ABSTRACT
Several studies have shown that natural light is preferred over electrical lighting in built environments. It has positive effects on user satisfaction, health, and energy saving. However, natural light is limited by time and space. A possible solution is to apply the new concept of virtual natural lighting solutions that ideally can artificially provide natural lighting and views, with all of their properties.

Computational modelling has the potential to steer the innovation process and early feasibility testing of this solution. Several available modelling approaches are reviewed, examining their ability to predict performance indicators of the system, in terms of lighting, view, space availability, thermal comfort, and energy consumption.

INTRODUCTION
Human beings have a strong preference for natural light. Several studies have shown that natural light is highly preferred over electrical lighting in the built environment for its positive effects on user satisfaction and health (e.g., Galasu and Veitch, 2006; Aries et al., 2010). Natural lighting solutions in buildings provide a view with information about the outside situation, such as time of the day and weather condition. They also have the potential to save on electrical energy by reducing artificial lighting energy consumption by 50% to 80% (e.g., Bodart and De Herde, 2002; Mardaljevic et al., 2009).

However, natural light is highly variable and limited by time and space. For instance, as a general rule of thumb, useful natural light will only reach a distance of 2.5 times the height of the top of the window above the workplane. According to Dutch regulations, admission of natural light into work places is strongly recommended. On the other hand, usable floor space in buildings is practically limited in depth, as farther depths would contradict the recommendations.

Furthermore, significant fractions of the working population in the world do their work during nighttime (Lockley, 2009). Night shift workers experience various discomfort issues, such as sleep problems, fatigue, and poor performance. They even have an increased long-term risk of some types of cancer due to a lack of synchronisation between the shift work schedule and the worker’s light-dark cycle (Stevens, 2009; Blask, 2009).

A possible way to overcome those problems is to develop and apply a Virtual Natural Lighting Solution (VNLS). A VNLS is a not-yet-existing system that ideally has the possibility to provide virtual natural lighting and realistic outside scene view, with all of its properties. This can be applied and integrated inside new and/or existing buildings.

One of the first challenges in developing such solutions is modelling their behaviour, and predicting their impact on spatial use and performance of buildings. In general, modelling is known as the act of constructing a schematic description of a system, theory, or phenomenon. Simulation is the act of manipulating a model in such a way that it operates on time or space, so that it can be studied to see how the system works. By changing variables, predictions can be made about the behaviour of the system.

Computational modelling and simulation can be used for steering the innovation process and early feasibility testing of new systems, with considerably lower required time and cost than real prototyping. These also include VNLS.

The objective of this work is to review available computational modelling approaches to predict and optimise performance indicators of the developed model of a VNLS. These are expected to be applicable in buildings.

STATE OF THE ART
For quantifying natural light, Dubois (2003) suggested a number of simple performance indicators, i.e. workplane illuminance, illuminance uniformity, and luminance ratios. For design purposes, Reinhart et al. (2006) suggested illuminance-based dynamic performance metrics such as daylight autonomy, continuous daylight autonomy, and useful daylight index. Pati et al. (2009) suggested performance indicators related to general work place lighting, classified in terms of energy efficacy, task lighting, view to outside, and
visual comfort. Other aspects are also considered to describe indicators of the work environment, in terms of thermal comfort, energy, and maintenance. Related to the VNLS, different modelling approaches are required to predict and optimise performance indicators. The approaches can be classified into five aspects that are considered important to the building environment where the solutions are placed in. Those aspects are lighting, view, space availability, thermal comfort, and building energy.

**Lighting**

In general, lighting simulation can be divided into two main types (Ochoa et al., 2011). The first type is photorealistic rendering, which produces images that are mostly used in the artistic sense. The second type is physically based visualisation, which produces physically accurate representation and predicts reality under given conditions (Ward and Shakespeare, 1998; Moeck and Selkowitz, 1996).

Lighting simulation algorithms and their supporting calculation methods have different classifications. Each has their own specific applications and limitations (Ochoa et al., 2011). The most generally used algorithms are:

- **Direct calculations used for artificial lighting**: these are specific physical formulas and simplifications, often delineated in national standards to cover most usual illumination situations. The algorithms are simple and often used as rules-of-thumbs, but can lack on accuracy in the real situation.

