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RESEARCH ARTICLE

Comparison between lighting performance of a virtual natural lighting solutions prototype and a real window based on computer simulation

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Virtual Natural Lighting Solutions; Light; View; Simulation; Virtual window; Prototype

Abstract
This article discusses the measurement and simulation of a first generation prototype of Virtual Natural Lighting Solutions (VNLS), which are systems that can artificially provide natural lighting as well as a realistic outside view, with properties comparable to those of real windows and skylights. Examples of employing Radiance as a simulation tool to predict the lighting performance of such solutions are shown, for a particular case study of a VNLS prototype displaying variations of a simplified view of overcast, clear, and partly cloudy skies. Measurement and simulation were conducted to evaluate the illuminance distribution on workplane level. The key point of this study is to show that simulations can be used to compare an actual VNLS prototype with a hypothetical real window under the same sky scenes, which was physically not possible, since the test room was not located at the building’s façade. It is found that the investigated prototype yields a less rapidly drop illuminance distribution and a larger average illuminance than the corresponding real window, under the overcast sky conditions.
1. Introduction

Many researchers have shown the significant role of windows in buildings. Windows are important in controlling the amount of natural light admitted from the exterior environment into the buildings. It has been shown that building occupants feel windows are important due to their preference for having natural light over electric light (e.g., Hartig et al., 2003; Chang and Chen, 2005; Aries et al., 2010). Several studies have reported beneficial and restorative effects of views on a natural scene (e.g., Tennessen and Cimprich, 1995; Berman et al., 2008), whereas views on human-built environments yield effects, which are similar to having no window at all (Kaplan, 1993). Kim and Wineman (2005) showed empirically that views and windows have psychological and economic values. Moreover, a proper use of natural light would potentially save considerable amount of energy from artificial lighting use (e.g., Hammad and Abu-Hijleh, 2010; Yun et al., 2010). In a general term, the correct application of a daylighting strategy in buildings increases visual comfort and energy efficiency (Galasiu and Veitch, 2006).

Despite all of its advantages, the quality and quantity of natural light is highly variable, and its availability is limited in time and space. For instance, there is not enough or no daylight at all during nighttime; buildings can be too deep to supply sufficient daylight throughout the space (Reinhart, 2005; Reinhart and Weismann, 2012) and some rooms are simply not provided with windows, skylights, or any form of daylight transporting systems, and therefore are not suitable for long-term working activities.

In the cases where a real natural lighting solution is absent or ineffective, for instance due to space and time limitation, the concept of Virtual Natural Lighting Solutions (VNLS) can be promising to overcome the problem of lack of daylight. VNLS are defined here as “systems that can artificially provide natural lighting as well as a realistic outside view, with properties comparable to those of real daylight openings”.

A number of efforts have been made to imitate one or more elements of natural light inside buildings, in the form of artificial solutions. Originally, the efforts were more focused on bringing ‘view’ of an outside condition into the room. Attempts to create a realistic artificial view have been under development for centuries. For example, in art history, trompe l’oeil is known as an art technique involving realistic imagery to create the optical illusion that the depicted objects appear in three dimensions, while actually being a two-dimensional painting. This technique can be traced back to the ancient Greek era around the year 400 BC, and was well-developed mostly by Italian artists between the 15th and 17th century. Despite very inspiring, this example is not discussed further in detail, since it is not an actual light source, nor a device that can transmit light from outside environment. Nevertheless, the concept of displaying artificial sceneries of nature is still used in the later form of VNLS prototypes. Some researchers have shown that artificial views, which do not emit light themselves, can actually give positive effect on human health (e.g., Heerwagen, 1990; Ulrich et al., 1993).

Interestingly, the inverse is also true. In its intense appearance without a sufficient view, artificial bright light can give a positive effect on human well-being, particularly for healing purpose (e.g., Eastman et al., 1998; Løgåarde et al., 1998; Avery et al., 2001). Many specific lighting products had been manufactured to generate a large amount of light with a particular spectral power distribution for this application. In general, the idea behind this type of VNLS prototypes is to recreate the situation with natural light and its qualities inside a space, and to harvest the benefit it may offer.

In addition, directionality of the light is another important property that distinguishes a real window or skylight from an artificial light source. In fact, directional light is something rarely appears on the existing VNLS prototypes, since most of them only generate light in a nearly diffuse direction. Therefore, a non-diffuse, or directional, light is considered a key feature that should appear in an ideal VNLS prototype. Based on these considerations, any VNLS prototypes (that exist) and models (that do not yet exist) can be classified based on their light and view qualities, as illustrated in Figure 1, into four categories: (1) those providing relatively simplified view and mainly diffuse light, (2) complex view and mainly diffuse light, (3) simplified view and mainly directional light, and (4) complex view and mainly directional light. Examples of the first two types already exist as prototypes or real products in reality, while the last two do not yet exist at the moment and are still under development, of which building performance simulation tools have the role to predict the performance.

