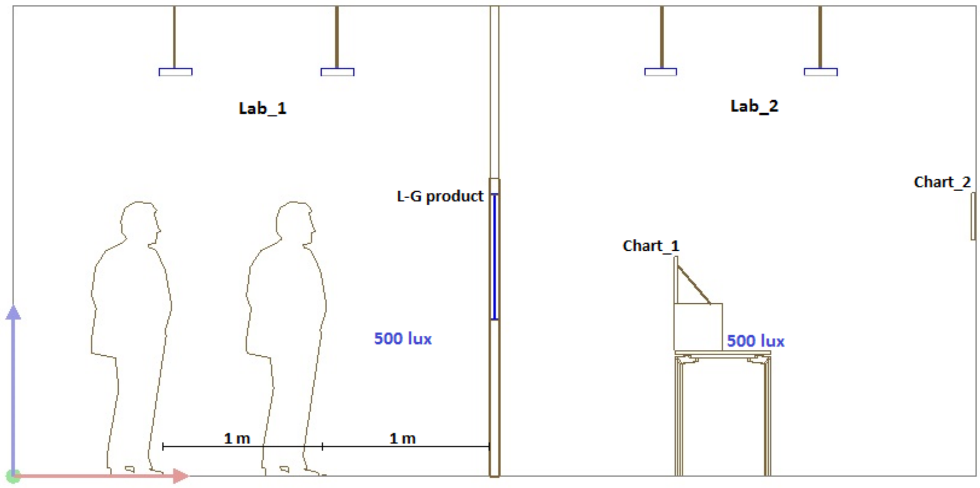


Figure 21. Section demonstration of office scene

2) **Corridor vision:** In this scene, Lab_1 represents a corridor in an office. The illuminance level is set to 100 lux at the floor level according to DIN 12464-1(2002). Lab_2 is always representing an interior office surrounding and illuminance is set 500 lux on the task area.

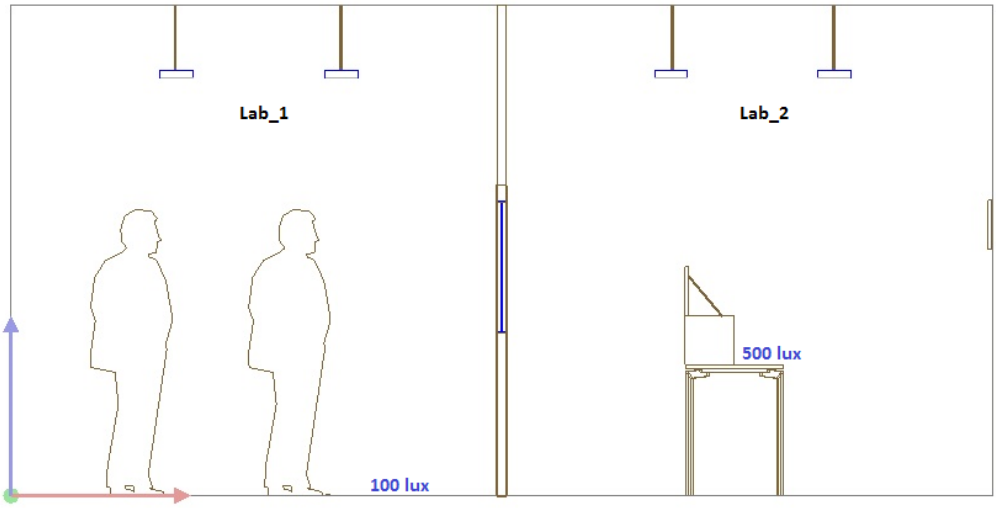


Figure 22. Section demonstration of corridor vision scene

3) **Outdoor vision:** Illuminance in Lab_1 is dimmed to the level of 20 lux. This value represents the CE street lighting class expressed in EN 13201-2 (2004). The lighting level is measured at 0.2 m from the floor level as the norm suggests. The lighting situation in Lab_2 refers to interior offices with 500 lux. This scene reflects the usage of the product as a window to the outdoor environment.

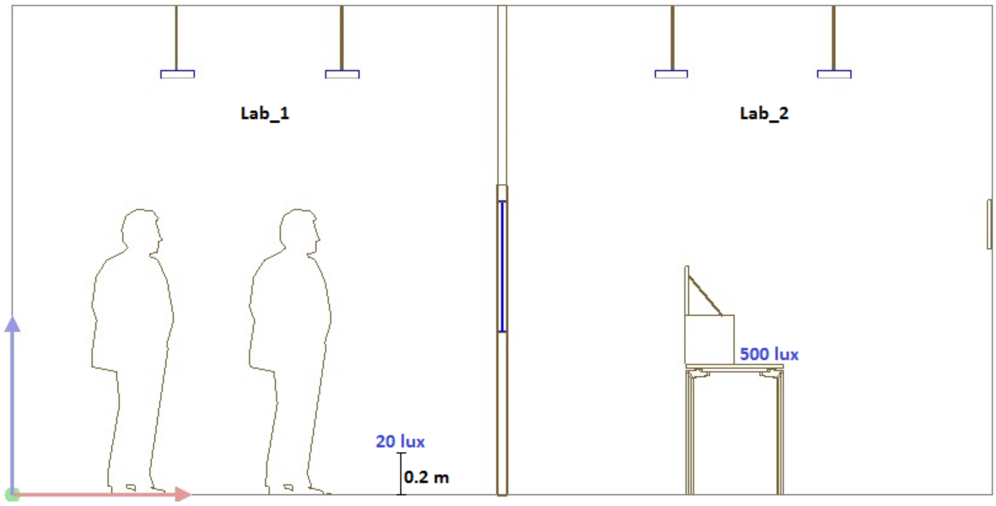


Figure 23. Section demonstration of outdoor vision scene.

4) **Night vision:** Light from the wall mounted luminaires is switched Off. Only the product is illuminated. This is a general situation meant to assess the visibility through the product when it is the only source of light.

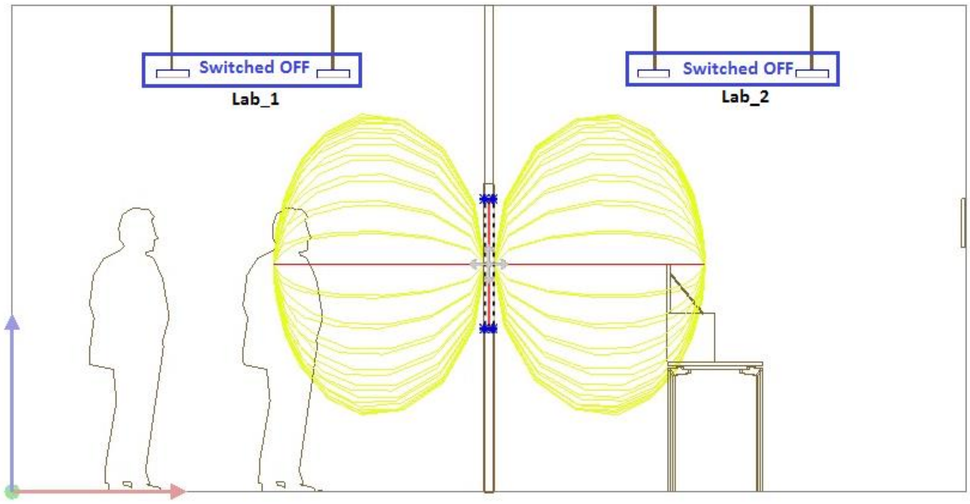


Figure 24. Section demonstration of night vision scene.

Illuminance measurements in Lab_1 and Lab_2 are checked using luxmeter Minolta T-10A (Table 5) and light dimming using a building monitoring system installed in the laboratory. No dimming is applied on the product which means it is always on full light output.

3 RESULTS & DISCUSSION

3.1 Overview

Results are presented and discussed in five sections in this chapter. The first section (3.2) contains results of the data analysis from the test bed sensors measurements. This section contains measurement of daylight, artificial light and combination of both. The second section (3.3) presents results of comparing daylight and artificial light data from the physical test bed and virtual test bed. The third section (3.4) covers the results of the hypothetical office space simulation; illuminance levels and glare evaluation are presented.

The fourth section (3.5) is reserved to the subjective visual acuity test. The results are presented based on the product interaction with the viewing distance and the interaction with the visual surroundings.

The discussion is presented in this chapter because of the interconnectivity of the results. It was necessary to discuss each topic after presenting the related results in order to ensure the clarity of the next one. In section 3.6 a summary of the result based on the product intended usage is presented.

3.2 Test bed data analysis

3.2.1 Frequency of occurrence

This analysis is a periodic assessment with the aim to put the recorded daylight illuminance into defined ranges; it consists of statistical analyses of illuminance values from the test bed based on the occurrence range of 300 lux. Parameters of the analyses are shown in the table:

Table 9. Analysis parameters.

Analysis parameters	
Period	01-11-2016 to 20-11-2016
Test bed orientation	South
Product illumination state	OFF
Sensors	lx3 and lx4
Office occupancy schedule	08:00 to 18:00
Sky conditions	Various

Sun path and daytime are relevant to the analysis period and the experiment location.

Sensors lx3 and lx4 are chosen since they measure daylight vertical illuminance on the test bed floor which represents a task area on the scale model. The frequency of occurrence of 300 lux range on lx3 and lx4 is shown in the next two figures.