- **View-dependant algorithms**: these are classified based on direction from which tracing rays are computed; i.e., from the light source (forward tracing), from the observer’s eyes (backward tracing), or from light source and observer (bidirectional raytracing). They are used for lighting calculations and renderings, and require a specific observer position.

- **Scene-dependent algorithms**: these are mainly radiosity calculations, adapted from heat transfer techniques. They are mainly used for calculations but not for rendering due to complex formulas.

There are some examples where two or more algorithms are combined, to increase efficiency and accuracy of the results. For example, in the Radiance model, backward ray-tracing is used to compute radiance values for a scene, while radiosity is used to store scene values (Ward and Shakespeare, 1998). In the photon map algorithm, packets of energy (photons) are used to compute radiosity and raytracing values (Jensen, 1996).

For calculation aids, the most widely used techniques are Monte Carlo methods. They assume the expected value of the sample is its correct value, and an average of estimates completes the solution. Algorithms must run for enough time to take many samples. Monte Carlo techniques have accuracy limitations, but sometimes are the best way to solve certain physical problems (Dutre et al., 2006).

As reported in Maamari et al. (2005), the CIE technical committee 3.33 has defined a set of simple test cases. They are based on analytical or experimental references, with the objective of assessing lighting computer programs. It has been shown that the use of the CIE test cases allow verifying the level of accuracy of the tested programmes with respect to lighting physical laws. Maamari et al. (2005) suggested that a single ideal lighting programme does not exist, but some programmes are adapted to given tasks and constraints. For Radiance, good accuracy was observed in general, except for the indirect lighting test with reflectance values of 0.8 and above.

Based on these observations, the Radiance model was chosen for lighting simulation of the case study that is discussed in the next section.

**View**

Initial investigations in identifying and testing the perceptual elements essential in creating a convincing virtual natural light opening, or virtual window, have been done. Such investigations have been done, for instance, by Ijsselsteijn et al. (2008), Friedman et al. (2008), and Kahn et al. (2008).

Ijsselsteijn et al. (2008) had studied the contribution of three monocular depths cues, i.e., motion parallax, occlusion and blur, to the illusion that a wall projected scene affords a window-like ‘see-through experience’. Results indicated that all three cues have a significant main effect on the viewer's 'see through experience', with motion parallax yielding the greatest effect size. However, many other sources of sensory information are still of relevance in creating a convincing window substitute, but will not be taken into account initially.

In order to model the view of lighting scenes, various methods have been developed in recent years to couple direct input from reality into lighting simulation models. Two of these methods are the use of photography to reconstruct a scene in a digital
model, and the use of High Dynamic Range (HDR) photography for scene analysis (e.g., Debevec and Malik, 1997).

In computer graphics scene rendering, HDR is a technique done in a larger dynamic range, to preserve details that may be lost due to limiting contrast ratios. Images produced can be used for further analysis or processing, i.e. for surface luminance analysis. The remaining challenge is how to find the correct tone mapping solution to compress the large dynamic range of the image to fit into the display range, so that the displayed image can represent the original scene in an appropriate way.

For the basis of colour computation in computer graphics, RGB (red, green, blue) combinations are often used. Basically, those are metamers in a virtual environment for the spectral power curves of light in the real world. The rendering software internally defines the CIE chromaticity coordinates of the RGB values (Inanici, 2003). CIE XYZ data for each pixel can be quantified from RGB through a series of conversions that involve the sampling of the spectral curve using the CIE 1931 (2° observer) colour matching functions (Hall, 1999).

Inanici (2003) introduced an image-based lighting analysis procedure and tool called Virtual Lighting Laboratory (VLL). This is a computer environment where the user has been provided with matrices of illuminance and luminance values extracted from HDR images. In VLL, per-pixel illuminance or luminance data extracted from physically based renderings are processed through mathematical and statistical operations. They perform lighting analysis with more detail and flexibility, compared to the traditional lighting analysis approaches. Analysis in the VLL focuses on investigations of the criteria to achieve the intended visual effect, performance, and comfort.

