Simulation of virtual natural lighting solutions with a simplified view

Citation for published version (APA):

Mangkuto, R. A., Aries, M. B. C., Loenen, van, E. J., & Hensen, J. L. M. (2014). Simulation of virtual natural lighting solutions with a simplified view. *Lighting Research and Technology*, 46(2), 198-218.
<https://doi.org/10.1177/1477153513476875>

DOI:

[10.1177/1477153513476875](https://doi.org/10.1177/1477153513476875)

Document status and date:

Published: 01/01/2014

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Simulation of virtual natural lighting solutions with a simplified view

RA Mangkuto MSc, MBC Aries PhD, EJ van Loenen PhD and JLM Hensen PhD

Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands

Short title: Simulation of virtual natural lighting solutions

Received 22 October 2012; Revised 7 December 2012; Accepted 11 January 2013

Daylight is limited in time and space. In situations where daylight is insufficiently available, Virtual Natural Lighting Solutions (VNLS), which are systems that artificially provide lighting and view comparable to those of real windows and skylights, can be promising. VNLS can turn currently unused floor space into space with daylight qualities. The space-gaining potential of VNLS in buildings can be predicted using computational building performance simulation. This paper describes the approach of modelling VNLS with a simplified view, using the *Radiance* tool to evaluate the lighting performance in a reference office. The VNLS is modelled as arrays of small light sources resembling the sky, the horizon, and the ground. The simulation results show that VNLS with wide beam angles generally offer a better uniformity and a larger percentage of sufficiently lit workplane area, compared to those obtained with real windows under overcast sky conditions, while the discomfort glare remains comparable to that received from real windows.

Address for correspondence: Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands
E-mail: r.a.mangkuto@tue.nl

1. Introduction

Health, wellbeing, and performance of people are very much related to the presence of daylight. Several studies show that people with sufficient access to daylight perceive less stress, have a higher productivity, and are more alert. (e.g.^{1,2,3}) However, daylight is highly variable and limited in time and space. For instance, during the night there is not enough or no daylight at all, buildings can be too deep to supply daylight throughout the building, and some spaces are simply not provided with windows, skylights, or any form of daylight harvesting systems.

In situations where daylight is not or insufficiently available, the Virtual Natural Lighting Solutions (VNLS) concept can be promising. VNLS are systems that can artificially provide lighting and an outside view, with properties comparable to those of real windows and skylights. The benefit of installing VNLS in a building is the ability to use more space which has very limited or no access to daylight, with the possibility of controlling the lighting and view quality.

Many researchers have shown that the view is an important aspect provided by a real window, and even cannot be separated from the daylight itself (e.g.⁴). The findings of Keighley^{5,6} and Markus⁷ showed that views should have three specific layers: a layer of sky, a layer of city or landscape, and a layer of ground. Each layer has its own specific function. Related to daylight and view, Hellinga and Bruin-Hordijk proposed certain quality levels for themes that influence visual comfort.⁸ They proposed parameters with qualitative levels, which are classified as: A (absolute best choice for that parameter), B (good), C (sufficient), and D (insufficient); as shown in Table 1. The values for the different quality levels are based on values found in the literature (e.g.^{9,10}).

The concept of VNLS is new and the real, ideal product does not yet exist. The currently available virtual windows and skylights are considered not suitable for meeting all the expectations since they are only able to meet part of the natural light expectation.^{11,12} Investigation of psychological effects of virtual windows is still an ongoing process. Some user perception studies on view and light (quality) aspects of virtual windows have been reported by, e.g., Tuaycharoen and Tregenza¹³ which focused on discomfort glare from screen projected images, IJsselsteijn et al.¹⁴, who focused on depth perception cues from screen projected images; de Vries et al.¹⁵, who focused on non-visual effects of “emulated windows” without an image; and Shin et al.¹⁶, who focused on subjective discomfort glare evaluation from a backlit, transparent printed image.

While the relationship between currently available virtual windows and user perception is still being investigated, there is very little discussion about the potential of virtual window system application for building performance. The potential here is defined as the gain of performance of a given building with a given virtual window system, compared to that of the same building with real windows. The building performance can be described in terms of its lighting and energy consumption. Since VNLS are future (non-existing) systems with lots of possible input variables, we apply computational building performance simulation to predict their performance. *Radiance* is used as the main tool in the lighting simulation part, where the VNLS in this case are modelled as arrays of small light sources with a “simplified view” that resembles the sky, the horizon, and the ground.

The work described in this paper focuses only on the numerical design appraisal of the ongoing development of VNLS. The actual, physical models are not yet realised. It is generally true that development of a new type of solution must be tested, evaluated, and pass through several stages. As a contribution to steer the development process of such solutions, this particular study is meant to demonstrate the role of building performance simulation in the research and development of VNLS, by predicting the performance of numerical model of VNLS relative to that of real windows. In particular, the objectives of this study are twofold. The first is to understand the effect of changing input variables of the VNLS, which in our case are: the window's

configuration, tilt angles of the sources, beam angle of the sources, and total luminous flux of the sources; on the lighting performance of a reference office space. The second one is to compare the lighting performance of the simulated VNLS in a reference office space, relative to that of real windows under CIE overcast sky.

The lighting performance is described in terms of the ability to meet the space availability demand, the illuminance uniformity on the workplane, the illuminance contribution from the ground elements on the ceiling, and the ability to produce minimal glare at predefined observer positions in the given space. We define space availability here as the percentage of workplane (at height of 0.75 m from the floor) meeting a certain minimum illuminance criteria. VNLS ideally provide space availability comparable to or better than real windows with the same configuration.

2. Methods

2.1. Modelling

While all detailed characteristics of the view from a window are considered very important for developing the requirement of VNLS, in this study we focus only on modelling the characteristics of direct light from the sky and reflected light from the exterior ground. One of the reasons that people distinguish the difference between a real and an existing virtual window with a view, either static or dynamic, may be

because the directionality of the light coming out of the surfaces is different. In general, most of the existing virtual windows behave like a diffuse light source, reducing the possibility of seeing the impression of direct and reflected light components on the interior surfaces.