1.1. Prototypes with a simplified view

One of the simplest versions of a VNLS prototype is the ‘light box’, which is generally constructed of a series of artificial light sources behind a diffuse surface. This prototype in general displays a low resolution and largely simplified view. With regards to health application, research has shown that light boxes can be installed for healing purpose. It is known that human bodies use natural (sun-) light to regulate a variety of functions that affect mood and energy level, cure skin disorders, and make vitamin D (Begemann et al., 1997). Without enough (sun-) light, humans often feel down, lack

energy, and sometimes even suffer physical disorders. To help reduce these symptoms, specific light boxes have been designed to provide illuminances up to 10,000 lx at a distance of approximately 50 cm, even though the spectral power distribution of the sources may be different from the natural light. The individual is required to sit in front of the light box for a specified duration. It has been shown that the so-called bright light therapy can have a positive effect on human well-being (e.g., Eastman et al., 1998; Lingjærde et al., 1998; Avery et al., 2001). A similar way for this purpose is using a set of blue light emitting diodes (LEDs) in a light box, designed with an enhanced blue spectrum component, based on independent clinical research showing that blue light from the summer sky can regulate mood and can trigger human bodies to become active and energetic (e.g., Webb, 2006; Glickman et al., 2006; Viola et al., 2008; Iskra-Golec et al., 2012). Another new application to create the effect of natural light uses gradually increasing levels of brightness, to wake up people in the morning in a natural way.

A number of studies have been performed using prototypes with a simplified view as an object in an office setting. For instance, in their experiments, de Vries et al. (2009) installed two units of ‘emulated windows’, each measuring 1.20 m x 1.20 m with 12 rows of tubular fluorescent lamps. The experiments were conducted in a standard office room (5.40 m x 3.60 m x 2.70 m), focusing on the performance of the test subjects when looking at daylight openings covered with a diffuse screen. Prototypes of the same type were used in the experiments of Smolders et al. (2012), focusing on the effect of eye illuminance on subjective measures, task performance, and heart rate variability. Experiments on glare sensation from another prototype with a simplified view were conducted by Rodriguez and Pattini (2014), observing its effects on glare-sensitive and glare-insensitive subjects when performing a computer task. In all of those studies, the prototype was installed to provide the intended light qualities such as vertical illuminance and view luminance.

Another VNLS prototype providing light with a simplified sky scene with sunlight has been developed by Philips (van Loenen et al., 2007). The prototype was a 1.20 m x 1.20 m luminaire with 12 rows of red, green, and blue tubular fluorescent lamps. Each lamp could be tuned to mimic the colour gradients of, for example, the sunrise, noon, or sunset. A halogen, parabolic aluminium reflector (PAR) spot light was added and could be controlled to mimic direct sunlight. The view variation of this prototype was slightly higher compared to those mentioned in the previous paragraph, since there was a possibility to control the colour gradient and to create the impression of having a patch of sunlight inside the space.

### 1.2. Prototypes with a complex view

While light from a window is beneficial for the building occupants, view is another important feature of a window. A number of commercial efforts have been developed to provide a detailed view from a VNLS prototype, using static, semi-transparent photographs in front of a light box. Application of these prototypes can be found for example in windowless healthcare environments such as critical care units and magnetic resonance imaging (MRI) environments to reduce the anxiety of the patient.

Next to the backlit and projection image technique, other researchers and manufacturers have utilised electronic large, high-definition (HD) monitor displays for the purpose of simulating window-views in a more flexible manner. For instance, a commercial virtual window has been developed, which consists of LCD screens displaying a recorded, realistic moving images that could be chosen by the users. However, the number of people who can simultaneously experience that effect is limited to one.

Another research on a VNLS prototype with a complex view was performed by Radikovic et al. (2005). They presented a system using a head-coupled display and image-based rendering to simulate a photorealistic view of nature with motion parallax. A pan-tilt-zoom camera tracked the observer as long as the face was visible to the camera. Below the camera was a large display showing the window view that should be seen.
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from the observer’s position. Evaluation data obtained from test subjects suggested the prototype was a better window substitute than a static image, and had significantly more positive effects on the observers’ arousal ($p=0.009$); positive affects ($p=0.007$); and interest ($p=0.032$). The test subjects judged the system prototype as an acceptable replacement for a real window, and gave it higher ratings for realism and preference than a static image ($p=0.000$).

Research on HD monitor displays was conducted, for example by Friedman et al. (2008) and Kahn et al. (2008). The monitors were installed on the walls of seven inside offices of faculty and staff at a university, and displayed, as the default image, real-time views of the immediate outside scene. Data were collected over a 16-week period to explore the user experience with these large display windows. The results showed that users deeply appreciated many aspects of the experience. One of the benefits was the reported increase in users’ connection to the wider social community, connection to the natural world, psychological wellbeing, and cognitive functioning.

Regarding subjective discomfort glare from such prototypes, investigations have been performed, for example by Shin et al. (2012) and Kim et al. (2012), using backlit, transparent printed photographs on top of a light box constructed of incandescent lamps arrays. Experiments on subjective discomfort glare were also performed by Tuaycharoen and Tregenza (2007), using a number of screen projected images displaying natural and man-made scenarios. A similar technique of using projected images on a screen was applied by IJsselsteijn et al. (2008), in their investigation on subjective depth perception cues. In all of those studies, the prototypes/displays were assumed to be the representation of what the subjects normally see through a real window.

1.3. Research gap and problems

The aforementioned state of the art shows that an ideal VNLS does not yet exist at the moment. The currently existing VNLS prototypes are not able to completely provide the full spectrum of daylight with varying intensity and colour temperature over time, and they are not able to provide time and environmental information associated with the view outside of the real window. In order to approach the ideal condition, a number of evaluation stages must be performed, such as theoretical analysis, initial design, numerical testing of the design, prototype construction, physical testing, subjective laboratory testing, field trials, and so on. In the early design stage, computational modelling and simulation is a powerful tool to predict the system performance in an efficient way, in terms of time and cost, and with regards to the relevant physical phenomena.