Related to the VNLS application, the extracted data can be used further analysis, for example to analyse luminance ratios in the visual field. These include foveal, binocular, and total vision; when the viewer is looking at different tasks. Luminance ratios can also be used to indicate directionality, which are described in directional-to-diffuse luminance ratio (Inanici and Navvab, 2006). Further analysis using numerical computation environment is yet required.

Space Availability

As suggested by Inanici and Navvab (2006), per-pixel data analysis allows even more detailed study. For instance, it can be used to calculate the Virtual Criterion Rating (VCR). This measure quantifies the probability that a specific (lighting) criterion is met within a defined space or area (Rea, 2000), as described in Equation (1).

\[
VCR = \frac{\text{Number of pixels satisfying criterion in space / surface}}{\text{Total number of pixels}} \times 100\%
\]  

Availability of a true Virtual Natural Lighting Solution would make it possible to use interior windowless spaces in buildings more effectively. For indicating space availability in the case of VNLS, the VCR may be applied to describe how much additional space can be used for working (e.g., on paper or computer task). This is due to enhancement of the lighting and view quality, after installing the VNLS in a given building space. The idea is to show the comparison between the VCR of a given space before and after the installation, in terms of task illuminance and surface luminance. Therefore, we propose a new performance indicator, namely Space Availability Ratio (SAR) in a given space at a given time, which is defined in Equation (2).

\[
SAR = \frac{VCR \text{ in a space after the VNLS installation}}{VCR \text{ in a space before the VNLS installation}}
\]

Thermal Comfort

Due to the fact that any artificial lighting solutions also generate heat, it is considered necessary to take indoor thermal comfort into account. There is several thermal comfort modelling methods, which examples are:

- **Whole body energy balance model**: this method assumes no thermoregulatoric effects covered; and considers a body as a whole, with reference to the concept introduced by Fanger (1970). Uniform, steady state conditions are achieved near thermal neutrality. The International Standard ISO 7730 uses Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices to calculate the thermal sensation of people exposed to moderate thermal environments, as well as to specify acceptable thermal environmental conditions for comfort (ISO, 2005).

- **Adaptive model**: this method assumes adjustments to oneself or surroundings to reduce physiological strain, either with conscious actions (e.g., clothing, activity level, ventilation) or with unconscious actions (e.g., shivering, sweating).

- **2-node model**: this method takes physiological responses to transient situations into account, and considers human as two concentric thermal compartments, i.e., skin and core (Gagge et al., 1986).

- **Equivalent temperatures / steady state in non-uniform conditions model**: this method assumes transformation of local different conditions to uniform cases.
compared to current boundary conditions (Wyon, 1989; Bohm, 1990).

Most building energy simulation programmes currently have the option to evaluate thermal comfort with the conventional whole body energy balance. These evaluation mechanisms have been set up for steady state, office-like environments, which are likely to be the case for VNLS applications. Therefore, the whole body energy balance method is considered sufficient for modeling thermal comfort of users in buildings where VNLS is applied.

Building Energy

Energy calculations provide a basis to calculate the economic viability of a building component solution. They mainly focus on average or typical conditions. They take into account whole year (annual) performance or multiple years’ consumption (Hui, 2009). Energy calculation methods can be generally classified into two categories:

1. Steady-state methods; can be classified further into:
   - Degree-day method; employs degree-day, i.e., the sum of the number of degrees that the average daily temperature is above (for cooling) or below (for heating) a base temperature times the duration in days. The degree-days are summed over a period or a year for indicating climate severity (effect of outdoor air on a building).
   - Variable based degree-day (VBDD) method; employs degree-day with variable reference temperatures to account for different building conditions and variation between daytime and nighttime. It requires tedious calculations and detailed processing of hourly weather data at a complexity similar to hourly simulations.
   - Bin and modified bin methods; derives building annual heating or cooling loads by calculating its loads for a set of temperature “bins”. For example, i.e. by multiplying the calculated loads by numbers of hours represented by each bin (e.g. 18~20, 20~22, 22~24°C). It totals the sums to obtain the loads. Original bin method does not take solar/wind effects into account, while the modified one does.

2. Dynamic method; this method tries to capture dynamic response of buildings, usually done on an hour-by-hour basis, by using computer-based building energy simulation. It can be developed based on transfer function and heat balance, and is applied by most building energy simulation tools.