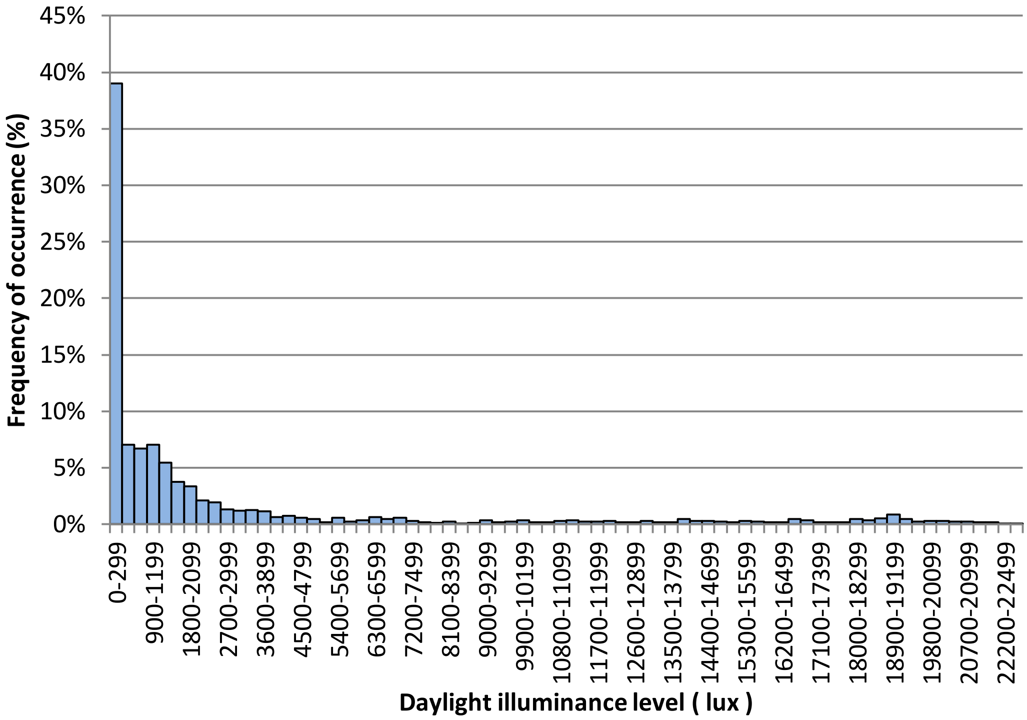


Figure 25. Frequency of occurrence of 300 lux range on lx3

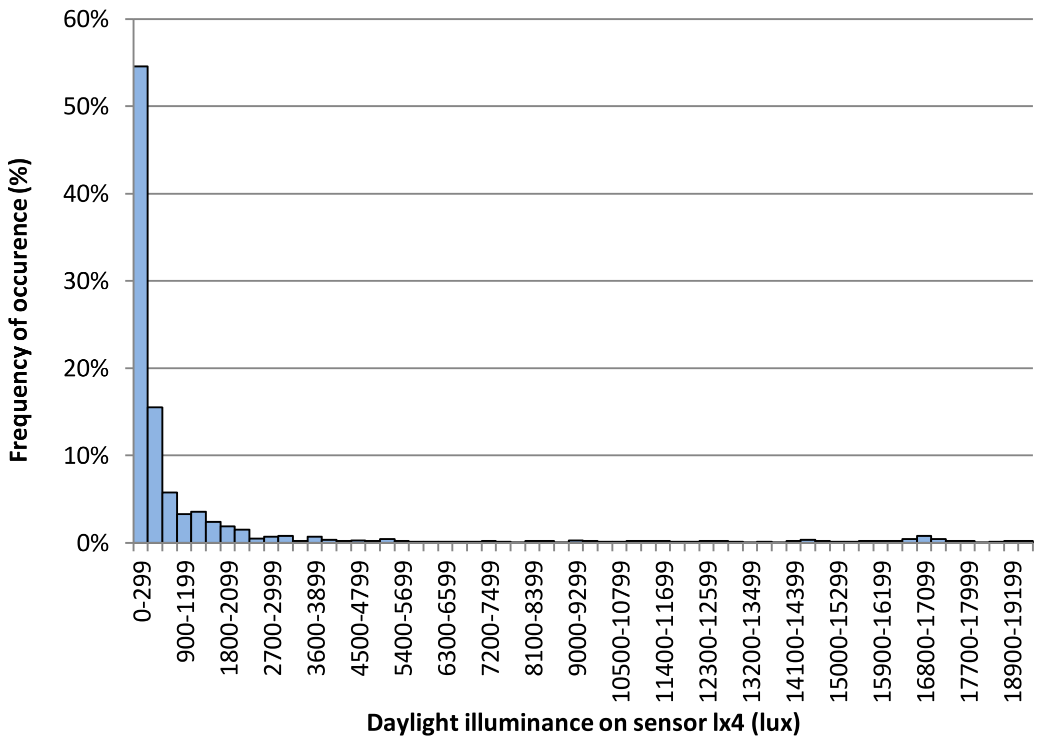


Figure 26. Frequency of occurrence of 300 lux range on lx4.

On figure 25 and figure 26, we can see the maximum illuminance values that occurred during the analysed period. Excessive levels occurred when direct sun penetrated the test bed through the product, this may lead to visual discomfort and unwanted solar heat gains, for these reasons, preventive measures are to be considered.

The next chart shows the results of a statistical analysis method similar to *Useful Daylight Illuminance (UDI)* and *Frequency of Visual Comfort (FVC)* mentioned in daylight assessment literature and explained in 2.6.1. It expresses the percentage of time within an analysis period in which average daylight illuminance falls in assumed appropriate ranges.

Three ranges are delimited by two assumed threshold values of daylight maintained illuminance ($\overline{\mathrm{E}}_{\mathrm{lower}}$, $\overline{\mathrm{E}}_{\mathrm{upper}}$) where:

- $\overline{\mathrm{E}}$ is the average daylight illuminance falling simultaneously on sensors lx3 and lx4

And:

- if $\overline{\mathrm{E}} < \overline{\mathrm{E}}_{\mathrm{lower}}$ there is an insufficient daylighting and artificial light is needed;
- if $\overline{\mathrm{E}}_{\mathrm{lower}} \leq \overline{\mathrm{E}} \leq \overline{\mathrm{E}}_{\mathrm{upper}}$ daylight illuminance values are in the appropriate range;
- if $\overline{\mathrm{E}} > \overline{\mathrm{E}}_{\mathrm{upper}}$ there is an excessive daylighting and discomfort may occur

$\overline{E}_{lower}$ is assumed to be 300 lux, while $\overline{E}_{upper}$ is assumed to be 1800 lux. (see. 2.6.1 Daylight metrics)

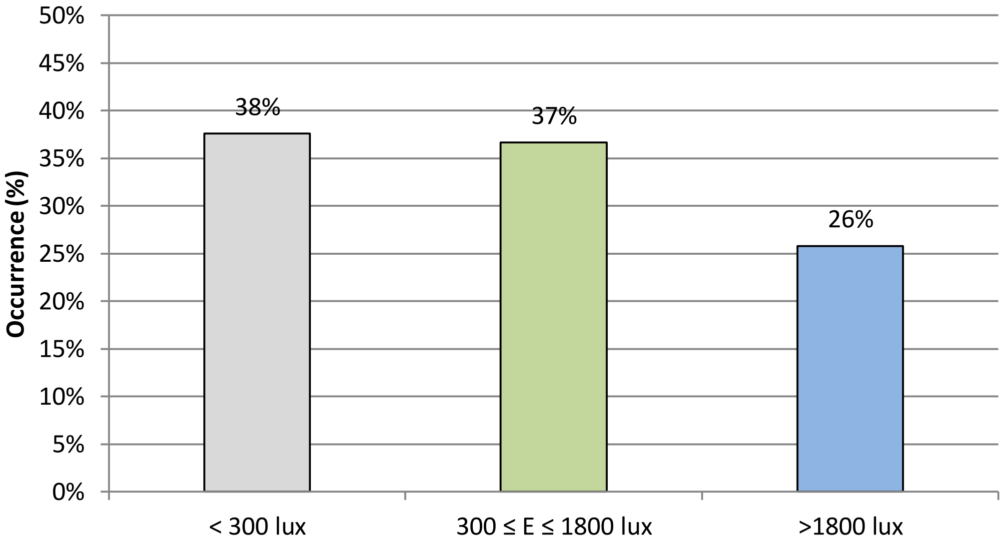


Figure 27. Occurrence ranges.

The chart shows that during 38% percent of the time additional light is needed. This percentage includes evening hours when daylight alone cannot illuminate offices till 18:00. However, during 37% daylight only can be sufficient and offers an adequate visual comfort. In the remaining 26% of the time, an oversupply of daylight is expected and a sun protection measure is required.

3.2.2 Daylight ratio

The ratio of daylight illuminance falling on the test bed interior sensors to the vertical daylight illuminance on exterior sensor lxo2 is presented in the next chart. The ratio is independent from the test bed orientation and the sun position since it is calculated on an overcast sky condition. Used data was recorded on 16.11.2016 where maximum horizontal global radiation of 100 W/m² was recorded at 10:45. The calculation equation is:

$$R_{ratio} = \frac{E_{interior}}{E_{exterior}} * 100 \quad (7)$$

Where:

$E_{interior}$ is illuminance on sensors lx1 to lx8

$E_{exterior}$ is simultaneous exterior illuminance on sensor lxo2

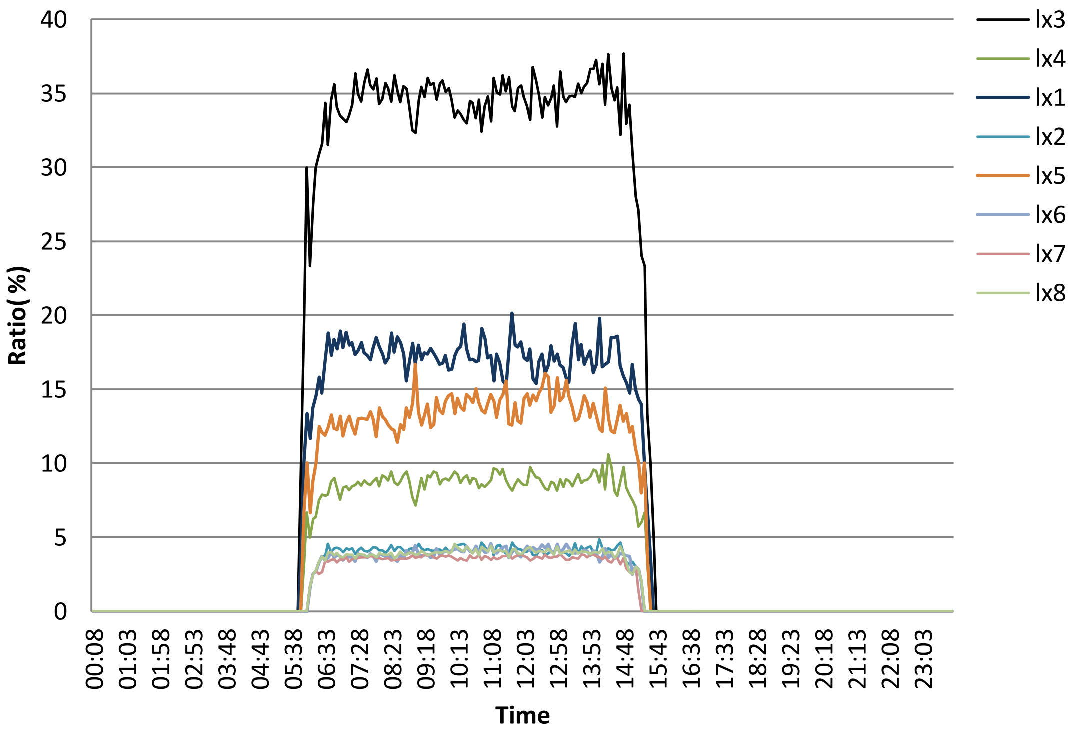
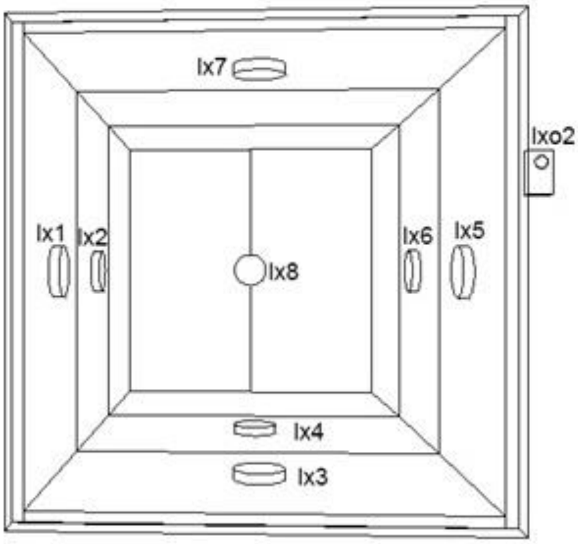


Figure 28. Overcast day illuminance ratio.