Another important conclusion from the literature review is, while there are reported findings from various researchers on some aspects of VNLS prototype and its impact on (multiple) users, objective studies addressing the indoor lighting and visual comfort aspect of the prototypes are rare. It is the aim of the current research to find how a certain VNLS prototype, with a certain display variation, will influence the indoor lighting condition and visual comfort. Another important question is how a VNLS prototype actually compares to the real daylight opening; can it perform as good as, or even better than the real one? A comparison to the real window is then required on that aspect; since such a comparison will be useful for designing a better solution in the future. Therefore, there is a need to create a representative model of the prototypes, and to predict their performance by mean of simulations.

To answer the questions, this study aims to address the issues on lighting measurement and simulation of a ‘first generation’ VNLS prototype, which is described in Section 2. It should be noted that this study does not aim to create an ideal VNLS prototype that performs entirely similar to real windows. The objectives are to evaluate the lighting performance of the prototype under existing display settings to confirm whether the results can be accurately replicated by performing computational modelling and simulation in Radiance (Ward and Shakespeare, 1998), and to compare the performance with corresponding real windows in simulation. The measurement and simulation protocols are described respectively in Sections 3 and 4. The measurement results are discussed in Section 5.1, whereas the simulation results of the prototype and real windows are respectively discussed in Sections 5.2 and 5.3. The article is concluded in Section 6.

2. Case description

An example of the so-called ‘first generation’ prototype is the one developed by Philips (van Loenen et al., 2007), which is briefly discussed in Section 1.1. Due to the possibility to vary the view display, though very limited, and to add a directional spot lamp for simulating the sun, this prototype was selected as the case study in this article to demonstrate how Radiance can be employed to recreate the scenes and obtain the lighting performance of the space, validated by an actual measurement.

The prototype (Figure 2) was installed in a kitchen laboratory setting, located in the ExperienceLab of Philips Research in Eindhoven, the Netherlands. The prototype was constructed of 12 colour tubular fluorescent (TL5) lamps of 54 W each, put in an array of 12 rows, and covered with a diffuse panel of 1.20 m $\times$ 1.20 m. A halogen, parabolic aluminium reflector (PAR) spot lamp of 70 W was installed in the upper right corner to simulate the sunlight.

The construction was put vertically in an adjacent control room behind a transparent, clear glass window which was a part of the kitchen room interior. During the experiment, the general lighting in the kitchen was switched off all the time. The room had no façades and real windows, ensuring no daylight admission. No motion parallax was associated with this prototype.

The TL5 lamp array was covered by a white, diffuse panel, installed 0.35 m behind the window glass plane. The dimension of the diffuse panel was 1.20 m $\times$ 1.20 m, while the window opening was 0.65 m $\times$ 0.65 m. The 12 TL5 lamps were divided into four groups; each group consisted of three lamps emitting red, green, and blue light, respectively. Every lamp had its own ballast so that it could be dimmed independently, using the Digital Addressable Lighting...
Interface (DALI) system. The overcast, clear, and partly cloudy sky scenes were realised by adjusting the intensity of each lamp and were subjectively evaluated to imitate the real sky scenes. Table 1 shows the type of colour emitted by each lamp, the electrical power rating, and the intensity level settings for the three scenes.

### Table 1: Intensity level settings for the three sky scenes of the prototype.

<table>
<thead>
<tr>
<th>Lamp’s row (from top)</th>
<th>Type</th>
<th>Power rating [W]</th>
<th>Overcast Intensity level [%]</th>
<th>Clear Intensity level [%]</th>
<th>Partly cloudy Intensity level [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Red</td>
<td>54</td>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Green</td>
<td>54</td>
<td>30</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Blue</td>
<td>54</td>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>Red</td>
<td>54</td>
<td>30</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>Green</td>
<td>54</td>
<td>30</td>
<td>15</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>Blue</td>
<td>54</td>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Red</td>
<td>54</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Green</td>
<td>54</td>
<td>45</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>Blue</td>
<td>54</td>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>Red</td>
<td>54</td>
<td>20</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>11</td>
<td>Green</td>
<td>54</td>
<td>20</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>12</td>
<td>Blue</td>
<td>54</td>
<td>20</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>n/a</td>
<td>PAR</td>
<td>70</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Colour temperature [K]</td>
<td></td>
<td>6500</td>
<td>17,000</td>
<td>15,000</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2](image_url) Interior view of the kitchen room with the prototype under the (a) overcast, (b) clear, and (c) partly cloudy sky scenes.
The actual lighting performance was measured and obtained by collecting the following data at certain lighting conditions:

- Horizontal illuminance on the workplane; data were collected for 55 horizontal points on the workplane height, i.e., the countertop (0.95 m from the floor).
- Vertical illuminance on the observer’s eye plane; data were collected for two vertical points on the typical observer height (1.20 m from the floor).
- Minimum, maximum, and average luminance perceived by the observer; data were collected for two points on the typical observer’s eye height (1.20 m from the floor).
- Reflectance of interior surface materials; data were collected for the relevant interior surface, such as floor, walls, ceiling, and furniture.