Therefore, in this study, we propose a model of VNLS in the form of arrays of small light emitting areas, displaying a simplified view of green ground, (horizon) and blue sky. The third layer (distant objects such as built landscape) is not represented yet. The bottom array acts as the “ground” which is tilted upward to mimic reflected light, directed to the ceiling. The rest of the light sources act as the “sky”, and are tilted downward to direct the light to the workplane area.

Figure 1 Schematic overview of the VNLS as used in the simulation. The light sources are constructed in arrays, such that the light from the “ground” is delivered to the ceiling and light from the “sky” is delivered to the floor

The light emitting areas are modelled to fit two individual vertical windows, each with the size of $0.80\text{ m} \times 1.21\text{ m}$ ($W \times H$), which corresponds to a window-to-wall ratio of 20%. Each light emitting area in each individual window has a size of $0.05\text{ m} \times 0.05\text{ m}$ and resembles a blue sky. In the lowest row, there are four light emitting areas ($0.20\text{ m} \times 0.20\text{ m}$ each) resembling a green ground surface.

In order to model the directionality of the entering light, the “sky” sources are tilted downward with a certain interval of tilt angle. Three variations of this interval are used, i.e. 1.0° , 1.5° , and 2.0° . The sources in the row directly above the “ground” are never tilted (i.e. 0°), while the sources in the second row above the “ground” are tilted downward by 1.0° , or 1.5° , or 2.0° . The sources in the third row above the “ground” are tilted downward by 2.0° , or 3.0° , or 6.0° , and so on. As a result of using the defined window height, the sources in the top row are tilted downward by 40° , 30° , and 20° . The “ground” sources are tilted at a 40° angle pointing upward. Figure 2 displays the views of an individual VNLS with upper tilt angle of 40° .

Figure 2 Front and side views of the individual VNLS with upper tilt angle of 40°

The sources have a certain beam angle, i.e. the angle between the two directions at which the luminous intensity is half that of the maximum luminous intensity. To see the effects of varying beam angle, three values of beam angle for the “sky” are used, i.e. 38° (relatively narrow spread), 76° (medium), and 114° (wide).

The luminous intensity distribution of each light source is written in an IES format file, based on the character of downlights with a certain beam angle. The distributions in every row have similar patterns. The luminous intensity values for the sources with a 114° beam angle are set in such a way that the combination of these sources gives an

average surface luminance (L [cd/m²]) of either 1000 cd/m² (low luminance setting), 1800 cd/m² (medium luminance setting), or 3200 cd/m² (high luminance setting). These are the first three values used in the experiments with an “emulated window” by Shin et al.¹⁶

The luminous intensity values for the “sky” sources with 38° and 76° beam angles are adjusted accordingly, so that the total luminous flux coming from the “sky” sources altogether remains the same. The technique for calculating the total luminous flux from the source is based on the zonal cavity method described by Lindsey.¹⁷ Given the luminous intensity values at various angles of a luminaire, and assuming that the luminous intensity distribution is direct (no values for angles more than 90°) and symmetrical around the luminaire’s axis, the area surrounding the luminaire can be divided into nine zonal cavities, which are the volumes of conic solid angles with a width of 10°, starting from 0°~10° up to 80°~90°.

The total luminous flux produced by the luminaire (Φ [lm]) can be determined as follows:

$$\Phi = \sum_{N=1}^9 (I_N \times 2\pi(\cos \theta_{\min_N} - \cos \theta_{\max_N})) \quad (1)$$

The minimum and maximum angles in each zonal cavity ($\theta_{\min N}$, $\theta_{\max N}$ [°]) determine the zonal constant which is multiplied by the average luminous intensity (I_N [cd]) to yield the luminous flux of that particular zonal cavity. The total luminous flux is then the sum of luminous flux of all zonal cavities.

For our case, the calculated total luminous fluxes of all “sky” sources (two windows) are approximately 6200 lm, 11100 lm, and 19900 lm, respectively for the low, medium, and high luminance settings. Figure 3 displays the nine evaluated luminous intensity distributions of the “sky” sources. Note that the luminous intensity values of the polar diagrams change with varying beam angle.

Each “ground” source has a maximum luminous intensity of 110 cd at the low luminance setting, 199 cd at the medium one, and 354 cd at the high one; all have a similar pattern of luminous intensity distribution. The beam angle of the “ground” source remains constant at 76° for all variations. A tilt angle of 40° upward is chosen so that the “ground” sources do not stand completely vertical, which can possibly create too much glare; and that they are not tilted too much, which can reduce the visibility of the “ground” itself.

$\Phi = 6200 \text{ lm}$
 $BA = 38^\circ$

(a)

$\Phi = 6200 \text{ lm}$
 $BA = 76^\circ$

(b)

$\Phi = 6200 \text{ lm}$
 $BA = 114^\circ$

(c)

$\Phi = 11100 \text{ lm}$
 $BA = 38^\circ$

(d)

$\Phi = 11100 \text{ lm}$
 $BA = 76^\circ$

(e)

$\Phi = 11100 \text{ lm}$
 $BA = 114^\circ$

(f)

Figure 3 Polar diagram of luminous intensity (in candela) of the light sources resembling the sky, with beam angles of 38° , 76° , 114° and total luminous flux of 6200, 11100, and 19900 lm

The variation in all input variables is summarised in Table 2. In total, there are 54 different combinations possible based on the input variables.

2.2. Settings

The space discussed in this study is a reference office with dimensions of $5.4 \text{ m} \times 3.6 \text{ m} \times 2.7 \text{ m}$ ($L \times W \times H$). There are two vertical window configurations chosen from the earlier studies of Diepens et al.¹⁸ and LBL¹⁹ (see Figure 4). Each VNLS is modelled with a simplified viewed image on its surface, which is explained in the Methods section. No real windows are present together with the VNLS in the modelled spaces.