The mean ratio from 07:00 to 15:00 on all interior sensors is shown in the next table. As we can see in the previous graph and the next table, from all daylight falling on the product exterior surface, first 40% is reflected or absorbed by the glazing; ratios of the remaining transmitted daylight are presented on table 11. The maximum calculated ratio is as expected on sensors lx3, because of the perpendicular emittance of the sky light. In the main time only 4% reaches lx8 placed vertically at the distance of 1.5m from the glass.

Table 10. Mean ratio of daylight on interior sensors

Sensor	Mean ratio (%)	Sensors position
lx1	17.3%	
lx2	4.2%	
lx3	34.9%	
lx4	8.8%	
lx5	13.6%	
lx6	3.9%	
lx7	3.6%	
lx8	4%	

3.2.3 Artificial light Illuminance

After launching the On/Off switch strategy, luxmeters recorded illuminance values related only to the product artificial light. This occurred in the evening hours when lxo2 was recording zero illuminance. Sensors recorded data in a five minutes interval. Values from five randomly chosen days are averaged. The final average illuminance levels are presented in the next bar chart.

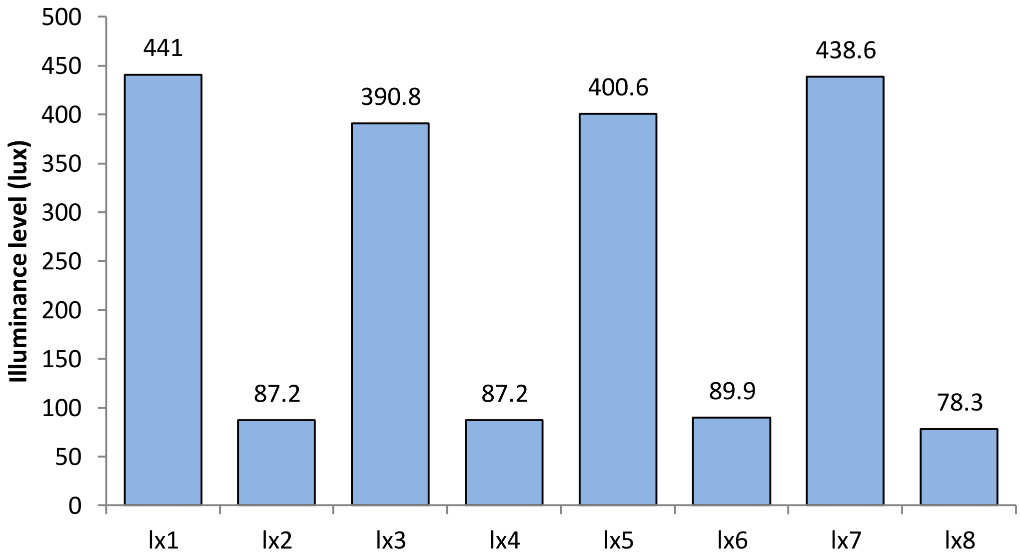


Figure 29. Artificial light illuminance at sensors.

3.2.4 Daylight transmission in the illuminated state

In order to investigate the daylight transmission behaviour of the product in the illuminated state, data on an overcast sky day (29.01.2017) was analysed. In the mentioned day, the On/Off switch strategy was active, which means that the sensors were measuring illuminance related to both daylight and artificial light during six times a day. Known artificial light illuminance levels of the product on the sensors lx3 and lx4 are subtracted from the measured values each time the product was illuminated.

An observation in lx3_Off and lx4_Off lines in figure 30, reveals a small reduction in illuminance values during the first minutes after the glass is illuminated. However, after one recording interval of five minutes, illuminance values return to be in correlation with data on lx3_On and lx4_On. The interpretation is that, a daylight transmission reduction occurs within the first five minutes after illuminating the product, then, the reduction disappears and the product permits full daylight transmission.

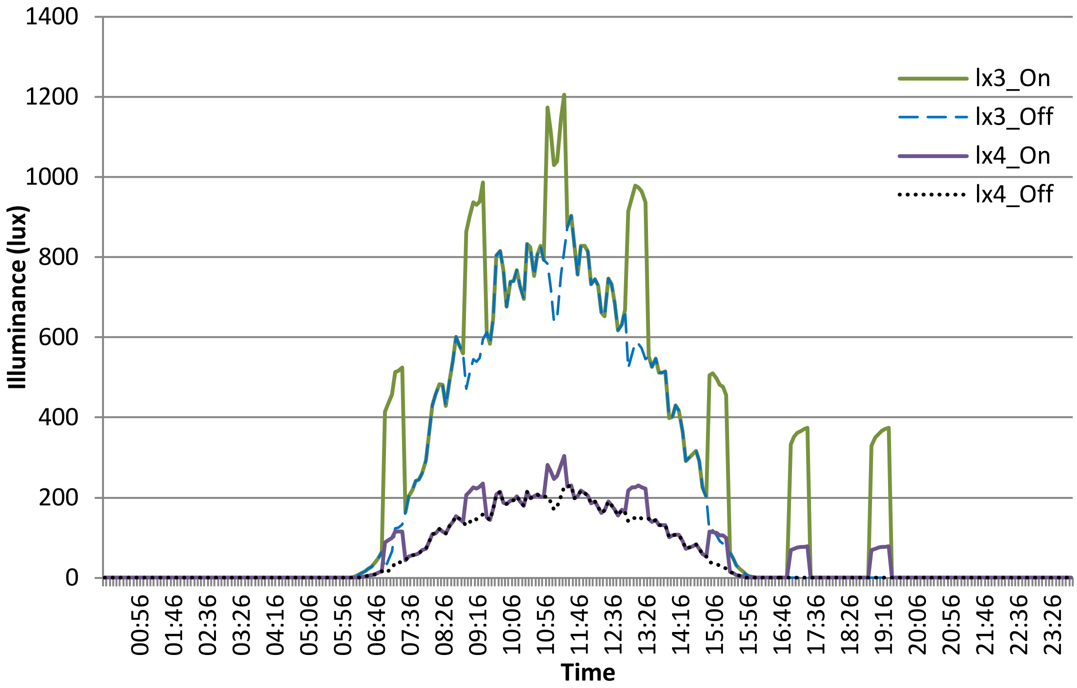


Figure 30. Illuminance during one day glass ON and OFF

3.2.5 Transmission coefficient

Daylight transmission coefficient of the product when it is turned off was measured as explained in 2.4.3. Measurements were made on 03.05.2017 between 10:00 and 11:00 am. The sky was cloudy, which means that no direct sun light was falling on the sensors. Measurement results and calculated coefficients are presented in table 11.

Table 11.Transmision coefficient results

Illuminance sensor used	Outside test bed (lux)	Inside test bed (lux)	Transmission coefficient
	1300	762	0.59
	1315	763	0.58
	1275	750	0.59
	1267	749	0.59
	1286	759	0.59
	1300	771	0.59
	1355	803	0.59
	1445	927	0.64
Minolta T-10A	1453	929	0.64

The measurement was performed several times, an average of all transmission coefficients was found to be 0.6, or 60%. The value was given to the transparent part in the simulation model.

3.3 Simulation validation

Aiming to ensure that the simulation represents the real word in an adequate manner, and in order to assess the reliability of the simulation models for further use in the assessment process, a comparison between the results on the physical sensors and the virtual sensors was performed.

3.3.1 Artificial light

Regarding the artificial light emitted by the product, it can be seen in the next comparison graph that values generated by the photometric file on virtual sensors predict illuminance values close to the actual measured ones. Small differences occurred. However, the mean relative error (RE) is less than 10%, and this means that differences are in an acceptable range and closely represent actual measurements. Moreover, simulation models are used to assess lighting in an office environment which focuses on horizontal illuminance on work planes, values on lx3 and lx4 are valid. Negligible differences of respectively 6 lux and 1 lux showed on lx3 and lx4.

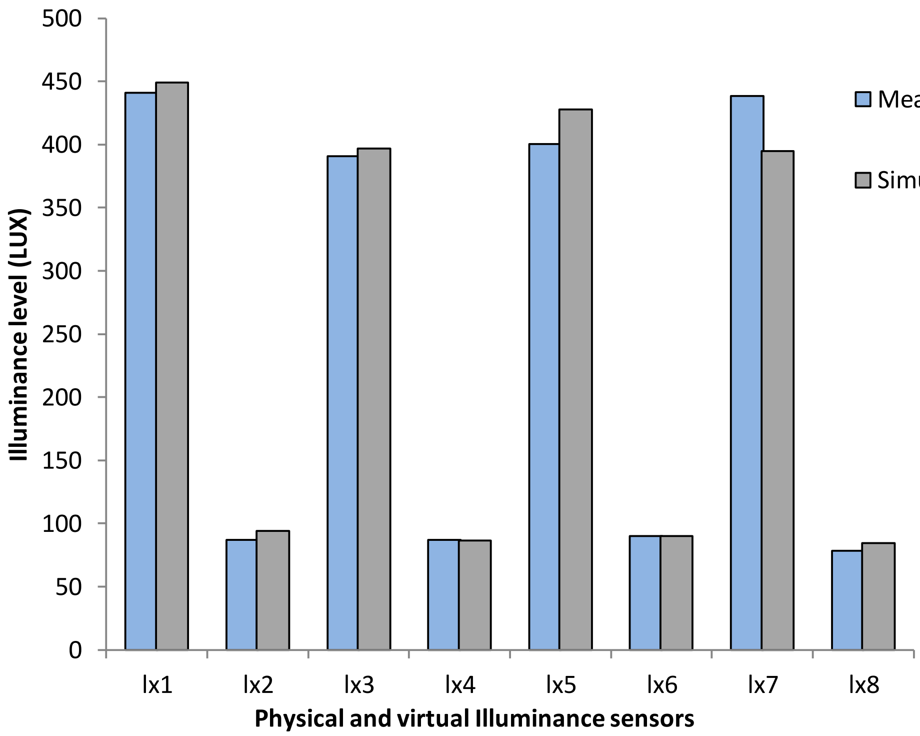


Figure 31. Comparison of artificial light Illuminance on physical and virtual sensors

The product artificial light distribution on all the test bed surfaces is shown with false colour rendering in the following image.