Furthermore, to evaluate the lighting performance, the horizontal illuminance data were post-processed to obtain the average illuminance values (\(E_{av}\) [lx]), the uniformity (\(U_0\)), and the space availability (\(\%A\))%. The latter is defined as the percentage of the measuring points satisfying minimum illuminance value of 500 lx, which is the typical illuminance criterion for interior areas, including kitchen (CEN, 2002). These three indicators can be expressed as follows:

\[
E_{av} = \frac{\sum_{i=1}^{N} E_i}{N} \quad (1)
\]

\[
U_0 = \frac{E_{min}}{E_{av}} \quad (2)
\]

\[
\%A = \frac{N_{E \geq 500 \text{lx}}}{N} \times 100\% \quad (3)
\]

where \(E_i\) [lx] is the horizontal illuminance on each measuring point, \(E_{min}\) [lx] is the minimum horizontal illuminance, \(N_{E \geq 500 \text{lx}}\) is the number of measuring points satisfying the criterion of minimum illuminance value of 500 lx, and \(N\) is the total number of measuring points.

To evaluate the visual comfort in this case, the Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006) was used as an indicator, which can be expressed as follows:

\[
DGP = 5.87 \times 10^3 E_v + 9.18 \\
\times 10^{-3} \log 2 \left( 1 + \frac{\sum_{i=1}^{n} L_s^2 \omega_s}{E_v^{1.87} P_i} \right) \quad (4)
\]

where \(E_v\) is the total vertical eye illuminance [lx], \(\omega_s\) is the solid angle of the glare source [sr], \(L_s\) is the glare source luminance [cd/m²], and \(P\) is the position index, i.e., a weighting factor based on position in the viewing hemisphere.

During the measurement, the following instruments were used:

- **SpectraDuo PR-680 photometer**; for measuring luminance and illuminance values, as well as spectral power distribution.
- **Canon EOS50D digital single-lens reflex camera + Sigma 4.5 mm fisheye lens + Photolux 3.1 software**; for taking multiple (20 in this case) photographs in equiangular 180° view with various exposure values, which in turn were post-processed to obtain the luminance pictures. The luminance values were calibrated with the SpectraDuo photometer.
- **Konica Minolta CM-2600D spectrophotometer**; for measuring the reflectance values of interior surface materials.

### 3. Measurement protocol

Horizontal illuminance data were collected on 55 points at a height of 0.95 m (countertop level), as displayed in Figure 3. Vertical illuminance and luminance perceived by the observer were measured by taking 20 photographs (ISO 400, f/5.6, shutter time varied from 4 s to 1/8000 s) each at positions 1 and 2, at a height of 1.20 m, with the view direction specified by the arrows in Figure 3.

To determine the glare index value at both observer’s positions, the obtained photographs were exported to

![Figure 3](image-url) Floor plan of the kitchen with the measuring points for horizontal illuminance.
Radiance, combined into High Dynamic Range (HDR) images using the HDRgen programme, and then were analysed using Evalglare (Wienold and Christoffersen, 2006).

4. Simulation protocol

Since the test room was not connected to the building’s façade, the condition under a real window could not be observed. Therefore, the real window scene was modelled and simulated in Radiance. In addition, the actual conditions under all scenes of the prototype were also modelled and simulated, to give an insight in the difference between simulation and actual measurement. Comparisons were made between the values of horizontal illuminance at the central line, where points P1 and 1 were located (i.e., the blue-coloured points on Figure 3). The difference between the average illuminance, uniformity, and space availability was also evaluated.

The front, top, and perspective views of the modelled prototype are displayed in Figure 4. The 12 TL5 lamps were modelled as 12 rows of cylinders, with a length of 1.20 m and a diameter of 0.016 m, constructed with a ‘light’ material.

Assuming a total luminous flux of 4250 lm for each lamp (Philips, 2013a), a conversion factor of 179 lm/W between photometric and radiometric units (Ward and Shakespeare, 1998), and a solid angle of the incoming radiation of \( \pi \) sr (Ward and Shakespeare, 1998), the following equation was applied to obtain the total radiance value of each lamp, i.e., 394 W/(sr m\(^2\)) at the maximum setting.

\[
L_i = \frac{\phi_i}{\Omega_i A_i}
\]

where \( L_i \) [W/(sr m\(^2\))] is the radiance from the surface on which the material type is applied, \( \phi_i \) [W] is the total radiative flux of the light source and \( A_i \) [m\(^2\)] is the projected light source surface over a solid angle \( \Omega_i \) [sr] of the incoming radiance.

In principle, Radiance solves the radiance equation for the red, green, and blue (RGB) values separately to obtain the radiance or the irradiance \( L_{R,G,B} \) [W/m\(^2\)], if integrated over the solid angle. When a picture is rendered, the spectral irradiance values in red, green, and blue \( (I_R, I_G, I_B) \), respectively) are summed and weighted to obtain the single value of \( L_{R,G,B} \), according to Ward and Shakespeare (1998):

\[
L_{R,G,B} = 0.265I_R + 0.670I_G + 0.0648I_B
\]

Eq. (6) was applied to obtain the red, green, and blue radiance components for the ‘light’ material. For the red-coloured lamps, the green and blue radiance components were assumed to be zero; for the green-coloured lamps, the red and blue were assumed to be zero; and for the blue-coloured lamps, the red and green were assumed to be zero. Hence, at the maximum setting, the red-coloured lamps were set to have a red component of 1487 W/(sr m\(^2\)), the green-coloured lamps have a green component of 588 W/(sr m\(^2\)), and the blue-coloured lamps have a blue component of 6059 W/(sr m\(^2\)). For other settings, the values were adjusted proportionally.