Figure 4 Elevation views of the VNLS window configurations on the wall

In the given space, VNLS are put on one side of the wall ($W 3.6 \text{ m} \times H 2.7 \text{ m}$). Frames of 5 cm wide are defined at the perimeters of the windows. Reflectance values

of the room's interior are: ceiling: 85%, walls: 50%, floor: 20%, door: 50%, window and door frames: 50%; all based on the IEA Task 27 reference office.²⁰

Three different observer positions, namely A, B, and C, are defined at the eye height of 1.2 m above the floor. Position A is near the window and viewing parallel to the window plane, B is in the middle of the room and viewing parallel to the window plane opposite to the viewing position A, while C is near the rear wall and directly facing the window plane, as shown in Figure 5.

Figure 5 (a) Plan view and (b) section view of the simulated space

For all simulations, the simulation parameters in *Radiance* simulations are set as shown in Table 3.

2.3. Assessment

2.3.1. Performance indicators

The assessment for this study is based on the performance indicators of interest, which are:

- *Space availability* (%A): The percentage of workplane area (at height of 0.75 m, with a size equal to the total floor area) with illuminance ≥ 500 lx (typical criteria for office work). Calculation is performed at 1944 ($= 54 \times 36$) points which are evenly distributed on the workplane. The %A is the percentage of the number of points with illuminance ≥ 500 lx ($n(E \geq 500 \text{ lx})$), compared to the total number of points (N).

$$\%A = \frac{n(E \geq 500 \text{ lx})}{N} \times 100\% \quad (2)$$

- *Uniformity* (U_0): The ratio between the minimum illuminance ($E_{\min}$ [lx]) to the average (E_{av} [lx]); based on the defined calculation points.

$$U_0 = \frac{E_{\min}}{E_{av}} \quad (3)$$

- *Ground contribution* (%G): The percentage ratio of illuminance contribution from the “ground” element sources (E_{ground} [lx]) to the total illuminance (E_{total} [lx]) received at a certain point on the ceiling, with the surface normal facing downward (z- axis).

Calculation is performed for $N = 10$ points on the ceiling, located as displayed in Figure 6. The average value is reported as $\%G_{av}$.

$$\%G = \frac{E_{ground}}{E_{total}} \times 100\% \quad (4)$$

$$\%G_{av} = \frac{\sum_{i=1}^N \%G_i}{N} \quad (5)$$

Figure 6 (a) Plan view and (b) section view of calculation points for ground contribution

- *Probability of discomfort glare*: The normalised values of all potentially relevant glare indices, i.e. Daylight Glare Probability (DGP), Daylight Glare Index (DGI), Unified Glare Rating (UGR), and CIE Glare Index (CGI) are calculated with the Evalglare programme.²¹ Those four indices are taken into account since to the best of

our knowledge, very little is known about which glare indices are most suited for the case of VNLS. Another often-used index, the Visual Comfort Probability (VCP) will not be considered, since it is specially developed for typically sized, ceiling-mounted, artificial lighting installations with uniform luminances.²² Because the calculated glare indices have different ranges of values, it is desirable to normalise the values for the purpose of comparison. The normalisation factors are suggested by Jakubiec and Reinhart to determine the “probability of discomfort glare”, by multiplying the DGI value with 0.01452, and multiplying UGR and CGI values with 0.01607.²³ No normalisation is required for DGP, since it is already defined within the range of 0 ~ 1. Thus, we define:

$$DGI_n = 0.01452 \times DGI \quad (6)$$

$$UGR_n = 0.01607 \times UGR \quad (7)$$

$$CGI_n = 0.01607 \times CGI \quad (8)$$

where DGI_n , UGR_n , CGI_n are the normalised DGI, UGR, and CGI values, respectively. Next, the four normalised glare indices are averaged, and then the value is reported as the average probability of discomfort glare (PDG_{av}).

$$PDG_{av} = (DGP + DGI_n + UGR_n + CGI_n) / 4 \quad (9)$$

2.3.2. Sensitivity analysis

To evaluate the effect of the current input variables on the defined performance indicators, a sensitivity analysis using multiple linear regressions was performed. This regression model assumes a linear relationship between the output variable y_i and the p -vector of input variables x_i . This relationship is modelled through an error variable ε_i , which is an unobserved random variable that adds noise to the linear relationship between the output and input variables. The mathematical model takes the general form as follows:

$$y_i = \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + \varepsilon_i, \quad i = 1, 2, \dots, n \quad (10)$$

where β_i is a p -dimensional regression coefficient. In this case: $p = 4$, $n = 2 \times 3 \times 3 \times 3 = 54$, x_1 is the distance between windows (d , in metres), x_2 is the interval of tilt angle (IA, in degrees), x_3 is the beam angle (BA, in degrees), and x_4 is the total luminous flux (Φ , in lumens); while y is evaluated for $\%A$, U_0 , $\%G_{av}$, and PDG_{av} , individually. Since the variables have different units, it is intended to standardise the values for each of the output and input variables, that is:

$$y_i' = \frac{y_i - \bar{y}}{\sigma_y} \quad ; \quad x_{ni}' = \frac{x_{ni} - \bar{x}_n}{\sigma_{x_n}} \quad (11)$$

where y_i' and x_{ni}' are the standardised output and input variables, y_i and x_{ni} are the actual output and input variables, $\bar{y}$ and $\bar{x}_n$ are the arithmetic mean of the output and input variables, and σ_y and σ_{x_n} are the standard deviation of the output and input variables. The standardised values are then put in the regression model, which can be expressed in matrix form as follows:

$$\begin{bmatrix} y_1' \\ \dots \\ y_n' \end{bmatrix} = \begin{bmatrix} x_{11}' & x_{12}' & x_{13}' & x_{14}' \\ \dots & \dots & \dots & \dots \\ x_{n1}' & x_{n2}' & x_{n3}' & x_{n4}' \end{bmatrix} \begin{bmatrix} \beta_1' \\ \beta_2' \\ \beta_3' \\ \beta_4' \end{bmatrix} + \begin{bmatrix} \varepsilon_1' \\ \dots \\ \varepsilon_n' \end{bmatrix}, \quad i = 1, 2, \dots, 54 \quad (12)$$

The built equations are then solved using the MATLAB toolbox to determine $\beta_1', \beta_2', \beta_3',$ and β_4' ; which are the standard regression coefficients that determine the sensitivity of the output as function of the input. The standard regression coefficients of all variables are displayed in Figure 7. A value of 1 or -1 shows a high sensitivity. The interaction between input variables was not investigated.

