A DESIGN METHOD TO ASSESS THE ACCESSIBILITY OF LIGHT ON PV CELLS IN AN ARBITRARY GEOMETRY BY MEANS OF AMBIENT OCCLUSION

dr. A.H.M.E. Reinders
Department of Design Production and Management, Faculty of Engineering Technology,
University of Twente, The Netherlands, Phone: +31 (0)53 4893681/2520, Fax, +31 (0)53 4893631,
E-mail: a.h.m.e.reinders@utwente.nl

ABSTRACT: A design method has been developed by which the accessibility of light on PV cells in an arbitrary geometry can be quickly visualized and quantified. Modelling of irradiance in this method is based on ambient occlusion, which indicates the likelihood of shading of object's surfaces due to self-shading or due to surrounding objects. The design method can be easily implemented in 3D modelling software for designers and architects, enabling them to design products and buildings with integrated PV systems.
Keywords: Product design, Building integration, PV modules, Shading

1 INTRODUCTION

In this paper we will illustrate a design method which has been developed to quickly visualize and quantify the accessibility of light on PV cells in different geometries. It supports the integration of PV technology in arbitray products whether these are consumer products, vehicles, boats or buildings [1, 2, 3].

PV cells which are integrated in product surfaces may not be flat or they might be subjected to self-shading due to the product's geometry or shading due to surrounding objects. The resulting non-uniform irradiance of curved or shaded surfaces might affect the performance of PV cells. Hence, in order to estimate the suitability for integration of PV elements at object's surfaces, it might be necessary to evaluate the accessibility of light on PV cells in the design phase of product development.

Methods for irradiance calculations on shaded surfaces have been developed by Quasching and Hanitsch [4] using Waldram diagrams of the surroundings, and by Kovach and Schmid [5] using a ray-tracing technique. Both methods require a lot of time for the preparation of calculations. Though ray-tracing techniques are very accurate, their application requires much computing power, especially when scene renderings get large which is common in architectural design and urban planning [6]. Hence, it would be sensible to use a simulation technique which significantly reduces computing effort.

Ambient occlusion is relatively simple and time-efficient compared to other methods for radiance calclations such as radiosity, ray-tracing and photon-mapping, For this reason we have implemented ambient occlusion in our design method.

Apart from the shading pattern on PV cells, the effect of non-homogenous irradiance on the electrical performance of the shaded, interconnected PV cells – the PV array – can be calculated. The method presented in this paper has not yet focused on this topic, for which reason we refer to Karatope et al [7].

The method is implemented in a software tool named 3D-PV which is a plug-in for the widely-used 3D animation software 3D Studio Max (3DSM).

In Section 2 we will explain the basics of ambient occlusion and how it is implemented in the design method of 3D-PV. Next in Section 3 several examples will be shown of the use of 3D-PV. The paper will be completed by conclusions in Section 4.

2 AMBIENT OCCLUSSION

2.1 Ambient occlusion

Modelling of irradiance in 3D-PV is based on ambient occlusion as published by Zhukov et al. [8]. Ambient occlusion refers to the attenuation of ambient light due to the occlusion of nearby geometry. The occlusion value for any given point on a surface is proportional to the solid angle projected by all geometry over a hemisphere around that point. The general equation for the occlusion term, S, of a point, p, in a certain surrounding is as follows:

$$S(p,n) = \frac{1}{\pi}\int_{\Omega} V(p,\omega)\,|n\cdot\omega|\,d\omega$$

Here, Ω is a hemisphere around the surface normal n at point p. V(p,ω) is the visibility function which returns zero if no geometry is visible in direction ω and 1 otherwise, see Figure 1.

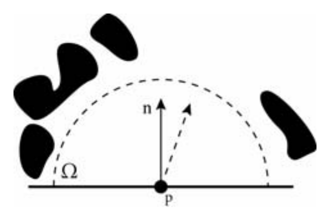


Figure 1: Point p and a hemisphere, i.e. sky dome, with occluding geometry.

In computer graphics (CG), ambient occlusion is related to accessibility shading. It is rendered in 256 shades of grey. Luminosity, the CG equivalent of radiance and luminance, is the average of the red, green and blue components. Greyscale colors are characterized by an equal value for the RGB components. Therefore to determine the luminosity of greyscale colors it suffice to evaluate a single component.

In the last decade movie industry and the production rendering community have put a lot of effort in refining and popularizing it, resulting in a mature technique which is available in most commercial CG, see Kontkanen and Laine [9].

2.2 Method of 3D-PV

In 3D - PV product geometry from a CAD program is combined with an environment with a certain luminance distribution. After applying ambient occlusion, results are being post processed, see Figure 2. Main results are the shades of grey representing luminosity of an object's surface.

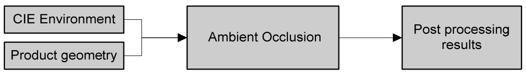


Figure 2: Scheme representing the procedure of 3D-PV.

In our method luminance distributions according to the CIE General Sky Standard from Darula an Kittler [10] are used. However, other arbitrary luminance distributions – of, for instance, indoor lighting - can be defined and used. For further processing in 3D Studio Max the simulated CIE irradiation distribution is is wrapped around a sky dome, see Figure 4.

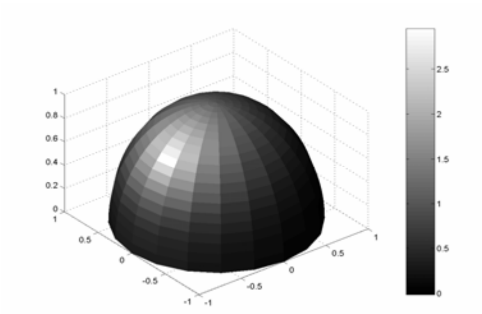


Figure 4: Spatial luminance distribution for a standard clear sky for a single solar position, wrapped around a sky dome in 3DSM.