The PAR lamp was modelled as a thin cylinder with a diameter of 0.12 m, aimed at an angle of 45°, and constructed with a ‘light’ material. Assuming a total luminous flux of 1415 lm (Philips, 2013b), and by applying Eq. 3.5, a total radiance value of 223 W/(sr m\(^2\)) is obtained. The red, green, and blue components were assumed to be equal.

Table 2 displays the assigned values for the light sources in the prototype.

The detailed values assigned for the window construction properties are specified in Table 3, together with the room’s interior surfaces reflectance as obtained from the measurement. The properties of the diffuse panel were estimated based on the ‘trans’ model of the translucent panel in Reinhart and Andersen (2006), by fine-tuning the diffuse transmissivity to 0.35.

Simulations were run for the three sky scenes, i.e., overcast, clear, and partly cloudy; by addressing the input defined in Table 2. Calculation was performed for the 55 measuring points on the workplane. One-to-one comparison between measurement and simulation was done for all values of horizontal illuminance at the ‘column’ where the points P1 and 1 were located. This column, at which there were seven measuring points, was located directly in the central projection of the window.

In addition, the prototype scenes were compared to real window scenes. The latter were modelled in Radiance by

\[\text{Figure 4} \quad (a) \text{Front, (b) top, and (c) perspective views of the modelled prototype.}\]
replacing the entire construction of artificial light sources with the corresponding sky models, i.e., overcast, clear, and partly cloudy. In general, for the purpose of daylighting modelling and simulation in particular, *Radiance* has been validated many times elsewhere (e.g., Mardaljevic, 1995, 1997; Reinhart and Herkel, 2000; Reinhart and Walkenhorst, 2001; Reinhart and Andersen, 2006). The three sky models were generated in *Radiance* using the Gensky programme by addressing the option \(-c\), \(-s\), and \(+i\), respectively.

Site location was set for Eindhoven, the Netherlands (51.45°N, 5.47°E), with south-facing window orientation, on 21 June at 12.20 h local time, to match the aiming angle of the PAR spot lamp.

The zenith radiance \([W/(sr \ m^2)]\) of each sky model was defined so that the illuminance values at the nearest point to the window (P1) were the same under the corresponding real and virtual window scenes. The relevant zenith radiance on the rest of the points at the central column were determined for the comparison. DGP values at position 1 and 2 (see Figure 3) were also analysed using *Evalglare*.

Furthermore, simulation parameters in *Radiance* were set as shown in Table 4.

In order to assess whether the simulation results are fit for the purpose of recreating the measured scene, several criteria can be applied. There is no definitive agreement on an acceptable degree of accuracy (Ochoa et al., 2012). For example, in their report on testing accuracy of various lighting simulation programmes (Maamari et al., 2006), suggested a criterion of two times the global error source, based on the estimated error sources in the measurements and in the scenario description, e.g., sensor cosine and colour corrections, sensor calibration, lumen output fluctuation, luminaire position and flux output distribution, room dimensions, and surface reflectance. These were approximately \(\pm 21\%\) from the true value, see also Slater and Graves (2002) and CIE-TC-3-33 (2005).

According to Fisher (1992), an acceptable criteria range would be 10\% for average illuminance calculations and 20\% for measured point values. The criterion of 20\% for use in real cases has been validated by Reinhart and Andersen (2006), as appeared in studies replicating built realities.

In view of subjective lighting perception, the European Standard EN 12464-1 (CEN, 2002) mentions that “a factor of approximately 1.5 represents the smallest significant difference in subjective effect of illuminance”, as given in the recommended scale of illuminance \([lx]\) for various

<table>
<thead>
<tr>
<th>Lamp’s row (from top)</th>
<th>Overcast</th>
<th>Clear</th>
<th>Partly cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Red</td>
<td>Green</td>
<td>Blue</td>
</tr>
<tr>
<td>1</td>
<td>446</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>176</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1818</td>
</tr>
<tr>
<td>4</td>
<td>446</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>176</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>1818</td>
</tr>
<tr>
<td>7</td>
<td>297</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>265</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>1818</td>
</tr>
<tr>
<td>10</td>
<td>297</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>118</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>1212</td>
</tr>
<tr>
<td>PAR</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 3  Material definitions in *Radiance* for the window construction and room's interior.

<table>
<thead>
<tr>
<th>Material</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>Specularity</th>
<th>Roughness</th>
<th>Diffuse transmiss.</th>
<th>Transmit. specularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse panel</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.08</td>
<td>0</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>Window glass</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Window frame</td>
<td>1.00</td>
<td>0.78</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ceiling</td>
<td>1.00</td>
<td>1.00</td>
<td>0.95</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Walls</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Floor</td>
<td>0.56</td>
<td>0.55</td>
<td>0.48</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Door</td>
<td>0.56</td>
<td>0.48</td>
<td>0.56</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Countertop</td>
<td>1.00</td>
<td>1.00</td>
<td>0.97</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
conditions in work places. This is approximately in line with the findings of Slater et al. (1993) in their subjective study, where illuminance ratios between two work stations of at least 0.7 (or 1.4 if the ratio is inversed) were ‘generally acceptable’. They mentioned that even though there was a trend of decreasing acceptability at lower illuminance ratios, there were indications that lower illuminance ratios may also be acceptable under some conditions.