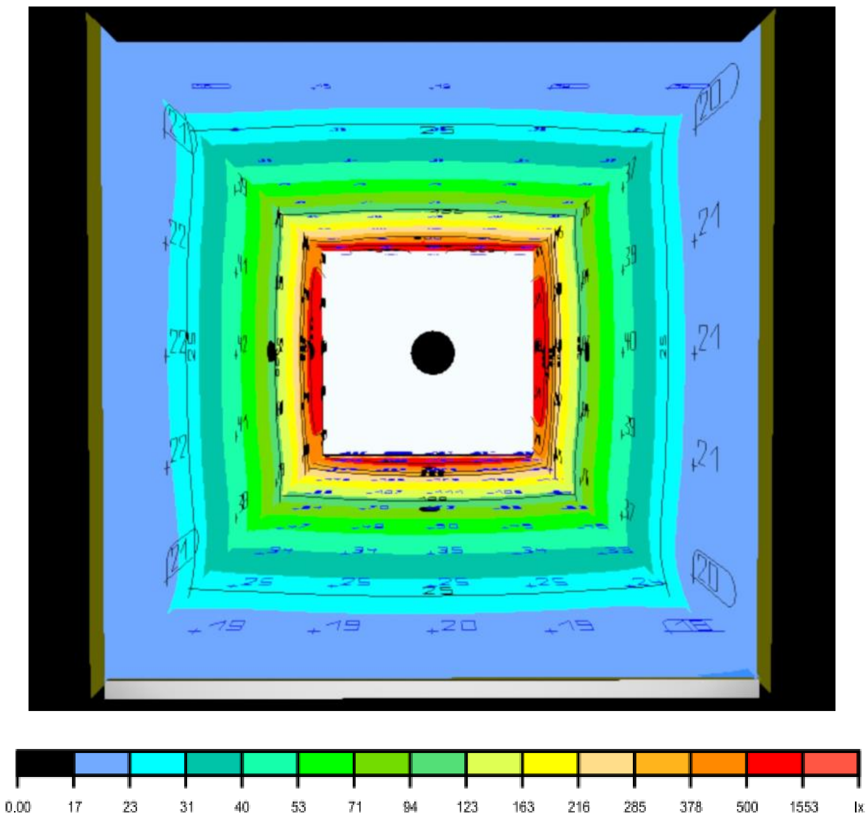


Figure 32.False colour view of virtual test bed showing artificial illuminance distribution (Rear view)

3.3.2 Daylight

Recorded data from the test bed on 29.01.2017 at 12:00 is used for the comparison with the simulation. The sky condition was overcast; the sky type was chosen since it represents an extreme daylight condition and it is similar to the overcast sky described by *CIE-110 (1994)* and used by the program for calculation (DIAL 2017). Measurements and simulation results show a correlation on all sensors, the mean relative error is less than 10%. This leads to the assumption that, under the previously mentioned conditions, simulation models can predict indoor illuminance values close to the actual measurements.

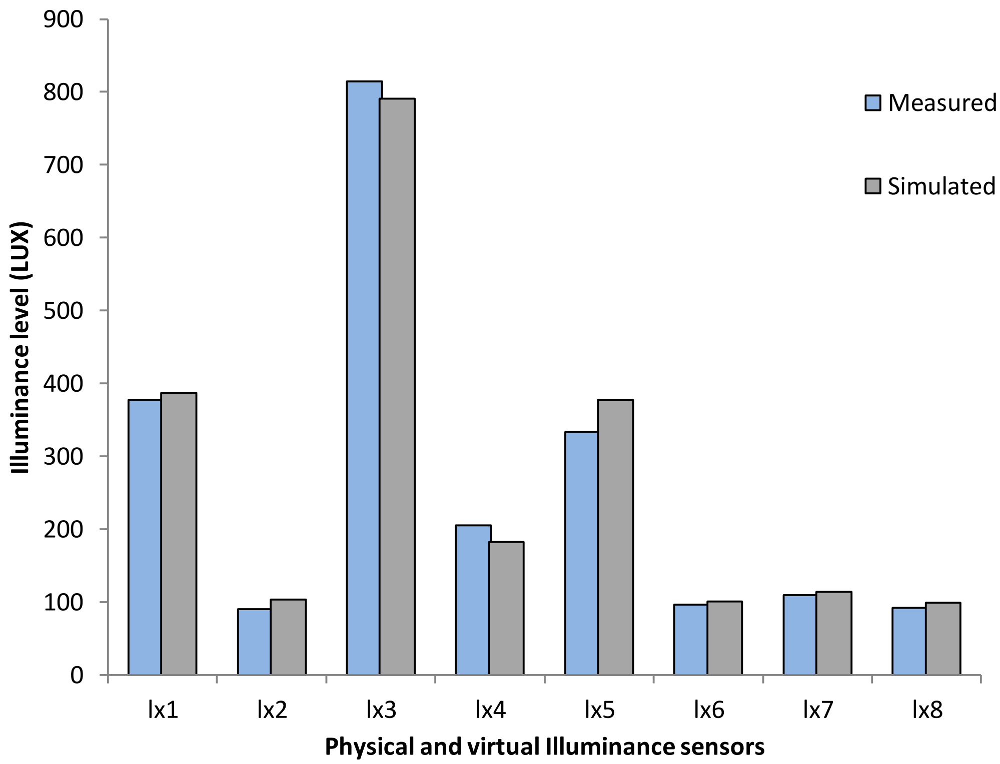


Figure 33. Comparison of daylight Illuminance on physical and virtual sensors.

Next image is a front view of the virtual test bed, showing daylight illuminance distribution on all surfaces. The false colour index helps to read illuminance values on the image.

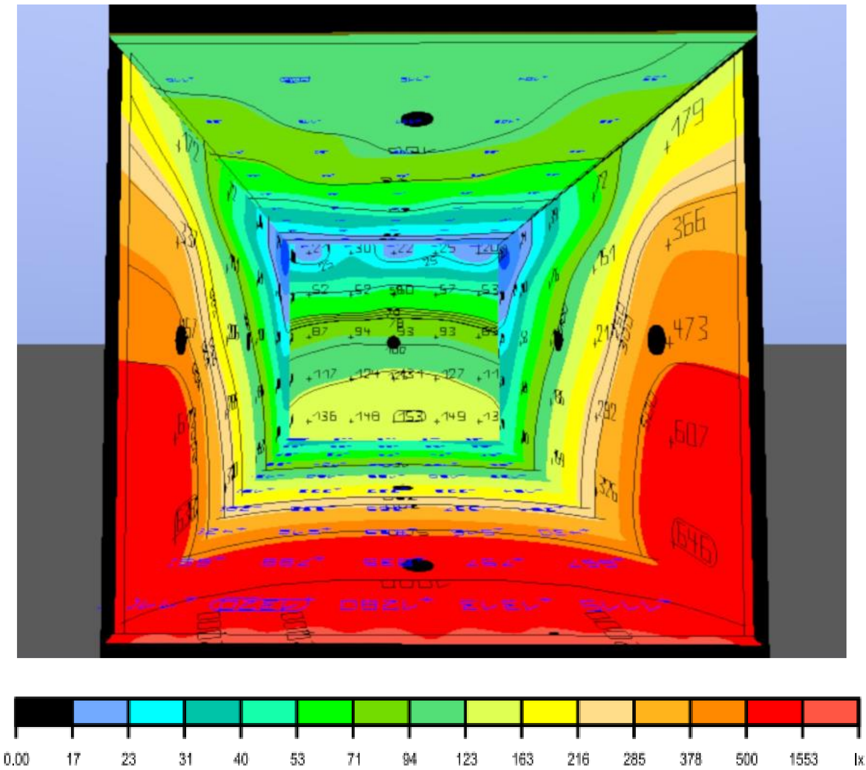


Figure 34.False colour view of virtual test bed showing daylight illuminance distribution (front view)

3.4 Simulation results

3.4.1 Window-to-wall ratio

The investigation into optimal window-to-wall ratio (WWR) in order to reach the required daylight factor is presented. The initial office design according to DIN 5034-1(2011) requires glazing of 5.8 m²; however, values are gradually increased. The product virtual window previously validated is distributed in the centre of the south oriented wall. The mean daylight factor is calculated on daylight factor effective area which is positioned 0.85 m from the floor and one meter far from the room walls. Relations between the product surface, WWR and daylight factor are presented in the following table. The simulation showed that the usage of at least 50% WWR is required in order to reach a daylight factor of 2% during overcast sky days.

Table 12. Optimal WWR based on daylight factor

Product surface (m²)	Window-to-wall ratio	Daylight factor (%)
5.8	27.6	1.14
8.76	41.7	1.66
11.68	55.6	2.14

Using a 55.6% window-to-wall ratio, illuminance on the room work plane area is calculated. The rectangle in figure 37 represents the daylight effective area. We can notice that an illuminance value of 300 lux accompanied with high uniformity is achievable in an area around 1.5m far from the wall where the windows are placed. However, daylight illuminance drops gradually the further you move from the window.

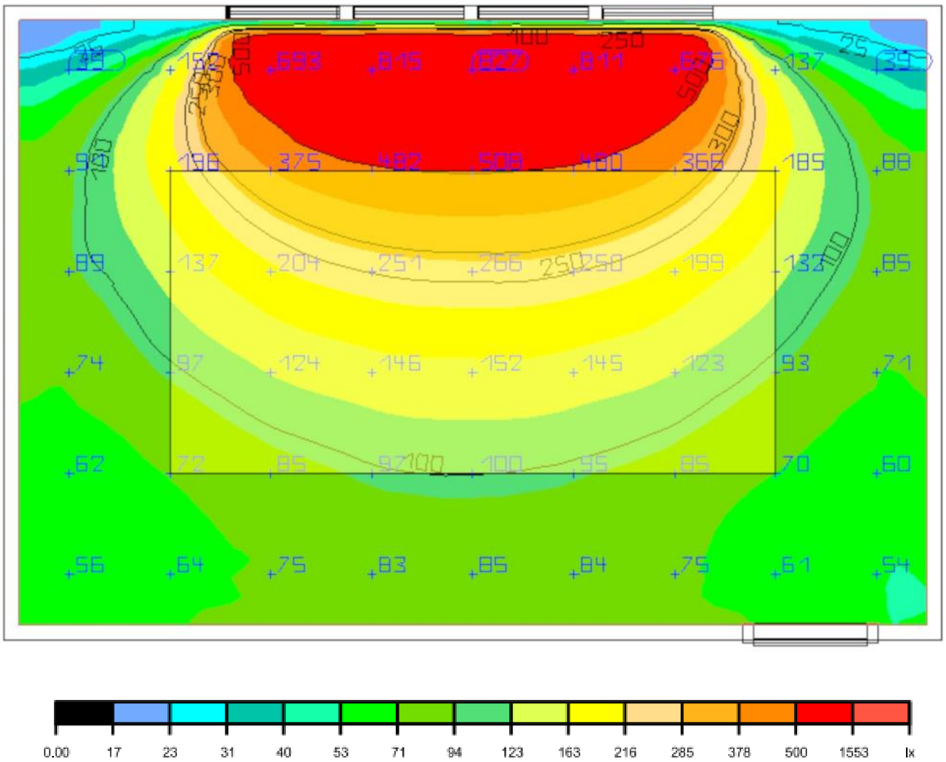


Figure 35.Daylight illuminance distribution on work plane (false colour rendering)

The office working desk is centred between the south and the north walls and 1.5 m far from the west wall. The illuminance on the desk surface which represents the task area is illustrated in the next figures. The simulated maintained illuminance on the surface is 202 lux. Values are about 100 lux less than the assumed optimal threshold. These results are simulated under the worst sky luminance distribution pattern..

