

## SPACE AVAILABILITY OF BUILDINGS WITH VIRTUAL NATURAL LIGHTING SOLUTIONS

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### ABSTRACT

Natural light is highly variable and limited in time and space. In situations where it is not or insufficiently available, Virtual Natural Lighting Solutions (VNLS) can be promising. This paper presents research based on computer simulation to explore the space-gaining potential of VNLS in offices, healthcare facilities, and industrial halls. The models are developed and simulated using the *Radiance* lighting simulation tool. The space-gaining potential of the virtual windows is determined by comparing space availabilities, i.e. the percentage of space with workplane illuminance more than a certain level, in situations with either real windows or virtual windows only. Criteria concerning visual comfort glare indices and luminance ratios are also considered. The paper demonstrates a comparison of space availability and visual comfort in some building types with virtual windows, compared to those of real windows with CIE overcast sky. The building type with the largest space availability and relatively low glare indices will be considered as the one with the biggest potential.

Keywords: e.g. Virtual natural lighting solution, space availability, visual comfort, buildings, virtual window

### 1. INTRODUCTION

Many researchers have shown the benefit of daylight with regard to health and well-being. In general, people with sufficient access to daylight perceive less stress, have a higher productivity, and are more alert (e.g. Boyce, 2003; Heschong et al., 2002; Heschong, 2003). In cases where natural light is unavailable, for instance during nighttimes or in deeper part of buildings, the Virtual Natural Lighting Solutions (VNLS) concept can be promising. VNLS 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. The benefit of installing VNLS in a building is the ability to use spaces which have very limited or no access to daylight, with the possibility to control the lighting and view quality.

The concept of VNLS is new and the real, ideal product does not yet exist at the moment. Some forms of virtual windows and skylights are available at the moment, but they are only able to meet parts of the natural light expectation (Mangkuto et al., 2011, 2013). Investigation on the psychological effects of virtual windows is still an ongoing process, for example, in the experiments of IJsselsteijn et al. (2008), de Vries et al. (2009), and Shin et al. (2012). While the relationship between currently available virtual windows and user perception is being investigated, there is very little known about the potential of virtual window system application related to building performance. The potential here is defined as the gain of performance of a given building with virtual windows, compared to that of the same building with only real windows.

The objective of this paper is to determine the potential, in terms of gained sufficiently 'daylit' area and visual comfort performance of VNLS, in some selected building types and sizes, i.e.

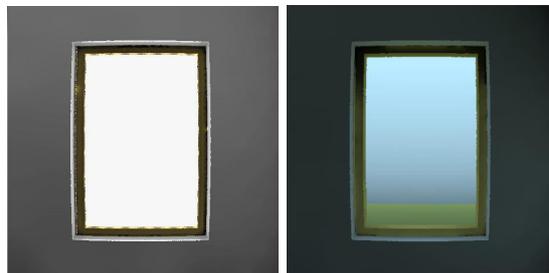
offices, healthcare facilities, industrial halls, and retail/shop. Comparisons to real windows are also shown to predict the lighting performance of both VNLS and the corresponding real windows of equal surface luminance. It is then important to have a clear understanding that the proposition is not to replace any real windows with VNLS. Instead, VNLS are proposed for solving the problem in spaces with no (or very limited) access to daylight.

## 2. METHODS

### 2.1. Windows model

The VNLS are modelled with a ‘simplified’ view (no detailed view) and diffuse light in *Radiance*, using the standard ‘light’ material to form a single, large light emitting area, with a uniform surface luminance. This technique is applicable to model a relatively simple virtual window, where the intensity of each light source (for instance, tubular fluorescent lamp) is equal, for instance as used in the experiments with users by de Vries et al. (2009). The window is then modelled as boxes constructed with a ‘light’ material with certain red, green, and blue radiance components [ $\text{W}/\text{m}^2/\text{sr}$ ], which in turn corresponds to an average surface luminance of  $1800 \text{ cd}/\text{m}^2$  and white colour display. This value corresponds to the middle value in the experiments of Shin et al. (2012).