2.3.3. Comparison with real windows

As a means of comparison, the VNLS in all configurations were replaced with real windows (double clear glass 6 mm, transmittance 88.5%) under a CIE overcast sky

condition. The comparison with real windows is considered necessary, since the general concept of this VNLS type is to increase the possibility of seeing the impression of direct light components from the sky and reflected light components from the ground, on the interior surfaces. This impression often appears in a space with real windows, but typically not in a space with a conventional electrical lighting installation. While the typical general lighting installation is ceiling-mounted, a fair comparison with wall-mounted VNLS will be difficult to achieve. Moreover, the display of a simplified view of blue sky and green ground is also an important feature of the proposed VNLS model, which should also be compared with a relatively simple view of overcast sky and plain ground outside the real windows.

The sky condition of the real windows scenes is defined in the Gensky programme in *Radiance*, by inserting the zenith brightness value (b [W/sr/m²]). This value is chosen so that the interior surface of the window will give approximately the same average luminance as the corresponding VNLS. It should be noted that VNLS with the same total luminous flux can have a different average surface luminance, particularly when the beam angles are different. Therefore, each VNLS scene is compared only to the real window scene with approximately the same average surface luminance. The assessments for determining the performance indicators are then performed for the real window scenes.

Since the three observer positions in the room are located in such a way that they are facing different directions, one can presume that position C, which is directly facing the window, may experience the most severe glare amongst the three positions. Therefore, the glare assessment may be reduced to focus only on position C, as it will be sufficient to reflect the worst situation. To demonstrate this, the glare assessment for positions A, B, and C are performed on the following sample of variations:

- VNLS: configuration 1a ($d = 0$), $IA = 2.0^\circ$, $BA = 76^\circ$, $\Phi = 11100 \text{ lm}$, $L_{av} = 3200 \text{ cd/m}^2$
- VNLS: configuration 2a ($d = 0.75 \text{ m}$), $IA = 2.0^\circ$, $BA = 76^\circ$, $\Phi = 11100 \text{ lm}$, $L_{av} = 3200 \text{ cd/m}^2$
- Real window: configuration 1a ($d = 0$), $L_{av} = 3200 \text{ cd/m}^2$
- Real window: configuration 2a ($d = 0.75 \text{ m}$), $L_{av} = 3200 \text{ cd/m}^2$

To evaluate the performance of all VNLS variations, four performance criteria are applied on the relative comparison between performance indicators of the VNLS and the real windows with the same average surface luminance. These are based on the expected benefit of having VNLS, i.e. gaining more well-lit and uniform space; while maintaining the ground contribution on the ceiling and the probability of discomfort glare comparable to those in real windows scenes. We define the criteria in terms of a

ratio, which is evaluated up to one significant digit after the decimal point. The criteria are:

- The VNLS should create larger space availability, compared to the real windows.
- The VNLS should create equal or better illuminance uniformity, compared to the real windows.
- The VNLS should create average ground contribution on the ceiling that is within ± 0.1 (10%) of that in the real windows scene.
- The VNLS should create equal or smaller average probability of discomfort glare as observed in position C, compared to the real windows.

The criteria are expressed in mathematical forms as follows.

$$\frac{\% A_{\text{VNLS}}}{\% A_{\text{RW}}} > 1.0 \quad (13)$$

$$\frac{U_{0 \text{ VNLS}}}{U_{0 \text{ RW}}} \geq 1.0 \quad (14)$$

$$0.9 \leq \frac{\% G_{av \text{ VNLS}}}{\% G_{av \text{ RW}}} \leq 1.1 \quad (15)$$

$$\frac{\text{PDG}_{av \text{ RW}}}{\text{PDG}_{av \text{ VNLS}}} \geq 1.0 \quad (16)$$

where the subscripts of VNLS and RW correspond to the VNLS and real windows scene with the same average surface luminance.

Moreover, it is preferable to have an average surface luminance which does not exceed 3200 cd/m^2 . This is the value given in the experiments of Shin et al.¹⁶, where on average people perceive the glare from simulated windows as “acceptable”, i.e. scored as 2.5 out of 4.5 on their discomfort glare scale.

3. Results and Discussion

The results of glare assessment for positions A, B, and C performed on the four aforementioned variations are showed in Table 4. The average probabilities of discomfort glare are shown together with their standard deviations.

Since the standard deviations in VNLS scenes are found to be very similar and never differing more than 0.01 from their real windows counterpart, the average probability of discomfort glare can be taken as an indicator for both the VNLS and the real windows scene. The results also show that the probability of discomfort glare at position C is always found to be the largest; hence it is considered sufficient to take into account only this position in the complete glare assessment for the entire variations.

Table 5 summarises the space availability (%A), uniformity (U_0), ground contribution (% G_{av}) and average probability of discomfort glare (PDG_{av}) for all

window variations/configurations with total luminous flux of 11,100 lm. Note that every three variations with the same distance between windows, beam angle, and total luminous flux are assumed to have the same reference real window, of which the performance indicators are shown directly above them in the table. For instance, configurations (1a, IA = 2.0°, BA = 38°, Φ = 11100 lm), (1a, IA = 1.5°, BA = 38°, Φ = 11100 lm), and (1a, IA = 1.0°, BA = 38°, Φ = 11100 lm), altogether are referred to real windows with an average surface luminance of 10000 cd/m².