The next assessment investigation (3.4.2) is related to artificial light emitted by the product under the same design settings. It will show to which extend the product emitted light can assist daylight on the task area.

Figure 36.Daylight illuminance on task area

3.4.2 Artificial light performance

The product emitted light as the only light source in the room is simulated using the photometric file previously validated. Illuminance distribution on the work plane shows a maximum value of 506 lux beneath the centre of the glazing area. Isolines contours show a value of 250 lux at 1m distance from the glazing and 100 lux at 2.5m.

The target values of 500 lux with 0.7 uniformity ratio are not achieved. Additional light sources are required to raise illuminance value and uniformity. The following figures 37 and 38 will give a better insight.

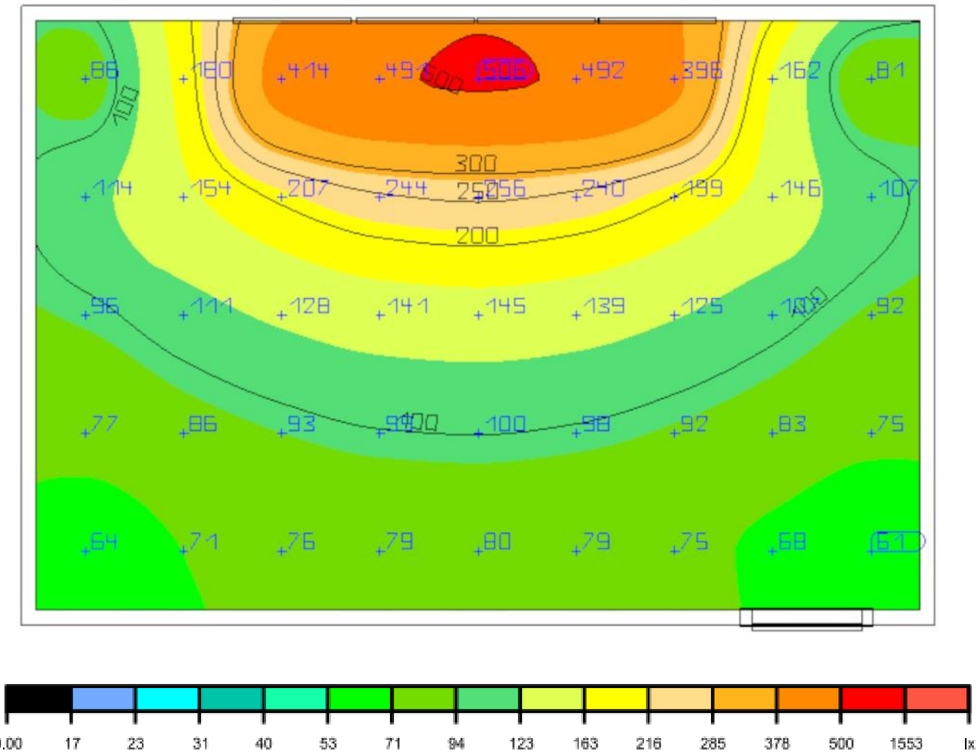


Figure 37.Artificial light illuminance distribution on work plane (false colour rendering)

As expected from the whole area assessment, the average illuminance on the desk is 148 lux with uniformity of 0.62. This value can only contribute with daylight or other light sources to reach the office lighting design requirement. Interior view and false colour illuminance distribution are presented in figure 38.

Figure 38 . Artificial light illuminance on task area

To summarize this part, because of the previously showed limitation to reach the optimal value, it is not advisable to rely on the product as the only source of light in an office work place.

3.4.3 Unified glare rate

Glare evaluation using the UGR method is performed for a person sitting behind the desk at a distance of 2m from the wall equipped with the product. The evaluation point is set at a typical sitting height of 1.2m from the floor. The viewing angle of 180° is assessed. As we can see in the next illustration, predicted discomfort from glare related to reading/writing activities might occur on the viewing sector from 15° to 90° with maximum UGR values of 23 (inner circle) at 45°. The viewer's right side viewing angles are glare free with UGR values less than the threshold of 19.

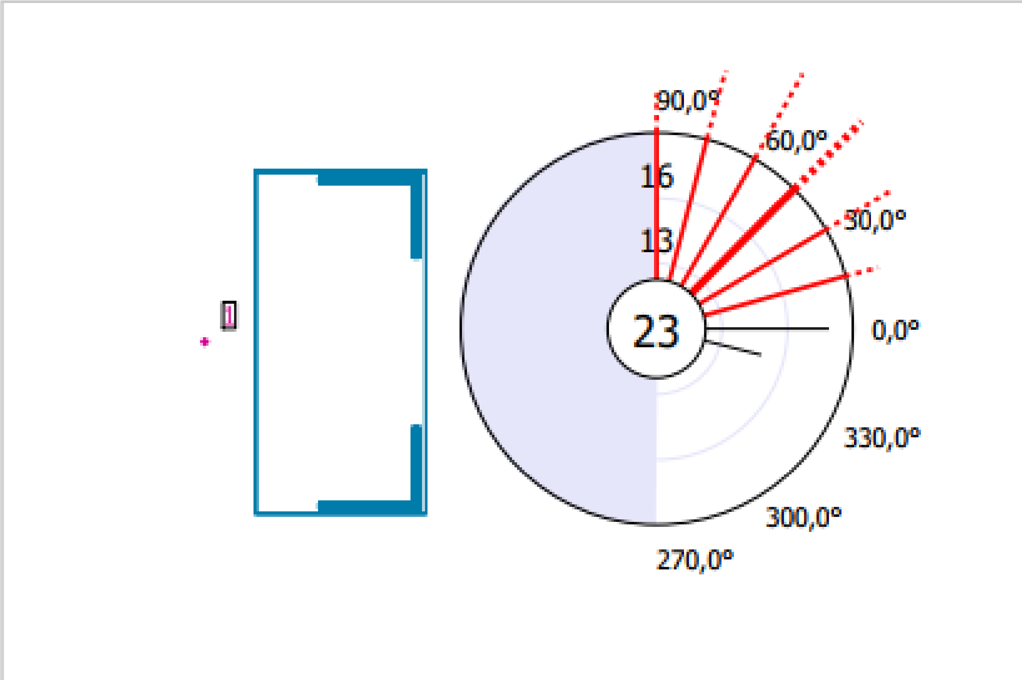


Figure 39. UGR calculation point

3.5 Visual acuity test

Results of the visual acuity test are presented in two axes. The first one concerns the interaction of the product with the viewing distance. Four situations are investigated from two viewer positions: a viewer from one meter distance from the product looking to details at one meters and two meters far from the other side of the glass, and the same procedure for a viewer at two meters from the product.

The second investigation axe is the product interaction with visual surroundings, as mentioned in (2.7.4). Four lighting scenes referring to lighting situations in office surroundings are set during the experiment. The viewer's capacity to distinguish details from the same position under different lighting situations is the method used to reveal the product interaction with its visual surroundings.

3.5.1 Interaction with viewing distance

The viewer acuity line when the glass is Off is used as reference, the difference between the line numbers the participant achieves when the product is Off and when is On serves as the acuity decrease score. In other words the following logic is used:

1 line decrease between product ON & product OFF = 1 acuity decrease

The bigger acuity decrease value means the illuminated product is capable to hide more details in that position. An acuity decrease value of zero occurs when the viewer is capable to see the same details regardless of the product illumination state.

Figures 40, 41 & 42 show the acuity decrease scores under each lighting scene on Chart_1 and Chart_2 at the viewing distance of one meter. The acuity decrease score of zero occurred more often on Chart _1. The scores of one and two acuity decrease are most often, however, the highest acuity decrease scored was three and it occurred only when the viewer was looking to Chart_2.

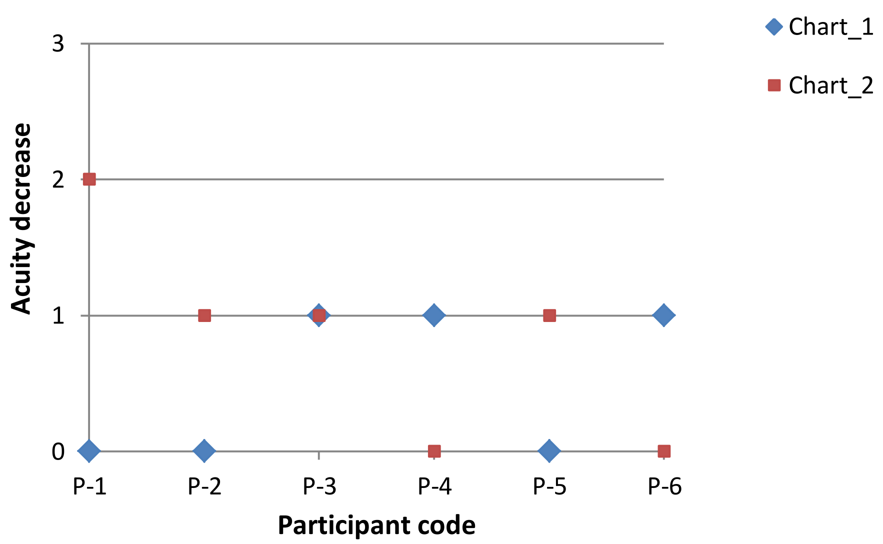


Figure 40. Acuity decrease per participant under office vision scene (1 m from the product)