Taken this recommendation into account, the criterion of which the difference between simulation \( E_{\text{sim}} \) (lx) and measurement \( E_{\text{mea}} \) (lx) values do not lead to a significant difference in their subjective effect is

\[
0.67 < \frac{E_{\text{sim}}}{E_{\text{mea}}} < 1.50
\]

(7)

In other words, the ratio of simulation and measurement values at any measuring point should not be less than 2:3 (or approximately 0.67) and not more than 3:2 (or 1.50), so that the values do not lead to a significant difference in their subjective effect. This criterion is applied in the following sections to evaluate the simulation results.

5. Results and discussion

Section 5.1 presents the measurement results of the prototype. Section 5.2 presents simulation results of the prototype, as well as the simulation results of the corresponding, hypothetical real windows under the same sky scenes.

5.1. Measurement

Measurement results of the average illuminance values \( E_{\text{av}} \) (lx), the uniformity \( U_{0} \), and the space availability \( \%A \) [%] under the three sky scenes of the prototype are summarised in Table 5.

Table 4  Radiance simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>-ab</td>
<td>Ambient bounces</td>
<td>4</td>
</tr>
<tr>
<td>-aa</td>
<td>Ambient accuracy</td>
<td>0.08</td>
</tr>
<tr>
<td>-ar</td>
<td>Ambient resolution</td>
<td>128</td>
</tr>
<tr>
<td>-ad</td>
<td>Ambient divisions</td>
<td>1024</td>
</tr>
<tr>
<td>-as</td>
<td>Ambient super-samples</td>
<td>256</td>
</tr>
</tbody>
</table>

The measurement results show that at the nearest point to the window, the horizontal illuminance value is found to be 400 lx under the partly cloudy scene, compared to 180 lx under the overcast one. Despite this large variation, the uniformity in the three scenes are relatively similar (0.27-0.28), which means the influence of the PAR spot lamp on uniformity is limited, mainly increasing the total light output.

Moreover, none of the points receives a horizontal illuminance larger than 500 lx, under all sky scenes, mainly due to the relatively small (approximately 5%) window-to-wall ratio. As a result, the space availability (taking 500 lx as the minimum criterion) in all cases is zero. It should be noted that the general lighting in the room was completely switched off, to ensure that only the prototype contributed to the light inside the room.

Vertical illuminance on the observer’s eye plane \( E_{v} \) (lx), together with the minimum \( L_{\text{min}} \) (cd/m²), maximum \( L_{\text{max}} \) (cd/m²), and average luminance \( L_{\text{av}} \) (cd/m²) perceived by the observer at positions 1 and 2 (referring to Figure 3) are displayed in Table 6. These values were extracted from the post-processing software Photolux 3.1. In addition, the DGP values obtained from Evalglare are also given.

In line with the measurement results of horizontal illuminance, the lowest measured vertical illuminance is also found under the overcast sky scene, while the highest is found under the partly cloudy one. This is also true for the minimum, maximum, and average luminance, as well as DGP perceived by the observer. While the vertical illuminance at position 1 under the partly cloudy scene is around 1.5 times the value under the overcast scene, the maximum luminance under the former is 4 times higher than that under the latter (6000-1550 cd/m²). The maximum luminance is actually found on the location of the ‘sun spot’, whereas the vertical illuminance at position 1 is determined by the total window.

According to discomfort glare classification of Jakubiec and Reinhart (2012), a DGP range of 0.30-0.35 corresponds to a ‘perceptible’ category, while DGP values of <0.30 are considered ‘imperceptible’. Hence, only the observers at position 1 under the partly cloudy and the clear sky scenes are expected to experience perceptible discomfort glare from the prototype.

Figure 5 displays the luminance false colour pictures of the prototype as seen from position 1; note there are different scales used in the three pictures. The window surface under the overcast scene obviously appears more uniform, whereas a bright spot of the PAR lamp in the upper right corner of the window is revealed under the other two scenes. Combined high dynamic range (HDR) images of the same views are displayed in Figure 2, in which the directional light from the PAR spot lamp leaves its pattern on the countertop (Figure 2b and c).

From the pictures in Figure 5, one can conclude that, as the mean view luminance of the prototype is more than 1800 cd/m², the display is capable of creating discomfort glare (Shin et al., 2012; Kim et al., 2012). This level is present in the clear and partly cloudy sky scenes. The contrast between the surrounding wall and the window is very often over 1:20 or 1:40, which is another sign of potential discomfort glare.
Table 6  Vertical illuminance on the observer's eye, minimum, maximum, average luminance, and DGP perceived by the observer at positions 1 and 2 under the three sky scenes of the prototype.