3.1. Sensitivity analysis

Figure 7 displays the standard regression coefficient of all input variables (i.e., distance between windows (d), interval of tilt angle (IA), beam angle (BA), and total luminous flux (Φ)), evaluated for the four performance indicators (i.e. %A, U_0 , % G_{av} , and PDG_{av})

Figure 7 Standard regression coefficient of all input variables (i.e. distance between windows, interval of tilt angle, beam angle, and total luminous flux), evaluated for the four performance indicators (i.e. %A, U_0 , % G_{av} , and PDG $_{av}$)

As can be seen in the graph, luminous flux and beam angle are the most influential input variables. Table 6 gives the summary of arithmetic mean, minimum, maximum, standard deviation, and 95% confidence level of the output. The graphs showing the relationship between arithmetic mean of the output and the most influential input variable(s) with a 95% confidence level are displayed in Figure 8.

Figure 8 Graphs showing the relationship between arithmetic mean of the output and the most influential input variable(s), with a 95% confidence level

3.1.1. Space availability

The space availability is largely influenced by the total luminous flux of VNLS. Figure 8a shows that on average, a total luminous flux of 6200 lm, 11100 lm, and 19900 lm will create space availability of around 10%, 32%, and 70%, respectively. Note that the total luminous flux values are set on a logarithmic scale, with an increment factor of around 1.8. The mean space availability values increase with a larger factor; that is 3.2 when increased from 6200 lm to 11100 lm, and 2.2 when increased from 11000 lm to 19900 lm.

3.1.2. Uniformity

The uniformity is highly influenced by the beam angle of VNLS. On average, a beam angle of 38°, 76°, and 114° will create uniformity of around 0.24, 0.32, and 0.37, respectively (see Figure 8b). The relationship between these input and output variables is almost perfectly linear.

3.1.3. Ground contribution on the ceiling

The average ground contribution on the ceiling is highly influenced by the beam angle of the VNLS. On average, a beam angle of 38°, 76°, and 114° will create an average ground contribution of around 57%, 47%, and 46%, respectively. The mean output values are decreased by around 10% (absolute difference), when the input is

increased from 38° to 76°; but they are only decreased by around 0.4% when the input is increased from 76° to 114°, see Figure 8c.

3.1.4. Probability of discomfort glare

The average probability of discomfort glare is highly influenced by the beam angle of the VNLS. Figure 8d shows that on average, a beam angle of 38°, 76°, and 114° will create an average probability of discomfort glare of around 0.45, 0.39, and 0.35, respectively, as observed at position C. The relationship between these input and output variables is almost perfectly linear.

3.2. Comparison with real windows

Table 7 summarises the ratio of space availability, uniformity, and average ground contribution of each VNLS configuration to those of real windows with the same average surface luminance; and the ratio of the average probability of discomfort glare at position C in the real windows scene to that in a VNLS scene with the same average surface luminance; with total luminous flux of 11100 lm. The bold-typed values are those satisfying the criteria, given that the average surface luminance should not exceed 3200 cd/m².

Most of the VNLS satisfying all criteria are those having a beam angle of 114° (wide spread). Most of the VNLS with beam angles of 38° (narrow spread) and 76° (medium

spread) fail to create larger space availability relative to the real windows. A luminous intensity from a VNLS with a 114° beam angle is more evenly distributed throughout the space; hence more space can satisfy the illuminance criterion of 500 lx on the workplane. The appearance of the CIE overcast sky model for the real windows, which is typically characterised by an almost diffuse luminous intensity distribution pattern over the workplane, can be best approached by using a wide spread beam angle for the VNLS model.

3.2.1. Space availability and uniformity

Within the variations satisfying all criteria, the gain of space availability is between 1.1 ~ 2.3, and the gain of uniformity is between 1.4 ~ 2.5, compared to real windows. For example, for an office of 19.4 m^2 floor area as in this case, the real windows with an average surface luminance of 1800 cd/m^2 produce a daylit area of approximately 2.9 m^2 . If VNLS with 114° beam angle and the same average surface luminance are used instead of the real windows, they can produce a daylit area of approximately $5.7 \text{ m}^2 \sim 6.0 \text{ m}^2$, which is a 100% increase. The uniformity is also increased from 0.16 in the real windows scene to 0.36 in VNLS scene.

Figure 9 displays two sets examples of images with isolux contour lines on the workplane of the following configurations which satisfy all criteria:

- Real window: configuration 1a ($d = 0$), $L_{av} = 1800 \text{ cd/m}^2$

- VNLS: configuration 1a ($d = 0$), $IA = 2.0^\circ$, $BA = 114^\circ$, $\Phi = 11100 \text{ lm}$, $L_{av} = 1800 \text{ cd/m}^2$
- Real window: configuration 2a ($d = 0.75 \text{ m}$), $L_{av} = 1800 \text{ cd/m}^2$
- VNLS: configuration 2a ($d = 0.75 \text{ m}$), $IA = 2.0^\circ$, $BA = 114^\circ$, $\Phi = 11100 \text{ lm}$, $L_{av} = 1800 \text{ cd/m}^2$

Figure 9 Isolux contour lines on the workplane of configurations (a) real window 1a ($d = 0$), $L_{av} = 1800 \text{ cd/m}^2$; (b) VNLS 1a ($d = 0$), $IA = 2.0^\circ$, $BA = 114^\circ$, $\Phi = 11100 \text{ lm}$; (c) real window 2a ($d = 0.75 \text{ m}$), $L_{av} = 1800 \text{ cd/m}^2$; (d) VNLS 2a ($d = 0.75 \text{ m}$), $IA = 2.0^\circ$, $BA = 114^\circ$, $\Phi = 11100 \text{ lm}$

From these shown examples, it can be seen that the VNLS has a similar isolux pattern compared to the corresponding real windows. The contour line for 500 lx values are however located at different distances from the window. The area covered by the 500 lx contour line, which is the space availability, in the VNLS scene is approximately double the size of that in the real windows scene. Consequently, the uniformity under the VNLS is also larger compared to the real window, by approximately the same factor of 2.