For real windows scenes, the CIE overcast sky was generated using the *Gensky* programme in *Radiance*. Float glass with light transmission of 90% is assigned for the window surface interior. The surface luminance is between  $500$  and  $3000 \text{ cd}/\text{m}^2$ , depending on the observer’s position. The front views of both window types are displayed in Figure 1.



**Figure 1 – Front views of the modelled VNLS (left) and the real window (right)**

For all office rooms, a Window-to-Wall Ratio (WWR) of 20% or 30% was chosen, based on Ozdemir (2010) and Keighley (1973). Rooms are provided with windows on one side of the wall.

### 2.2. Buildings model

This paper focuses on offices, healthcare facilities, industrial halls, and retail buildings; resulting in a broad spectrum containing the most frequently found building types. According to van Meel (2000), typical offices in continental Europe (except the United Kingdom) have narrow floor plans, linear shapes, and are highly compartmented. Offices in the United Kingdom are more similar to their American counterpart, with deeper floor plans and often open-plan layout. Most offices have a core, which is the portion of the building that are not rented but serve all tenants indirectly, e.g. public restrooms, electrical distribution, elevator shafts, and stairwells. In most buildings, these elements are close together, typically near the centre of the building.

Concerning healthcare facilities, while most patient rooms have real windows on one side of the wall, VNLS can possibly be applied on the opposite wall. Dowdeswell et al. (2004) stated that the majority of European patient rooms are multi-bedded, although there is a trend towards single-bedded (EuHPN, 2004). In the United States, there is also a trend towards single-bedded patient rooms (Chaudhury et al., 2003). In this work, only a multi-bedded patient room and a large ward for intensive care units were simulated.

Industrial halls differ very much in dimensions between and within countries. Only the height seems fixed, generally around 7.5, 12, or 18 m (Philips, 2012). Many industrial halls have saw-tooth, sloped, or flat roofs; in this case only the saw-tooth roof type was simulated. VNLS can possibly be applied during nighttimes, for the benefit of the night-shift workers.

Table 1 gives an overview of the simulated building types with their internal dimensions.

**Table 1 – Simulated building types and their dimensions**

<b>Building type</b>	<b>Dimensions [m]</b>
Office – individual (reference)	5.4 × 3.6 × 2.7
Office – open-plan with core	32 × 32 × 2.7, core 14 × 14
Office – open plan without core	31.3 × 22.0 × 2.7
Healthcare – patient room	10.1 × 4.5 × 2.7
Healthcare – intensive care unit	13.5 × 7.8 × 2.7
Industrial hall	56 × 32 × 7.5
Retail – small shop	4.0 × 8.0 × 3.5

### 2.3. Performance indicators

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

1. *Space availability (%A)*: the percentage of workplane area with illuminance larger than or equal to the minimum criterion. The %A is the percentage of the number of points with illuminance satisfying the criterion ( $n(E \geq E_{crit})$ ), compared to the total number of points on the workplane ( $N$ ). In all building types,  $E_{crit}$  is 500 lx on the workplane; except in the healthcare facility, where it is 300 lx on the bed level.

$$\%A = \frac{n(E \geq E_{crit})}{N} \times 100\% \quad (1)$$

2. *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), which are calculated with the *Evalglare* programme. DGI is normalised into  $DGI_n$ , UGR into  $UGR_n$ , and CGI into  $CGI_n$ , following the normalisation procedures of Jakubiec and Reinhart (2012), to determine the ‘probability of discomfort glare’. The average of these four normalised glare indices is reported as the average probability of discomfort glare ( $PDG_{av}$ ).

$$PDG_{av} = (DGP + DGI_n + UGR_n + CGI_n) / 4 \quad (2)$$

Simulations were run individually in *Radiance* for every variation of the VNLS. *Evalglare* (Wienold and Christoffersen, 2006) was employed to calculate glare indices at several observer

positions in each building type. The  $PDG_{av}$  at the worst position, i.e. usually the one directly facing the window, is reported.