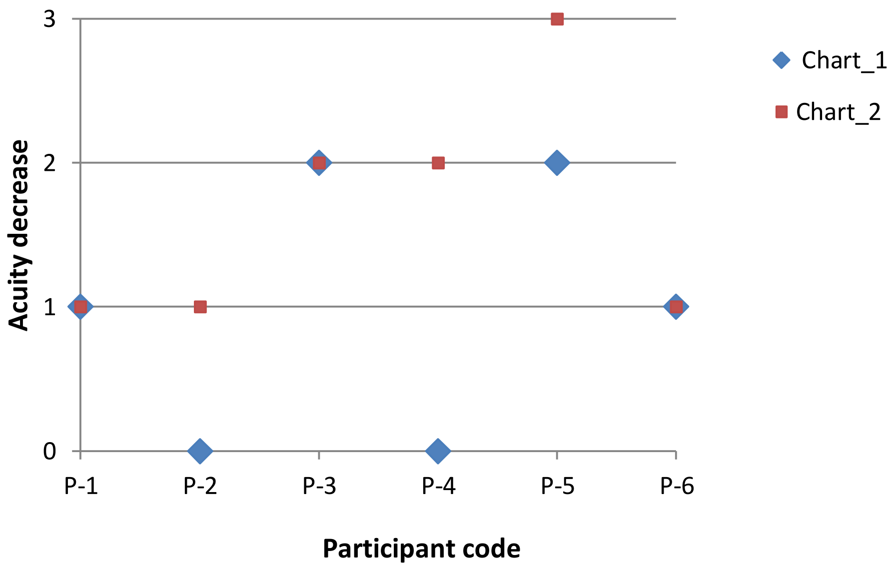


Figure 41. Acuity decrease per participant under corridor vision scene (1m from product)

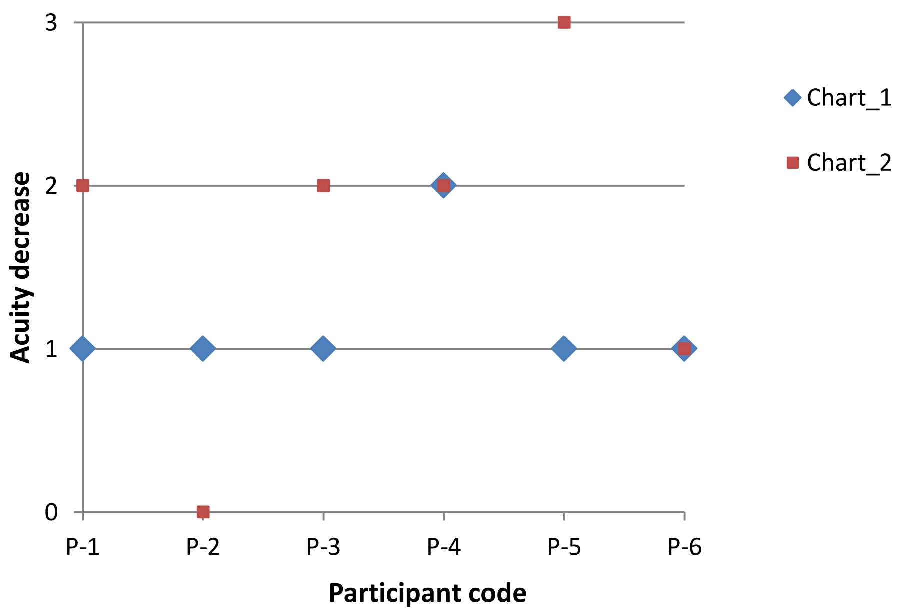


Figure 42. Acuity decrease per participant under outdoor vision scene (1m from the product)

A percentage of acuity decreases scored on Chart_1 and Chart_2 during the experiment is graphically presented in the figure 43. A look at the graph shows that higher acuity decrease scores occurred when the viewer was one meter from the product and looking to the Chart_2 than when looking at Chart_1.

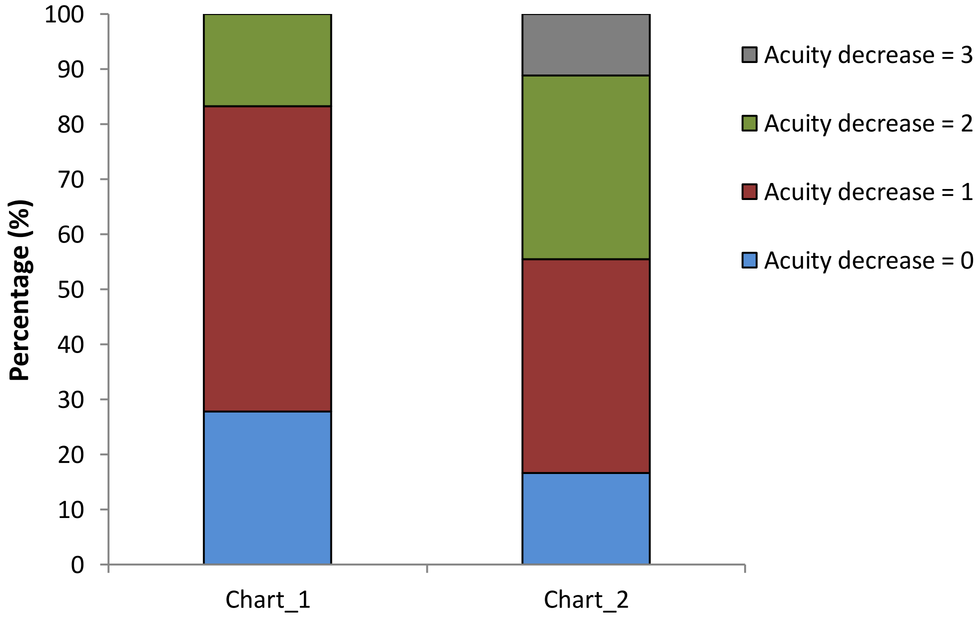


Figure 43. Percentages of acuity decrease scores on Chart_1 & Chart_2 from 1 m viewer distance

The viewer position of one meter from the product is presented in the next image. As the image reveals, it is easier to see the Chart_1 than the Chart_2.

Figure 44. Image of acuity test at 1m viewer distance

The same procedure is used to analyse the two meters viewer distance. The percentages of acuity decrease scores two meters far from the product is shown in the next figures. It is hard to assume any difference between the scores on Chart_1 and Chart_2 since the statistics show very close results.

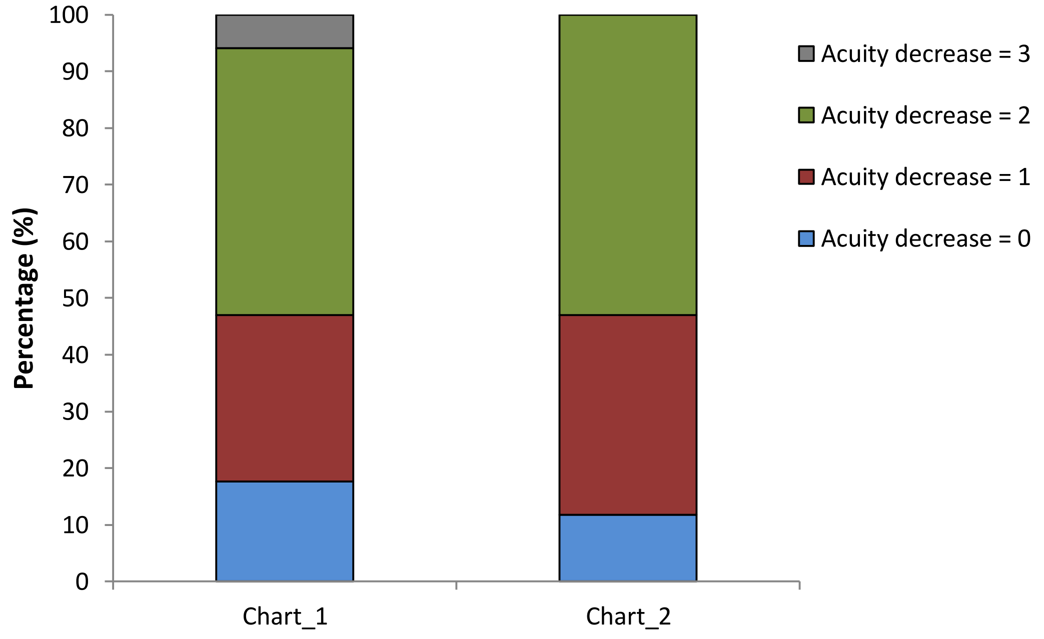


Figure 45. Percentages of acuity decrease scores on Chart_1 & Chart_2 from 2 m viewer distance

3.5.2 Interaction with visual surroundings

In order to compare the effect of lighting surroundings on the product capability to hide details, minimum lines that participant are capable to achieve are compared under all lighting scenes from the same position and looking to the same chart. Results are presented in the next graphs.

From all positions, and in more than 95% of the cases, the maximum difference between office vision, corridor vision and outdoor vision is only one acuity line. The night vision scene where luminaire on both rooms are turned Off and only the product is the source of light, shows a clear drop in the number of lines, however, participants are still capable to identify details on both charts with the help of the light emitted by the product.