3.2.2. *Ground contribution on the ceiling*

Within the variations satisfying all criteria, the ratio of average ground contribution on the ceiling is found to range from 0.9 to 1.1. In general, a relatively large difference is found between the pattern of ground contribution propagation in the VNLS and real windows scene. Figure 10 displays graphs showing the ground contribution

propagation for a selected number of VNLS variations; all with $\Phi = 11100$ lm, together with the reference real window case.

Figure 10 Graphs showing propagation of ground contribution on the ceiling for a selected number of variations of VNLS (solid lines), displayed together with the reference real windows (dotted line)

From Figure 10, it can be seen that the ground contribution on the ceiling propagates differently under real windows and under VNLS with different beam angles. In the real windows scene, the ground contribution values are always within 30% to 70% (configuration 1a) or within 40% to 70% (configuration 2a). In the VNLS scene, these values can reach up to 90% near the window, but then rapidly decline. The row of light sources that represents the ground in the VNLS sources have their role here, where the beam angle is set at 76° (medium spread, constant in all variations) and tilted with a 40° angle pointing upward.

In general, given a constant beam angle and tilt angle of the “ground” source, the lower the beam angle of the “sky” source, the higher the average “ground” contribution on the ceiling; since the “sky” will contribute less to the ceiling. The results show that there is an inverse correlation between the beam angles chosen for the light sources that represent the “sky” and the average “ground” contribution on the ceiling. However, a low beam angle of the “sky” source creates a rapid decline in propagation, making it less similar to the situation with real windows (with an overcast sky condition).

3.2.3. Probability of discomfort glare

Within the variations satisfying all criteria, the ratio of average probability of discomfort glare (real windows to VNLS) is found to be 1.0. In the other variations, this ratio is 0.9, thus in no cases are these ratios found to be larger than 1.0. It means that relative to the corresponding real windows, the VNLS generally create similar or slightly worse average probability of discomfort glare. Figure 11 displays the impression of the selected configurations whose isolux contour lines are displayed in Figure 9.

(a)

(b)

(c)

(d)

Figure 11 Impression of configurations (a) real window 1a ($d = 0$), $L_{av} = 1800 \text{ cd/m}^2$; (b) VNLS 1a ($d = 0$), $IA = 2.0^\circ$, $BA = 114^\circ$, $\Phi = 11100 \text{ lm}$; (c) real window n 2a ($d = 0.75 \text{ m}$), $L_{av} = 1800 \text{ cd/m}^2$; (d) VNLS 2a ($d = 0.75 \text{ m}$), $IA = 2.0^\circ$, $BA = 114^\circ$, $\Phi = 11100 \text{ lm}$ (Available in colour in electronic version)

From these shown examples, it can be seen that the VNLS with 114° beam angle have some similarities and differences compared to the corresponding real windows. While the average window surface luminance and the average probability of discomfort glare are approximately similar, a few differences are still recognisable. For instance, the luminance from the “ground” element sources of VNLS are significantly larger than that from the real ground element, if viewed from position C. This high luminance is needed for the VNLS to be able to resemble the impression of ground reflection on the ceiling. Despite the high luminance of the “ground” sources in VNLS, the average probability of discomfort glare viewed from the observer positions is still comparable to that in real window scenes. The wide spread beam angle of the “sky” sources reduces the green-coloured impression on the ceiling, but on the other hand also distributes the light to a wider area of the space, hence creating a more uniformly lit space.

4. Conclusions and future research

In this simulation study, we modelled a VNLS configuration composed of light emitting sources with a size of $0.05\text{ m} \times 0.05\text{ m}$. It shows the possibility to model the direction of light from the “ground” to the ceiling and from the “sky” to the floor. We show comparisons between simulated VNLS and real windows (under CIE overcast sky) with similar average surface luminance, to evaluate the lighting performance indicators, i.e. space availability, uniformity, average ground contribution, and average probability of discomfort glare. It is concluded that:

- The total luminous flux of VNLS influences the space availability greatly.
- The beam angle of VNLS influences the uniformity, average ground contribution on the ceiling, and average probability of discomfort glare greatly
- Most of the VNLS satisfying all criteria are those with a beam angle of 114° (wide spread)

Compared to real windows (under the CIE overcast sky), the gain of space availability is between $1.1 \sim 2.3$, and the gain of uniformity is between $1.4 \sim 2.5$. For example, real windows with an average surface luminance of 1800 cd/m^2 produce a daylit area of approximately 2.9 m^2 in an office of 19.4 m^2 floor area. The VNLS with 114° beam angle and the same average surface luminance can produce a daylit area of $5.7\text{ m}^2 \sim 6.0\text{ m}^2$ in the same space without real windows. The uniformity is also increased from 0.16 to 0.36. To some extent, it shows the benefit of VNLS compared to

the real windows. Further subjective evaluation with users is then required to understand how people will appraise VNLS in reality.

As mentioned in the introduction, the work presented in this paper is a report on progress in the VNLS development. The results of this study are based on simulation of VNLS with a rather simple image and the light sources in the same row are all set with a same horizontal angle. The rendered images are very different from actual window views. Therefore, further studies involving more detailed images on the window view, as well as more features of real daylight that influence visual comfort as mentioned in Table 1, are required to improve the similarity to real windows. More sophisticated configurations and source parameters will be studied to further improve the visual comfort characteristics. Nevertheless, the results presented in this paper show clear examples on how building performance simulation contributes in the research and development of non-existing solutions, by demonstrating that the numerical model of VNLS can perform better in some ways than that of real windows.

Funding

This work is a part of, and funded by the Sound Lighting research line of the Intelligent Lighting Institute, Eindhoven University of Technology.