To evaluate the performance of all VNLS variations, some performance criteria were applied on the relative comparison between performance indicators of the VNLS and the real windows. These were based on the expected benefit of having VNLS, i.e. gaining more well-lit and uniform space; while maintaining the probability of discomfort glare comparable to those in real windows scenes. The criteria were defined in terms of a ratio, which was evaluated until one significant digit, i.e.:

- The VNLS should create larger space availability, compared to the real windows.
- The VNLS should create equal or smaller average probability of discomfort glare as observed in the worst position, compared to the real windows.

These criteria are expressed in mathematical forms as follows, where the subscripts V and R correspond to VNLS and real windows, respectively.

$$\frac{\%A_V}{\%A_R} > 1.0 \quad (3)$$

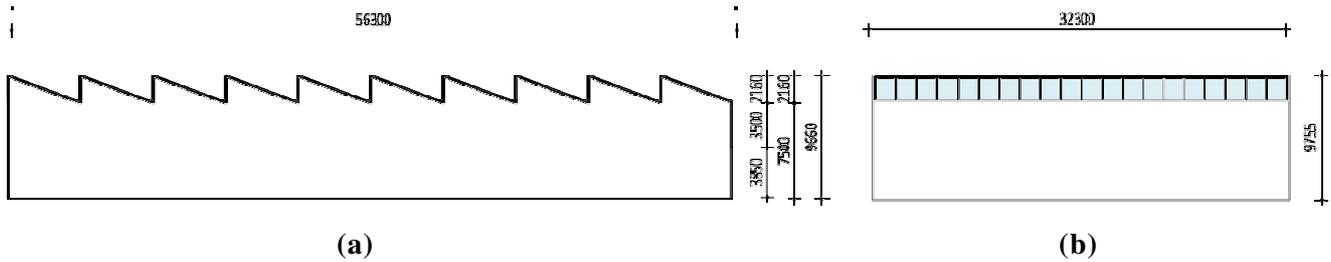
$$\frac{PDG_{av R}}{PDG_{av V}} \geq 1.0 \quad (4)$$

### 3. RESULTS AND DISCUSSION

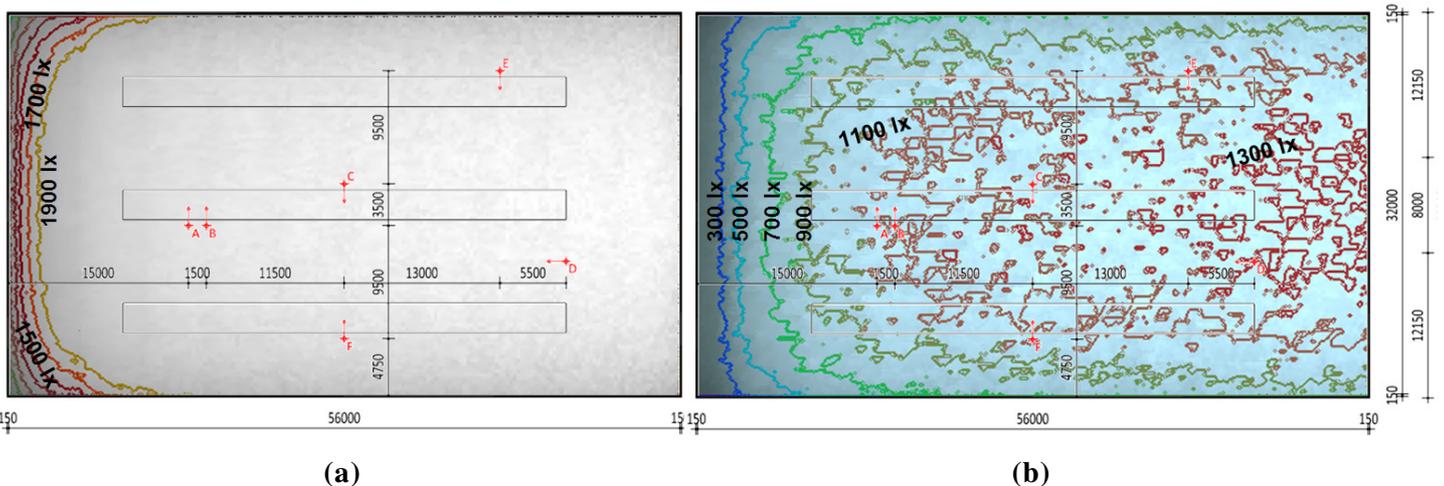
A summary of the space availability and average probability of discomfort glare in each building type with VNLS and real windows is given in Table 4.