Most building energy simulation tools nowadays use the dynamic method. This method will also be used for modelling the thermal performance of VNLS cases. Various tools are available either as free (simplified or detailed) or as commercial (proprietary) softwares. Some examples of simplified free tools are Energy-10, ENER-WIN, Solar-5, and EnergyScheming; while examples of detailed free tools are DOE-2, BLAST, ESP-r, VA114, and EnergyPlus.

CASE STUDY

A few modelling approaches were evaluated to show how they can work when modelling a VNLS. A case study was taken, where performance of a real (vertical) window is compared with that of a virtual one. For the preliminary case study, a simple office environment was used. It had two windows on the west façade, and corresponded to an experimental room for which measurement data are available by De Vries (2009). It was chosen to be modelled and simulated for lighting aspect, as real-life performance data is known. It was also modelled and simulated to evaluate direct impact of the real and virtual windows installation to the thermal comfort and building energy consumption.

Lighting

For lighting simulation, horizontal illuminance at the workplane will be taken into account as indicator. The real illuminance measurements were conducted by De Vries (2009) in Laboratory of Building Physics and Systems in Eindhoven University of Technology, the Netherlands, on 21 June 2008 at around 10.00 hrs. The weighted average reflectance value of the inside room surface is 0.75. A floor plan of the experiment room is displayed in Figure 2.

Two scenarios were measured: (1) two real windows with clear glass in the west façade without screens, and (2) two large luminous areas (i.e. Philips Strato luminaires) which were placed behind diffuse screens. The large luminous areas simulated the window locations, and considered as virtual windows in this case. For all scenarios, general artificial lighting (eight Etap Lighting TL fluorescent lamps), was on all the time.

![Figure 2 Floor plan of the experiment room](image-url)
The actual sky condition during the measurement was not known. It was estimated using an integrative backward ray-tracing approach with CIE overcast and/or intermediate (partly cloudy) skies. For CIE overcast sky modelling, the zenith brightness was estimated until the closest result with the real measurement was obtained. The results graphs for the first scenario (daylight without diffuse screens) are given in Figure 3. It is found that a zenith brightness of 60 W/sr/m² will give results close to the real measurement. The maximum difference between real and simulated values is 9% at 1 m from the window.

For the second scenario (large luminous areas behind diffuse screens), the choice of the sky condition did not influence the indoor illuminance, as the virtual windows completely blocked the natural light coming from outside. The results graph is given in Figure 4. The obtained simulated values trend is in line with the real values trend, showing good agreement, with a consistent difference between real and simulated values. The maximum difference between real and simulated values is 18% at 1 m from the window.

Thermal Comfort and Building Energy

ESP-r was used to calculate thermal comfort indicators of the same office space. It also was used to obtain annual heating, cooling, and electrical energy demands. Three scenarios were studied: (1) two real windows; (2) two virtual windows (large luminous areas behind diffuse screens); and (3) no real nor virtual windows (closed box). For all scenarios, general artificial lighting was switched on all the time.

The room was modelled as one zone (z1), with two adjacent zones, as displayed in Figure 5. The additional zones (z2 and z3) were modelled to represent the real situation, where the experimental room was located between two adjacent rooms with the same façade orientation. Two 1.2 m × 1.2 m windows were added on the west façade of z1 in scenario 1. The virtual windows were modelled as additional eight fluorescent lamps behind a screen (with total heat gain of 16 W/m²). They were considered as small equipments in scenario 2.

Basic heating and cooling controllers and setpoints, i.e., 21°C and 23°C, were applied for all zones from 07.00 until 21.00 hrs on every weekday. Each fluorescent lamp (in the general lighting and in the virtual windows) was assigned to use 28 W of electrical power input.
The thermal comfort indicators, i.e., Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) for the three scenarios are given in Table 1. Data are given in maximum, minimum, and average values in one year. The minimum values of PMV, as well as the maximum and minimum values of PPD, were achieved during the unconditioned hours (i.e., time between 21.00 until 07.00 hrs).

![Table 1](image)

The annual energy demands, as well as the number of hours required for the three scenarios are given in Table 2. Total energy consumed in each scenario is the sum of energy demands for sensible heating, sensible cooling, lighting and equipment for the whole year.