References

1. Boyce PR, Hunter C, Howlett O. *The Benefits of Daylight Through Windows*. Troy, NY: Lighting Research Center, 2003.
2. Heschong L. *Window and Offices: A Study of Office Worker Performance and the Indoor Environment*. P500-03-082-A-9. Gold River, CA: Heschong Mahone Group, 2003.
3. Heschong L, Wright RL, Okura S. Daylighting impacts on human performance in school. *Journal of the Illuminating Engineering Society* 2002; 31: 101-114.
4. Tuaycharoen N, Tregenza PR. View and discomfort glare from windows. *Lighting Research and Technology* 2007; 39: 185-200.
5. Keighley EC. Visual requirements and reduced fenestration in office buildings - A study of window shape. *Building Science* 1973; 8: 311-320.
6. Keighley EC. Visual requirements and reduced fenestration in offices - A study of multiple apertures and window area. *Building Science* 1973; 8: 321-331.
7. Markus TA. The function of windows - A reappraisal. *Building Science* 1967; 2: 97-121.
8. Hellenga HY, de Bruijn-Hordijk GJ. A new method for the analysis of daylight access and view out. *Proceedings of Lux Europa 2009 - 11th European Lighting Conference*; Istanbul: Turkish National Committee on Illumination, 2009.
9. Kaplan R, Kaplan S. *The Experience of Nature: A Psychological Perspective*. Cambridge: Cambridge University Press, 1989.
10. Tregenza PR, Loe D. *The Design of Lighting*. London: E and FN Spon, 1998.
11. Mangkuto RA, Aries MBC, van Loenen EJ, Hensen JLM. Properties and performance indicators of Virtual Natural Lighting Solutions. *Proceedings of CIBAT 2011*; Lausanne: LESO-PB, EPFL, 2011.

12. Mangkuto RA, Ochoa CE, Aries MBC, van Loenen EJ, Hensen JLM. Review of modelling approach for developing Virtual Natural Lighting Solutions. *Proceedings of Building Simulation 2011*; Sydney: IBPSA Australasia and AIRAH, 2011.
13. Tuaycharoen N, Tregenza PR. Discomfort glare from interesting images. *Lighting Research and Technology* 2005; 37: 329-341.
14. IJsselsteijn WA, Oosting W, Vogels I, de Kort YAW, van Loenen EJ. A room with a cue: The efficacy of movement parallax, occlusion, and blur in creating a virtual window. *PRESENCE* 2008; 17: 269-282.
15. de Vries HJA, Aarts MPJ, Knoop M, Cornelissen H. Beneficial non-visual effects of daylight, Research into the influential parameters. *Proceedings of Lux Europa 2009 - 11th European Lighting Conference*; Istanbul: Turkish National Committee on Illumination, 2009.
16. Shin JY, Yun GY, Kim JT. View types and luminance effects on discomfort glare assessment from windows. *Energy and Buildings* 2012; 46: 139-145.
17. Lindsey JL. *Applied Illumination Engineering*. 2nd edition. Lilburn: The Fairmont Press, Inc., 1997.
18. Diepens JFL, Bakker F, Zonneveldt L. *Daylight Design Variations Book*. 2000. TNO-TUE Centre for Building Research. Retrieved 14 August 2012, from <http://sts.bwk.tue.nl/daylight/varbook/index.htm>
19. Lawrence Berkeley National Laboratory (LBL). *Virtual Lighting Simulator*. 2010. Retrieved 14 August 2012, from <http://gaia.lbl.gov/vls/>.
20. van Dijk D, Platzer WJ. Reference office for thermal, solar and lighting calculations. *Report no. swift-wp3-tno-dvd-030416*. 2003.
21. Wienold J, Christoffersen J. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings* 2006; 38: 743-757.
22. Harrold R. *IESNA Lighting Ready Reference: A Compendium of Materials from the IESNA*. New York: Illuminating Engineering Society of North America, 2003.

23. Jakubiec JA, Reinhart CF. The 'adaptive zone' – A concept for assessing discomfort glare throughout daylight spaces. *Lighting Research and Technology* 2012; 44: 149-170.

Table 1. Quality levels for themes that influence visual comfort, adapted from Hellinga and Bruin-Hordijk ⁸

Parameter	A	B	C	D
Daylight opening				
- Size of daylight opening in office buildings	Size, geometry, position can be adapted to optimise daylight access and view out	Glazing 20~40% of the façade	> 1/20 of floor area	< 1/20 of floor area
Daylight				
- Daylight factor	> 5%	2 ~ 5%	1 ~ 2%	< 1%
- Luminance contrast (task : direct surroundings : periphery)	1 : 3 : 10 + individual control	1 : 3 : 10	1 : 10 : 30	Worse than 1 : 10 : 30
- Sun hours in dwellings (living room)	Between sunrise and sunset direct sunlight possible + individual control of sunlight	Min. 3 sun hours per day, between 21 Jan ~ 22 Oct in the middle of the window-sill	Min. 2 sun hours per day, between 19 Feb ~ 21 Oct in the middle of the window-sill	No attention to sun access in living room
View out				
- Green, sky, and distant objects	The view contains all 3 elements	The view contains 2 of the 3 elements	The view contains 1 of the 3 elements	The view contains none of the 3 elements
- Information	The view gives maximum information about outside environment: weather, season, time of day, (human) activities	The view gives information about weather, season, time of day, and (human) activities	The view gives information about weather, season, and time of day	Not much to see
- Organisation	The view is highly complex and coherent	Medium complexity and coherence	Low complexity and coherence	The view is simple and incoherent

Table 2. Input variables and their values

Variable	Symbol	Unit	Values
Distance between windows	d	m	0, 0.75
Interval of tilt angle	IA	deg	1.0, 1.5, 2.0
Beam angle	BA	deg	38, 76, 114
Total luminous flux	Φ	lm	6200, 11100, 19900

Table 3. *Radiance* simulation parameters

Parameter	Description	Value
-ab	Ambient bounces	4
-aa	Ambient accuracy	0.15
-ar	Ambient resolution	128
-ad	Ambient divisions	512
-as	Ambient super-samples	256
-ds	Direct sub-sampling	0.2

Table 4. Results of glare assessment for positions A, B, and C performed on the four variations in both VNLS and real windows (RW) scenes