**Table 4 – Space availability of all building types with VNLS and real windows**

Building type	$\%A_V$ [%]	$\%A_R$ [%]	$\frac{\%A_V}{\%A_R}$	$PDG_{av V}$ [-]	$PDG_{av R}$ [-]	$\frac{PDG_{av R}}{PDG_{av V}}$
Individual office, 1 window, WWR = 20%	13	10	1.3	0.34	0.33	1.0
Individual office, 1 window, WWR = 30%	30	19	1.6	0.34	0.33	1.0
Individual office, 2 windows, WWR = 20%	20	9	2.1	0.33	0.34	1.0
Individual office, 2 windows, WWR = 30%	32	20	1.6	0.34	0.34	1.0
Open-plan office, with core	17	8	2.1	0.36	0.35	1.0
Open-plan office, without core	10	4	2.3	0.38	0.36	1.0
Patient room	38	21	1.8	0.40	0.42	1.0
Intensive care unit	12	7	1.8	0.36	0.39	1.1
Industrial hall, saw-tooth roof	100	92	1.1	0.32	0.33	1.0
Small shop	27	18	1.5	0.36	0.34	0.9



**Figure 2 – Section views of the simulated industrial hall along the (a) long and (b) short walls**



**Figure 3 – Illuminance contour lines on the workplane in the simulated industrial hall: (a) with VNLS and (b) with real windows**

To give an example, Figure 3 illustrates the illuminance contour lines on the workplane in the simulated industrial hall with saw-tooth roof, of which section views are given in Figure 2, with VNLS and with real windows. Under the scene with VNLS, the entire workplane has an illuminance value of larger than 500 lx; hence its space availability is 100%. With real windows, the 500 lx contour line is still visible, and the area with illuminance above this level is 92%, giving a ratio of 1.1 between the VNLS and real windows. Nonetheless, the average probability of discomfort glare at the worst position (in this case position F) under both scenes is very similar, as shown by the ratio of 1.0. Also note that the windows are placed at about 7.5 m from the floor, way above the occupants' line of sight. Therefore, no significant concern of discomfort glare would be expected.

From Table 4, it is seen that the VNLS generate larger space availability in every simulated building type, as compared to the real windows. The largest ratio (2.3) is achieved by the open-plan office without core, while the smallest (1.1) is achieved by the industrial hall. Nonetheless, as illustrated in Figure 2, the industrial hall actually has the largest absolute value of space availability, due to the large amount of windows installed near the roof.

In terms of glare perception, VNLS and real windows in all building types give relatively similar results, shown by the ratios which range between 0.9 and 1.1. This suggests that relative to the corresponding real windows, the VNLS generally create comparable average probability of discomfort glare. This is expected, since the average surface luminance of both the VNLS and the corresponding real windows are set to be equal.

#### 4. CONCLUSIONS

This paper explains how future solutions such as VNLS have the potential of gaining ‘daylit’ area, without losing visual comfort, in some selected building types. In general, the simulated VNLS generate larger space availability, compared to real windows with equal surface luminance, in the selected building types. The largest ratio (2.3) is achieved by the open-plan office without core, while the smallest (1.1) is achieved by the industrial hall. The industrial hall however has the largest absolute value (100%) of space availability, due to the large number of windows installed near the roof. Both VNLS and real windows give similar results of discomfort glare in all building types.

Adding VNLS in non-daylit spaces has the potential of gaining effective building space. This paper shows that VNLS can even outperform real windows on some aspects. It is noticed that the described work in this paper reports only a part of the VNLS concept evaluation, based on the selected performance indicators using computational simulation tools. Additional studies involving more detailed image scenes on the VNLS, different sky conditions, as well as more features of real daylight, are required to improve the degree of similarity to real windows. Moreover, further subjective evaluation with users is also required to understand how people will actually appraise VNLS in reality.

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