<table>
<thead>
<tr>
<th>Position - scene</th>
<th>$E_v$ [lx]</th>
<th>$L_{min}$ [cd/m²]</th>
<th>$L_{max}$ [cd/m²]</th>
<th>$L_{av}$ [cd/m²]</th>
<th>DGP [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Overcast</td>
<td>403</td>
<td>0.23</td>
<td>1550</td>
<td>73</td>
<td>0.24</td>
</tr>
<tr>
<td>2 - Overcast</td>
<td>208</td>
<td>0.18</td>
<td>1540</td>
<td>39</td>
<td>0.21</td>
</tr>
<tr>
<td>1 - Clear</td>
<td>427</td>
<td>0.28</td>
<td>5500</td>
<td>80</td>
<td>0.32</td>
</tr>
<tr>
<td>2 - Clear</td>
<td>246</td>
<td>0.22</td>
<td>3400</td>
<td>47</td>
<td>0.28</td>
</tr>
<tr>
<td>1 - Partly cloudy</td>
<td>600</td>
<td>0.40</td>
<td>6000</td>
<td>111</td>
<td>0.34</td>
</tr>
<tr>
<td>2 - Partly cloudy</td>
<td>348</td>
<td>0.30</td>
<td>4200</td>
<td>66</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Figure 5  Luminance false colour pictures of the prototype observed at position 1, under (a) overcast, (b) clear, and (c) partly cloudy sky scene.

5.2.  Simulation of prototype

Table 7 summarises the simulation results of the horizontal illuminance point at the central column on the workplane, together with the overall average illuminance values ($E_{av}$ [lx]), uniformity ($U_0$), and space availability (%$A$ [%]) under the three sky scenes of the prototype. For comparison, the measurement results and ratio between simulation and measurement values are also shown.

The lighting simulation and measurement results of the prototype generally show similar trends with a maximum relative difference of 26%, found on the farthest point from the window, under the overcast sky scene. The maximum relative difference for the average illuminance is 18%, also found under the overcast sky scene. However, the ratio of the simulated value to the measured one at all points is always in the range of 0.67-1.50, which represents the smallest significant difference in subjective effect of illuminance (CEN, 2002). Looking at the criterion, the models are therefore considered sufficient for the purpose of reproducing the scenes without giving a significant subjective difference, even though more care should be taken when interpreting the modelling results of scenes with relatively low lighting levels, as shown here in the overcast sky scene.

5.3.  Simulation of real windows

Figure 6 displays the graphs showing the relationship between horizontal illuminance and the distance to the window under the three sky scenes, based on the measurement and simulation of the prototype (VW) and simulation of real window (RW). Table 8 summarises the simulation
Figure 6  Graphs showing the relationship between horizontal illuminance and distance to window under the (a) overcast, (b) clear, and (c) partly cloudy sky scene.

Table 7  Simulation (sim.) and measurement (meas.) results of horizontal illuminance point at the central column, together with the average illuminance values ($E_{av}$ [lx]), uniformity ($U_0$), and space availability (%A [%]) under the three sky scenes of the prototype.

<table>
<thead>
<tr>
<th>Distance to window [m]</th>
<th>Overcast</th>
<th>Clear</th>
<th>Partly cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>245</td>
<td>204</td>
<td>1.15</td>
</tr>
<tr>
<td>0.9</td>
<td>155</td>
<td>155</td>
<td>1.00</td>
</tr>
<tr>
<td>1.4</td>
<td>79</td>
<td>88</td>
<td>0.89</td>
</tr>
<tr>
<td>1.9</td>
<td>52</td>
<td>61</td>
<td>0.85</td>
</tr>
<tr>
<td>2.4</td>
<td>38</td>
<td>44</td>
<td>0.86</td>
</tr>
<tr>
<td>2.9</td>
<td>28</td>
<td>36</td>
<td>0.77</td>
</tr>
<tr>
<td>3.4</td>
<td>25</td>
<td>34</td>
<td>0.74</td>
</tr>
<tr>
<td>$E_{av}$ [lx]</td>
<td>42</td>
<td>52</td>
<td>0.82</td>
</tr>
<tr>
<td>$U_0$ [-]</td>
<td>0.19</td>
<td>0.28</td>
<td>0.68</td>
</tr>
<tr>
<td>%A [%]</td>
<td>0</td>
<td>0</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 8  Average illuminance values ($E_{av}$ [lx]), uniformity ($U_0$), and space availability (%A [%]) under the three sky scenes of the simulated, hypothetical real window.

<table>
<thead>
<tr>
<th></th>
<th>Overcast</th>
<th>Clear</th>
<th>Partly cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{av}$ [lx]</td>
<td>28</td>
<td>97</td>
<td>80</td>
</tr>
<tr>
<td>$U_0$ [-]</td>
<td>0.27</td>
<td>0.47</td>
<td>0.41</td>
</tr>
<tr>
<td>%A [%]</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

results of the average illuminance values ($E_{av}$ [lx]), uniformity ($U_0$), and space availability (%A [%]) under the three sky scenes of the real window.

Figure 6 shows how the light from the real window rapidly drops at the distance of more than 1 m from the window, while the decreases are less dramatic under the prototype scenes. The investigated prototype yields a less rapidly-drop illuminance distribution and a larger average illuminance than the corresponding real window, under the overcast (52 lx compared to 28 lx) and partly cloudy (102 lx compared to 80 lx) sky scenes. Under the clear sky scene, the real window yields a higher average illuminance on the workplane (97 lx), compared to the prototype (71 lx). This is due to the influence of direct sunlight in the real clear sky, which delivers more light into the far side of the test room.