Type	Conf.	IA (°)	BA (°)	Φ (lm)	Pos.	DGP	DGI _n	UGR _n	CGI _n	PDG _{av}	SD
RW	1a	$L_{av} = 3200 \text{ cd/m}^2$			A	0.24	0.21	0.35	0.39	0.30	0.08
					B	0.21	0.19	0.31	0.33	0.26	0.07
					C	0.26	0.31	0.43	0.45	0.36	0.09
VNLS	1a	2.0	76	11100	A	0.24	0.21	0.36	0.39	0.30	0.09
					B	0.21	0.20	0.32	0.35	0.27	0.08
					C	0.27	0.33	0.46	0.48	0.38	0.10
RW	2a	$L_{av} = 3200 \text{ cd/m}^2$			A	0.22	0.26	0.36	0.39	0.31	0.08
					B	0.21	0.22	0.32	0.34	0.27	0.07
					C	0.26	0.33	0.43	0.45	0.37	0.09
VNLS	2a	2.0	76	11100	A	0.21	0.17	0.32	0.35	0.26	0.09
					B	0.21	0.21	0.31	0.34	0.27	0.07
					C	0.27	0.34	0.45	0.47	0.38	0.09

Table 5. Summary of space availability, uniformity, average ground contribution, and probability of discomfort glare for all variations and position C in both VNLS and real windows (RW) scenes with $\Phi = 11100$ lm

Conf.	IA (°)	BA (°)	Φ (lm)	%A	U_0	% G_{av}	PDG $_{av}$
1a	RW – 10000 cd/m²			70	0.19	51	0.42
1a	2.0	38	11100	32	0.21	61	0.43
1a	1.5	38	11100	33	0.23	59	0.45
1a	1.0	38	11100	34	0.26	55	0.46
1a	RW – 3200 cd/m²			27	0.16	51	0.36
1a	2.0	76	11100	31	0.28	50	0.38
1a	1.5	76	11100	32	0.30	47	0.39
1a	1.0	76	11100	32	0.32	44	0.39
1a	RW – 1800 cd/m²			14	0.18	50	0.34
1a	2.0	114	11100	28	0.37	49	0.35
1a	1.5	114	11100	29	0.37	47	0.35
1a	1.0	114	11100	30	0.37	45	0.35
2a	RW – 10000 cd/m²			63	0.17	48	0.43
2a	2.0	38	11100	35	0.23	59	0.44
2a	1.5	38	11100	35	0.25	57	0.46
2a	1.0	38	11100	32	0.28	55	0.47
2a	RW – 3200 cd/m²			30	0.15	50	0.37
2a	2.0	76	11100	34	0.32	49	0.38
2a	1.5	76	11100	34	0.33	47	0.39
2a	1.0	76	11100	33	0.35	44	0.39

2a	<i>RW – 1800 cd/m²</i>			<i>15</i>	<i>0.16</i>	<i>48</i>	<i>0.35</i>
2a	2.0	114	11100	29	0.36	48	0.35
2a	1.5	114	11100	31	0.36	46	0.35
2a	1.0	114	11100	31	0.38	45	0.35

Table 6. Summary of mean, minimum, maximum, standard deviation, and 95% confidence level of the output and the most influential input variable(s)

Input	Output	Mean	Min.	Max.	SD	Conf. 95%
$\Phi = 6200$ lm		10	1	16	3	2
$\Phi = 11100$ lm	%A [%]	32	28	35	2	1
$\Phi = 19900$ lm		70	56	84	9	4
BA = 38°		0.24	0.21	0.28	0.02	0.01
BA = 76°	U_0 [-]	0.32	0.28	0.35	0.02	0.01
BA = 114°		0.37	0.36	0.38	0.00	0.00
BA = 38°		57	54	61	2	1
BA = 76°	%G _{av} [%]	47	44	50	2	1
BA = 114°		46	44	49	2	1
BA = 38°		0.45	0.40	0.51	0.03	0.01
BA = 76°	PDG _{av} [-]	0.39	0.36	0.42	0.02	0.01
BA = 114°		0.35	0.32	0.38	0.02	0.01

Table 7. Ratio of %A, U_0 , % G_{av} , of each VNLS configuration to those of real windows with the same average surface luminance; and ratio of PDG $_{av}$ at position C in real windows scene to that in VNLS scene with the same average surface luminance, with $\Phi = 11100$ lm

Conf.	IA (°)	BA (°)	Φ (lm)	$\frac{\% A_{\text{VNLS}}}{\% A_{\text{RW}}}$	$\frac{U_{0 \text{ VNLS}}}{U_{0 \text{ RW}}}$	$\frac{\% G_{av \text{ VNLS}}}{\% G_{av \text{ RW}}}$	$\frac{\text{PDG}_{av \text{ RW}}}{\text{PDG}_{av \text{ VNLS}}}$
1a	2.0	38	11100	0.5	1.1	1.2	1.0
1a	1.5	38	11100	0.5	1.2	1.1	0.9
1a	1.0	38	11100	0.5	1.4	1.1	0.9
1a	2.0	76	11100	1.1	1.7	1.0	0.9
1a	1.5	76	11100	1.2	1.8	0.9	0.9
1a	1.0	76	11100	1.2	2.0	0.9	0.9
1a	2.0	114	11100	2.0	2.1	1.0	1.0
1a	1.5	114	11100	2.0	2.1	0.9	1.0
1a	1.0	114	11100	2.1	2.1	0.9	1.0
2a	2.0	38	11100	0.6	1.3	1.2	1.0
2a	1.5	38	11100	0.6	1.4	1.2	0.9
2a	1.0	38	11100	0.5	1.6	1.1	0.9
2a	2.0	76	11100	1.1	2.1	1.0	1.0
2a	1.5	76	11100	1.1	2.1	0.9	0.9
2a	1.0	76	11100	1.1	2.3	0.9	0.9
2a	2.0	114	11100	2.0	2.2	1.0	1.0
2a	1.5	114	11100	2.1	2.3	1.0	1.0
2a	1.0	114	11100	2.1	2.3	0.9	1.0