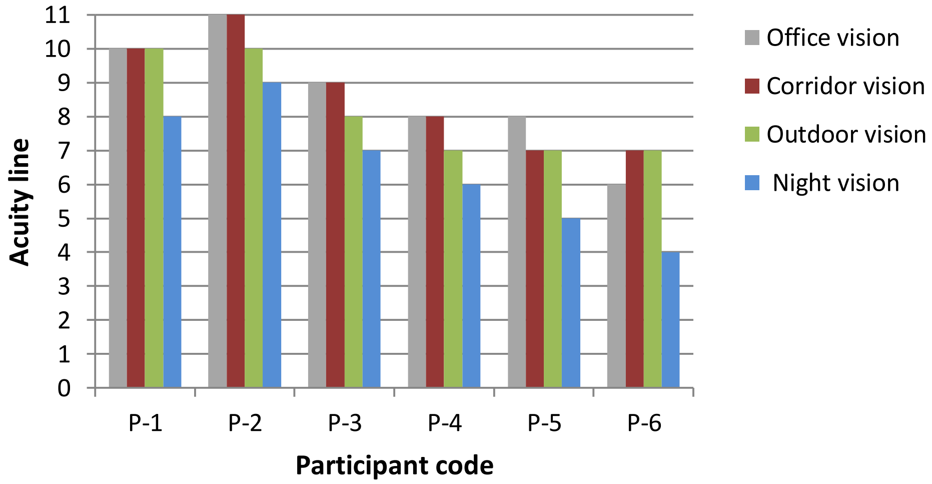


Figure 46. Viewer reading lines from 1m on Chart_1

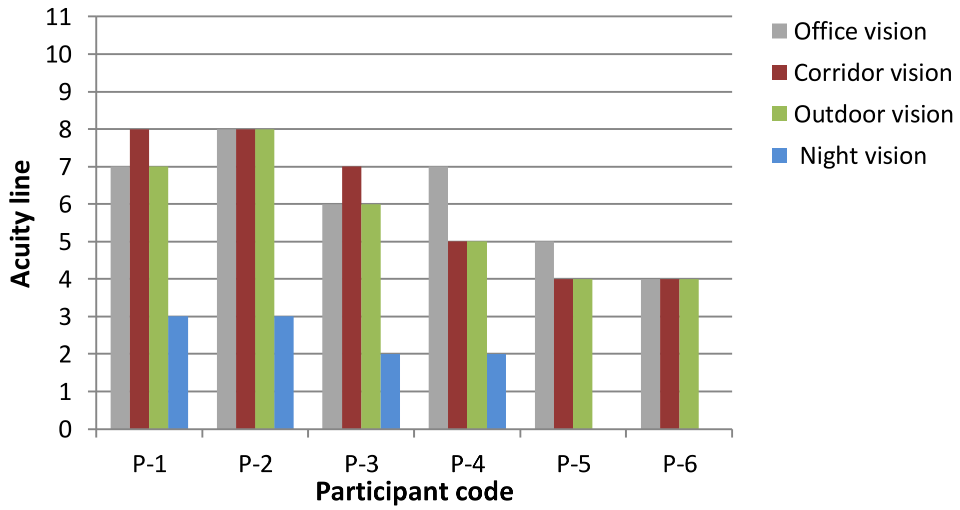


Figure 47. Participant reading lines from 1m on Chart_2

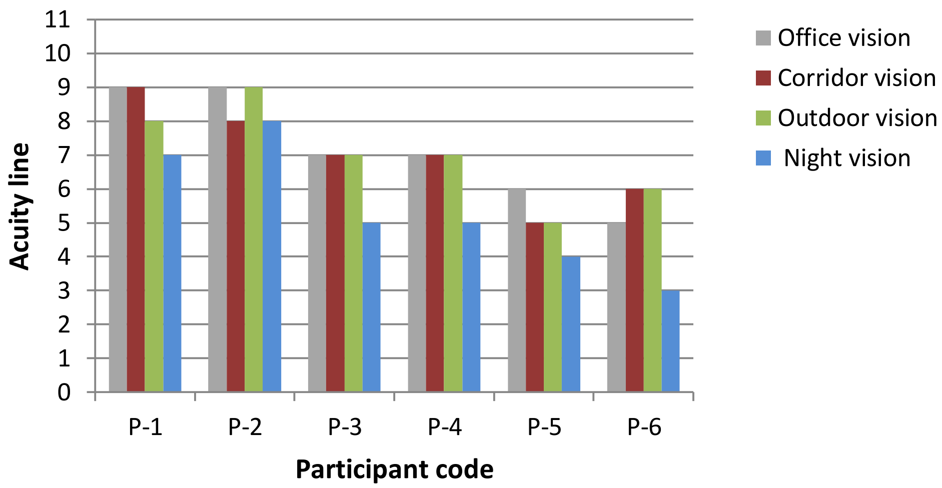


Figure 48. Participant reading lines from 2m on Chart_1

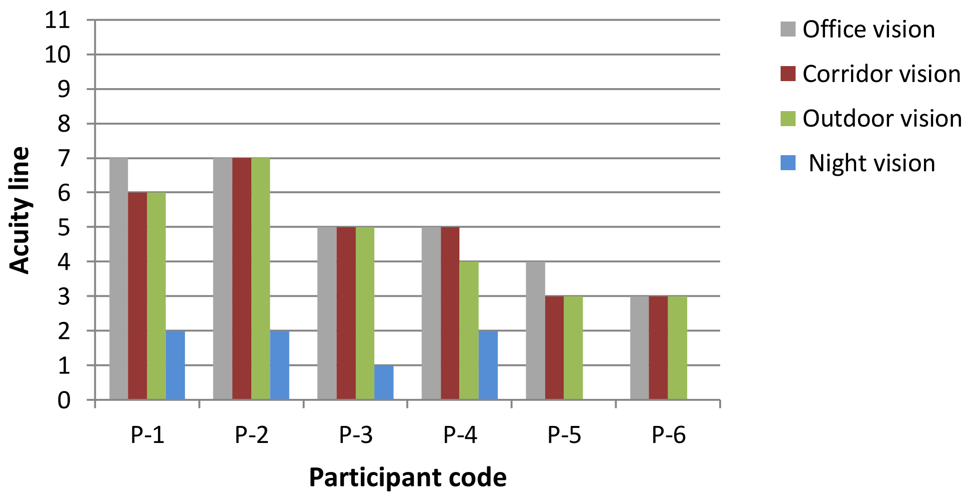


Figure 49. Participant reading lines from 2m on Chart_2

3.6 Summary of results

In this section, a summary of the results is presented and discussed based on possible intended usages of the product in office work places.

3.6.1 Office window

In order to use the product as an office window, the appropriate glazing surface should be determined. The aim is to maximize daylight penetration into indoors and reduce the usage of electric lighting and therefore contribute to energy saving. In the discussed case, a window-to-wall ratio of at least 50 % is found to be appropriate according to building standards. Using this ratio under overcast sky conditions showed daylight values reaching acceptable levels in perimeters close to the product mounting wall. However, light levels drop gradually and starting from 1.5 m distance from the glazing additional light is needed. Illuminating the product enlarges the perimeters but light uniformity on the work plane remains an issue. During evening hours, the light emitted from the product as the only source of light showed limitations in adequately and uniformly illuminating the work plane and task area. In general, the product cannot offer the ambient light condition required in offices, therefore a combination with other lighting sources which offer the ambient features on the work plane will assist in order to achieve the required visual comfort.

As measurements showed excessive illuminance levels entering the indoors through the product during times when direct sun light reached the surface, shading or solar protection measures are needed in order to avoid discomfort glare caused by daylight. Nonetheless, once illuminated, the examined product emits light in both directions, the light emitted to the outdoor is considered to be unnecessary when the product serves as office window glazing, and can collide with the shading system applied.

In the illuminated state, the view to the outdoors through the product is altered. In the main time, the privacy of indoors is not assured since the experiment showed that although the visual clarity decreases, the outdoor viewer can see better indoor elements the closer she/he is.

3.6.2 Interior partitioning

When used in office interior partitioning, the product can offer the option to switch between transparency and translucency when illuminated. Visual clarity through the illuminated part increases the closer the viewer and the visual target are. Light emitted from the product cannot offer ambient light for large areas. However, illuminating narrow area like office corridors can be achieved by a successive arrangement at the appropriate mounting height.

3.6.3 Task lighting

In the illuminated state, the emitted light can help to raise illuminance levels on the task area and on the immediate surroundings. The level of light increase depends on the product's distance from the task area. The issue in installing the product close to the task area is the occupant's visual comfort while having the emitted light in their field of view for a long time. The Unified Glare Rate (UGR) method used in this study showed limitation to assess the issue in an accurate and appropriate manner. The method assumes that light is emitted from a relatively narrow angle of emittance and the luminaire is ceiling mounted. This was not the case of the examined product. Because of these limitations it is not appropriate to construct an opinion about the occupant's comfort in the surroundings of the product emitted light.

4 CONCLUSION

In the course of this work, the performance of a light emitting glass product was assessed towards its usage in buildings. Daylight transmission through the glass is a main research inquiry. The empirical methods showed that daylight entering the test bed through the product is directly dependent on outdoor sky conditions and can reach very high levels where solar protection is needed. However, the product alone as a source of daylight can offer comfortable lighting condition during specific sky conditions. Once the product is illuminated, a small decrease in daylight transmission occurs within a scale of five minutes, after which the product permits full daylight transmission to indoors. Artificial light emitted can assist daylight in order to raise indoor brightness.

The assessment of the product in an office context when it is used as a daylight source under standard design parameters showed its capability to reach required values for office practices in perimeters close to the mounting wall. However, illuminating the product can extend the perimeter. Concerning evening time, the experiment with the product’s artificial light as the only source of lighting demonstrates incoherence with office lighting requirements. Light distribution pattern emitted by the wall-mounted product is perpendicular to the office task area, thus, issues of illuminance level and illuminance uniformity on the task area require an additional ambient lighting layer. Daylight transmitted and artificial light emitted together with an ambient lighting directed towards the task area can help to satisfy office lighting requirements.

As expected, discomfort glare assessment using the Unified Glare Rating (UGR) method shows values that exceeded the requirements at certain viewing angles. However, UGR threshold values might not be fully meaningful in assessing glare from light sources similar to the analysed product. The reason is that the calculation formula considers that lighting emittance is reaching the viewer’s eye from a relatively small solid angle of emittance and from conventional ceiling mounted luminaire. However; this is not the case of the product since it emits light through the entire surface and it is wall mounted. Despite of the discrepancies, glare values were not critical as they did not reach the imperceptible or significant discomfort condition. An adaptation of UGR formula or glare based subjective assessment would help to overcome the limitations.

Visual acuity tests reveal that the product has an adequate level of transparency when it is not illuminated. Participants in the experiment who reported not having a vision issue were capable to distinguish the designed targets. In the illuminated state, the product decreases the visual clarity. However, the level of details the product covers is dependent on the viewer and the visual target distances from the product and the lighting condition in the surroundings. The experiment results showed that a viewer close to the product can see better details on the product's approximate surroundings and that the visual acuity decreases the further the vision target moves. In the meantime, the further the viewer moves from the product, the fewer the visibility is dependent on the visual target position. Surrounding lighting conditions have a reduced impact on the visibility through the product; however, the experiment showed that under dark conditions on both sides, the light emitted by the product helps the viewer to distinguish details. The product interaction with the viewing distance has more impact on the visual acuity than the interaction with visual surroundings.

To summarize, the product has features that can benefit architectural lighting in buildings, however, as the empirical results showed limitations to fulfil the lighting requirements when it is used as the only source of light in office spaces, it is not advisable to rely on the product to offer office ambient light conditions. Nevertheless, an adaptation based on the intended usage would enhance the product performance.

The current study focused on a lighting related assessment of the product. Further assessment of other glass properties that have a direct impact on indoor conditions including solar and thermal performances will help to construct a wider view about the product performance.

The experiment showed that under direct sun light levels reach high values; this might lead to discomfort from glare and unwanted heat gains, thus, suitable shading or solar protection strategies are also to be investigated.

Since the product is intended to be vertically mounted emitted light will be in the occupant's field of view. Available assessment methods show limitations in accurately assessing the case, thus, further investigations into appropriate methods to address the question will help to better clarify the issue.

Finally, the inclusion of various lighting strategies like glass and LED's with transparent foils aiding light propagation in one product is a new industry practice. An assessment of the final products towards the potential use in buildings is not yet addressed or still very rare in scientific literature. This research addressed the topic empirically starting by traditional early assessment methods using a scale model, than using physically measured data to validate virtual building components towards the further use in simulation in order to closely predict the real word. This thesis provided also detailed insights about the performance of the examined product and can be used as a roadmap for further research on this type of light sources.