Figure 7 displays false colour maps of horizontal illuminance values under the three sky scenes, from both the measured prototype and the simulated real window. Comparison of the corresponding illuminance contour maps reveals that the prototype yields a wider illuminance distribution throughout the workplane. This is mainly due to the fact that the light sources of the prototype are placed at a certain distance from the window glass; whereas under the real window scenes, the sun and sky are at infinity, therefore the light distribution rapidly drops throughout the space. Under the clear sky scene, the real window gives a wider distribution at the left-hand side of the workplane, as shown in Figure 7d, since the direct sunlight comes from the upper-right corner of the window. Under the overcast and partly cloudy scenes, the diffuse
panel plays a role not only in creating the blur and cloudy display of the window, but also in spreading the generated light onto the back of the room.

It should be noted that the simulation result of the real window may not necessarily be the same with the measurement and/or the simulation result of the prototype, since they are actually two different systems. In fact, this study aims to find the difference between the real and the (existing) virtual window. On the other hand, the measurement and simulation result of the prototype must be similar at a certain degree of accuracy, which is discussed in Section 5.2.

It would be theoretically possible to adjust the settings of the prototype under each sky scene, so that the illuminance distribution matches that of the corresponding real window, for instance by reducing the intensity level of some of the TL5 lamps, so that the delivered light is focused on the area near the window. However, this is not discussed in this study, as the objectives are to evaluate the lighting performance of the prototype under existing display settings, and to compare the performance with corresponding real windows in simulation.

Table 9 displays the maximum luminance and DGP perceived at positions 1 and 2, from the simulated real window under all sky scenes, as compared to those in the measured prototype. It is interesting to see that even though both scenes have the same illuminance value at the nearest point (P1 in Figure 3), the luminance values perceived by the observers greatly differ.

![False colour maps of the measured horizontal illuminance [lx] under the (a) overcast, (c) clear, and (e) partly cloudy sky scene of the measured prototype; and under the (b) overcast, (d) clear, and (f) partly cloudy sky scene of the simulated real window.](image-url)
Under nearly all sky scenes and observer’s positions, the maximum luminances of the real window are lower, and so are the DGP values, than that of the virtual one.

The real window, particularly in appearance of the sun, generates a discomfort glare perception that is still relatively low compared to the corresponding situation with the prototype. On the other hand, the VNLS prototype generates generally higher luminance values compared to the corresponding real window, which leads to higher DGP values. This is mainly due to the fact that the light sources of the prototype are placed at a certain distance from the window glass, instead of at infinity as is the sky outside the real window. Under the real window scenes, the light is scattered in a more diffuse way, therefore the discomfort glare under the real window scenes is less than that under the prototype scenes. It is also noticed that the placement of the PAR spot lamp as a virtual sun at the upper corner of the prototype cannot always represent the real sun’s position at the site location of the test room, particularly for low solar elevation angles; it should be placed at a sufficient distance behind the window glass in order to do so.

In general, the measurement and simulation results give an idea of how a VNLS prototype with various sky scenes compares to a real window under a similar sky scene, in terms of physical light phenomena. The VNLS prototype analysed here had a limited complexity level of the view. Additional features such as motion parallax and sound transmission could also improve the degree of similarity between the virtual and real windows, even though it may not be directly related to the lighting performance on the workplane.

It can also be argued that while the investigated prototype lacked some features that are usually associated with a real window, this prototype was designed and constructed to create a subjective, rather than accurately measured, impression or feeling of being connected to the outside world, without necessarily reproducing all of the details. For instance, the addition of curtains or Venetian blinds on the window frame makes it less visible, which in some cases can remove the impression that the window is artificial (van Loenen et al., 2007). Compared to other prototypes with a simplified view discussed in Section 1.1, this particular prototype scores better in terms of visual appearance, due to the possibility to vary the sky view, colour gradients, and directional light. The future work on this subject will be to investigate how building occupants actually appraise such artificial solutions in reality. Therefore, thorough user’s performance and perception studies are required.

### 6. Conclusions

A number of efforts have been made to recreate the elements of natural light inside buildings, in the form of artificial solutions. Such solutions, the so-called VNLS, can be generally classified based on light directionality and view complexity. Computational modelling and building performance simulation can help steering the process of VNLS design development. An example of the influence of simulation in VNLS development is shown in this article, where Radiance was applied to reproduce the scenes and to evaluate the lighting performance of a first generation VNLS prototype displaying view of overcast, clear, and partly cloudy sky scenes. Using the designed setting, none of the measuring points received a horizontal illuminance of 500 lx or larger, suggesting the need of a higher intensity setting for each scene, or a larger window-to-wall ratio, to ensure sufficient amount of light for typical working activities.

The key point of this study is to show that simulations can be used to compare an actual VNLS prototype with a hypothetical real window under the same sky scenes, which was physically not possible, since the test room was not located at the building’s facade. Based on the lighting simulation in Radiance, the investigated prototype yields a wider light distribution and a higher average illuminance than the corresponding, hypothetical real window under the overcast and partly cloudy scenes; even though that does not necessarily mean better, given that the real daylight provides varying light distribution across the space. Under the clear sky scene, the real window yields a higher average illuminance, due to the influence of direct sunlight.

Further work should be focused on getting the sun mimicking under the clear sky scene right, in terms of angle and directionality. Moreover, the greatest next challenge possibly is to understand how people will actually appraise VNLS in reality. Therefore, thorough user’s performance and perception studies are required in the future.

### Acknowledgements

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