![Table 2](image)

DISCUSSION

Based on state of the art of the lighting modelling approaches, it can be seen that it is necessary to combine two or more simulation algorithms. Applying only one algorithm at a time will be ineffective in terms of completeness, calculation time, and results accuracy. The CIE test cases showed that in general Radiance has good accuracy, except in the indirect lighting test with reflectance values of 0.8 and above (Maamari et al., 2005). This suggests further test case may be required, particularly to evaluate performance of VNLS application in spaces with high reflectance values.

As also suggested by Maamari et al. (2006), the new CIE set of test cases should be covering other aspects of lighting propagation, for example, the spectral and bidirectional effects of glazing materials and the influence of interior obstructing surfaces and exterior environmental conditions. These test cases are useful in the future for testing more advanced solutions.

An advantage of employing Radiance is its ability to create HDR image output, which can be processed further using per pixel data analysis for predicting the view indicators. Per pixel data analysis can be every useful in giving information about luminance ratios and distribution of the image details. The concept of VCR can also be used to determine space availability ratio, as a comparison between the indicators after and before installation of the solution.

Using lighting simulation for the real window case study, it was found that a high difference of simulated illuminance values (9%) appeared at 1 m from the windows. This can be explained due to the presence of instantaneous direct sunlight, which is not taken into account in the CIE overcast sky model. A good match of real and simulated values was found at points farther from the windows in both scenarios. At that distance the influence of direct sunlight in the real window scenario was no longer significant.

The large difference (up to 18%) of real and simulated values in virtual windows scenario is possibly caused by the luminous distribution of the general lighting which is not exactly matched with the manufacturer specification. At the back of the room, virtual windows could give approximately the same illuminance values as the real windows did. To obtain higher illuminance values and more evenly distributed light, it is suggested to install one or more different kinds of virtual windows.

Concerning thermal comfort simulation, the conventional whole body energy balance method is still likely to be applied for its simplicity on the calculation. For building energy, the dynamic method, which tries to capture dynamic response of buildings, is most likely to be applied due to its advantage on accuracy and practical availability.

Based on the building energy simulation of the case study, installation of two large luminous areas as virtual windows resulted in lower annual heating energy and higher cooling energy. Virtual windows also act as heat sources in the room. In total, the scenario gave slightly lower total annual heating and cooling energy demands (around 1770 kWh).
compared to that of the real windows scenarios (around 1800 kWh), see Table 2. However, the addition of virtual windows also increased the annual electrical (lighting and equipment) energy demand. The virtual windows scenario gave around 1170 kWh of total annual energy demand, twice as much as the real windows scenario, due to the addition of lighting and equipment (i.e., the virtual windows themselves).

The thermal comfort simulation showed that using virtual windows gave the best performance between the three scenarios, in term of average PMV (closer to zero value) and PPD (lower value). The maximum PMV value is obtained using the virtual window scenario. This is also very likely due to the heat produced by the lamps. Therefore, significant improvement to virtual window solutions is required, by optimising the generated heat and electrical energy demand, to achieve much better thermal comfort and building energy performance indicators.

CONCLUSION

Even though the VNLS concepts are still new and not fully tested yet, simulation methods can help in their development. Several modelling approaches are available to predict and optimise performance indicators of VNLS. In this case study, different aspects are taken into account in simulation to characterise properly the potential effects of VNLS. Concerning lighting, high variation of simulated illuminance values were found at points near the windows in the real windows scenario. For energy performance, using virtual windows resulted in lower annual heating energy but higher cooling energy demands, compared to real and no windows scenarios. The total (heating, cooling, and electrical) annual energy demand for the virtual window scenario was found to be the highest between the three scenarios. In term of thermal comfort (average PMV and PPD), virtual windows had the best performance between the three scenarios. The modelling approaches will be applied to improve the existing solutions, by optimising the relevant performance indicators.

For further research, it is suggested to investigate the view and space availability aspects. The concept of Virtual Criterion Rating (VCR) is important to indicate how much additional space can be used for working after installation of the VNLS. The ratio between the VCR of a given space after and before the VNLS installation, namely Space Availability Ratio (SAR), is proposed as a new performance indicator that will be investigated by employing modelling approach.

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