5 INDEX

5.1 5.1 List of abbreviation

CIE - International Commission on Illumination

IESNA - Illumination Engendering Society of North America

EN - European Standard

DIN - German Institute for Standardization

LBNL – Lawrence Berkeley National Laboratory

LED – Light Emitting Diodes

UGR- Unified Glare Rate

ISO -International Standards Organization

DF-Daylight Factor

VDF- Vertical Daylight Factor

5.2 List of Figures

5.3 List of Tables

5.4 List of Formulas

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7 APPENDIX

A. Lighting metrics table

Table 13. Summary of the features for every visual comfort index (Carlucci et al. (2015))

Source	Visual comfort metric	Scope of the index	Light source	Space discretization	Time discretization	Acceptability criterion	Presence of a comfort threshold
Not available	Illuminance (E_P)	Amount of light	Natural Artificial	Local	Short-term	One-tailed	Yes
Not available	Luminance (L)	Glare	Natural Artificial	Local	Short-term	One-tailed	Yes
Not availabe	Luminance ratio	Glare	Natural Artificial	Local	Short-term	One-tailed	Yes
Petherbridge and Hopkinson [53]	British Glare Index (*BGI*)	Glare	Artificial	Local	Short-term	One-tailed	Yes
Walsh [54]	Daylight Factor (*DF*)	Amount of light	Natural	LocalZonal	Short-term	One-tailed	Yes
Guth [55]	Visual Comfort Probability (*VCP*)	Glare	Artificial	Local	Short-term	One-tailed	Yes
Judd [56]	Flattery Index (R_f)	Light quality	Artificial	Not applicable	Short-term	Not applicable	Yes
Thornton [57]	Color Discrimination Index	Light quality	Artificial	Not applicable	Short-term	Not applicable	Yes
Thornton [58]	Color Preference Index	Light quality	Artificial	Not applicable	Short-term	Not applicable	Yes
DIN 5035 [59]	Illuminance Uniformity (U_0)	Light distribution	Natural Artificial	Zonal	Short-term	Not applicable	Yes
Einhorn [60]	CIE Glare Index (*CGI*)	Glare	Natural Artificial	Local	Short-term	One-tailed	Yes
Chauvel and Collins [61]	Discomfort Glare Index (*DGI*)	Glare	Artificial	Local	Short-term	One-tailed	Yes
Xu [62]	Color Rendering Capacity	Light quality	Artificial	Not applicable	Short-term	Not applicable	No
Pointer [63]	Pointer's color rendering index	Glare	Artificial	Local	Short-term	One-tailed	Yes
CIE 17.4 [64]	Color Rendering Index (*CRI* or R_a)	Light quality	Artificial	Not applicable	Short-term	Not applicable	Yes
Meyer and Francioli [65]	J-Index	Glare	Artificial	Local	Short-term	Not applicable	No
CIE 17 [66]	Unified Glare Rating (*UGR*)	Glare	Artificial	Local	Short-term	One-tailed	Yes
Tokura et al. [36]	Predicted Glare Sensation Vote (*PGSV*)	Glare	Artificial	Local	Short-term	One-tailed	No
Hashimoto and Yano [67]	Feeling of Contrast Index	Light quality	Artificial	Not applicable	Short-term	Not applicable	Yes
Reinhart and Walkenhorst [38]	Daylight Autonomy (*DA*)	Amount of light	Natural	Local	Long-term	One-tailed	No
CIE 146/147 [68	Unified Glare Rating for small light sources	Glare	Artificial	Local	Short-term	One-tailed	Yes
CIE 146/147 [68]	Great-room Glare Rating (GGR)	Glare	Artificial	Local	Short-term	One-tailed	Yes
Nazzal [21]	New Discomfort Glare Index (DGI_N)	Glare	Artificial	Local	Short-term	One-tailed	No
Wienold and Christoffersen [69]	Discomfort Glare Probability (*DGP*)	Glare	Natural Artificial	Local	Short-term	One-tailed	Yes
Nabil and Mardaljevic [32]	Useful Daylight Illuminance (*UDI*)	Amount of light	Natural	Local	Long-term	Two-tailed	No
Rogers and Goldman [70]	Continuous Daylight Autonomy (DA_{CON})	Amount of light	Natural	Local	Long-term	One-tailed	No
Wienold and Jiang [33]	Wienold's Simplified Discomfort Glare Probability (*DGPs*)	Glare	Natural Artificial	Local	Short-term	One-tailed	No
Hviid et al. [34]	Hviid's simplification of the Discomfort Glare Probability (*DGPs*)	Glare	Natural Artificial	Local	Short-term	One-tailed	No
Wienold [35]	Enhanced Simplified Discomfort Glare Probability (*eDGPs*)	Glare	Natural Artificial	Local	Short-term	One-tailed	No
Davis and Ohno [71]	Color Quality Scale	Light quality	Artificial	Not applicable	Short-term	Not applicable	Yes
Sicurella and Evola [72]	Frequency of Visual Comfort (*FVC*)	Amount of light	Natural	Zonal	Long-term	Two-tailed	Yes
Sicurella and Evola [72]	Intensity of Visual Discomfort (*IVD*)	Amount of light	Natural	Zonal	Long-term	Two-tailed	Yes
IES [73]	Spatial Daylight Autonomy (*sDA*)	Amount of light	Natural	Zonal	Long-term	One-tailed	No

B. Images of the acuity test

Figure 50. Vision acuity experiment .lab_1(0 lux). Lab_2(500 lux). Product OFF

Figure 51.Vision acuity experiment .lab_1(0 lux). Lab_2(500 lux). Product ON

Figure 52. Vision acuity experiment .lab_1(100 lux). Lab_2(500 lux). Product ON

Figure 53. Vision acuity experiment .lab_1(500 lux). Lab_2(500 lux). Product OFF

C. Acuity experiment results

Table 14. Visual acuity test results for participant 1. P-1

	Viewer distance	Chart	Line (Off)	Line (On)
Office vision 500 lux_500 lux	1m	Chart_1	10	10
	1m	Chart_2	9	7
	2m	Chart_1	9	9
	2m	Chart_2	7	7
Corridor vision 100 lux_500 lux	1m	Chart_1	11	10
	1m	Chart_2	9	8
	2m	Chart_1	9	9
	2m	Chart_2	8	6
Street vision 20 lux_500 lux	1m	Chart_1	11	10
	1m	Chart_2	9	7
	2m	Chart_1	10	8
	2m	Chart_2	7	6
Night vision 0 lux_0 lux	1m	Chart_1	N/A	8
	1m	Chart_2	N/A	3
	2m	Chart_1	N/A	7
	2m	Chart_2	N/A	2

Table 15. Visual acuity test results for participant 2. P-2

	Viewer distance	Chart	Line (Off)	Line (On)
Office vision 500 lux_500 lux	1m	Chart_1	11	11
	1m	Chart_2	9	8
	2m	Chart_1	10	9
	2m	Chart_2	8	7
Corridor vision 100 lux_500 lux	1m	Chart_1	11	11
	1m	Chart_2	9	8
	2m	Chart_1	10	8
	2m	Chart_2	9	7
Street vision 20 lux_500 lux	1m	Chart_1	11	10
	1m	Chart_2	8	8
	2m	Chart_1	9	9
	2m	Chart_2	8	8
Night vision 0 lux_0 lux	1m	Chart_1	N/A	9
	1m	Chart_2	N/A	3
	2m	Chart_1	N/A	8
	2m	Chart_2	N/A	2

Table 16. Visual acuity test results for participant 3. P-3

	Viewer distance	Chart	Line (Off)	Line (On)
Office vision 500 lux_500 lux	1m	Chart_1	10	9
	1m	Chart_2	7	6
	2m	Chart_1	9	7
	2m	Chart_2	7	5
Corridor vision 100 lux_500 lux	1m	Chart_1	11	9
	1m	Chart_2	9	7
	2m	Chart_1	9	7
	2m	Chart_2	6	5
Street vision 20 lux_500 lux	1m	Chart_1	9	8
	1m	Chart_2	8	6
	2m	Chart_1	9	7
	2m	Chart_2	7	5
Night vision 0 lux_0 lux	1m	Chart_1	N/A	7
	1m	Chart_2	N/A	2
	2m	Chart_1	N/A	5
	2m	Chart_2	N/A	1

Table 17. Visual acuity test results for participant 4. P-4

	Viewer distance	Chart	Line (Off)	Line (On)
Office vision 500 lux_500 lux	1m	Chart_1	9	8
	1m	Chart_2	7	7
	2m	Chart_1	8	7
	2m	Chart_2	7	5
Corridor vision 100 lux_500 lux	1m	Chart_1	8	8
	1m	Chart_2	7	5
	2m	Chart_1	8	7
	2m	Chart_2	5	4
Street vision 20 lux_500 lux	1m	Chart_1	9	7
	1m	Chart_2	7	5
	2m	Chart_1	8	5
	2m	Chart_2	6	4
Night vision 0 lux_0 lux	1m	Chart_1	N/A	6
	1m	Chart_2	N/A	2
	2m	Chart_1	N/A	5
	2m	Chart_2	N/A	2

Table 18. Visual acuity test results for participant 5. P-5

	Viewer distance	Chart	Line (Off)	Line (On)
Office vision 500 lux_500 lux	1m	Chart_1	8	8
	1m	Chart_2	6	5
	2m	Chart_1	7	6
	2m	Chart_2	6	4
Corridor vision 100 lux_500 lux	1m	Chart_1	9	7
	1m	Chart_2	7	4
	2m	Chart_1	7	5
	2m	Chart_2	5	3
Street vision 20 lux_500 lux	1m	Chart_1	8	7
	1m	Chart_2	7	4
	2m	Chart_1	7	5
	2m	Chart_2	5	3
Night vision 0 lux_0 lux	1m	Chart_1	N/A	5
	1m	Chart_2	N/A	No line
	2m	Chart_1	N/A	4
	2m	Chart_2	N/A	No line

Table 19. Visual acuity test results for participant 6. P-6

	Viewer distance	Chart	Line (Off)	Line (On)
Office vision 500 lux_500 lux	1m	Chart_1	7	6
	1m	Chart_2	4	4
	2m	Chart_1	6	5
	2m	Chart_2	4	3
Corridor vision 100 lux_500 lux	1m	Chart_1	8	7
	1m	Chart_2	5	4
	2m	Chart_1	7	6
	2m	Chart_2	4	3
Street vision 20 lux_500 lux	1m	Chart_1	8	7
	1m	Chart_2	5	4
	2m	Chart_1	7	6
	2m	Chart_2	4	3
Night vision 0 lux_0 lux	1m	Chart_1	N/A	4
	1m	Chart_2	N/A	No line
	2m	Chart_1	N/A	3
	2m	Chart_2	N/A	No line