Full isometric rendering of the occlusion can be necessary to identify areas of high irradiation on the product surface. By a feature in 3DSM an object can be rendered to a bitmap by flattening and separating the object's surface elements. In this way each surface element - more specifically PV cells - can be observed without geometrical distortion.

3 ILLUSTRATION OF THE METHOD

In this section we will illustrate the application of the method of 3D-PV by three examples.

3.1 Pocket calculator

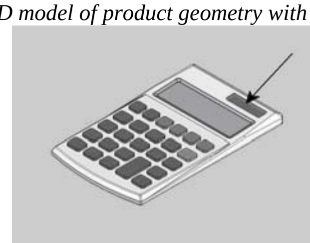
The following example in Figure 5 shows how the accessibility of irradiance on PV cells is calculated for the case of a PV powered pocket calculator with PV cells which are slightly sunken in the casing. A CAD model of the product geometry (a) is imported in 3DSM. Next the scene is rendered using ambient occlusion (b). Subsequently the illuminated PV surface is visualized as an bitmap of pixles with a grey scale ranging from 0 to 255 (c) showing the probability of shading by the grey value of the pixles.

Next, the mean luminosity value L_{mean} is calculated over the entire PV surface by averaging the grey values of the bitmap. This value is used to calculate the accessibility of light, A_{cc}, on the cell according to:

$$A_{cc} = \frac{L_{mean}}{255}$$

In the case of the pocket calculator A_{cc} = 91 %. Experimentally it can be proven that the accessibility term can be increased to 100 % by raising the PV cell to the same level as the calculator's casing.

a. CAD model of product geometry with PV cell



b. Scene rendering using ambient occlusion

c. Bitmap of PV cell

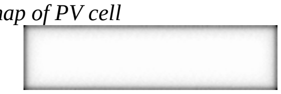


Figure 5: Procedure to determine the accessibility of light on PV cells in a pocket calculator under a luminous dome.

3.2 PV cells in curved surfaces

Curvature of a PV surface due to an object's geometry can be an important contributor to inhomogeneous irradiance distributions over PV cells. In this case study a PV surface with a constant bending radius is assessed. The PV element is placed under a uniform luminous dome. The orientation of the PV element is chosen to maximally cause inhomogeneous irradiance, while the PV surface is still facing upward, see Figure 6. The accessibility factor is measured at 3 locations.

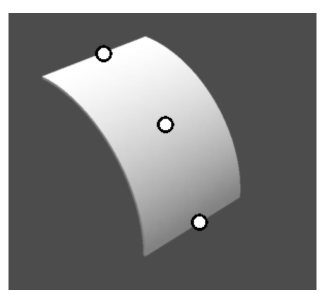


Figure 6: Curved PV element. Measurement locations are indicated with an "o".

In 3D-PV curved PV surfaces can be flattened and visualized as bitmaps. Figure 7 shows the front, side and back of two flattened flexible PV cells which are integrated in the PV surface shown in Figure 6. An assessment of the accessibility of light over the full area results in a relative measure for the inhomogenity of light based on the maximum and minimum value of

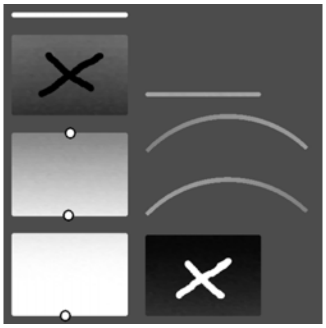


Figure 7: Bitmap of flattened PV element as shown in Figure 6. Areas marked with an X correspond with the backside of the PV element.

accessibility according to:

$$\frac{Acc_{min}}{Acc_{max}} = \frac{0.52}{1} = 0.52$$

Depending on the product application certain values of accessibility of light are required and other values might not be acceptable. Therefore, the method of 3D-PV enables to assess the effect of curvature on the accessibility on PV cells.

3.3 Building integration

The appearance of shading on building integrated PV systems can be evaluated by means of 3D-PV as is shown by the following example in Figure 8 showing a scene of a tree standing next to a dwelling. The accessibility of light has been rendered and a number of bitmaps of elements of which the scene is constructed is generated, see Figure 9. Each element represents a wall, roof part or part of the tree. The tree causes a shade on the lightened wall and the roof, which is shown by variation of the grey color on the elements in Figure 9.

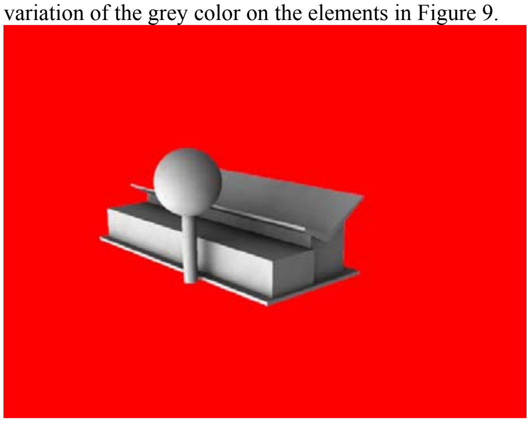


Figure 8: Dwelling with tree.

4 CONCLUSIONS

The design method of 3D-PV yields useful results in a rapid way for the assessment of accessibility of light on object-integrated PV cells and PV modules in an arbitrary geometry or surrounding.

Future activities will focus on improving 3D-PV by

- implementing irradiance data for monthly or yearly evaluations,
- implementing indoor lighting environments,
- dynamic simulation of product use, which is called scenario-based design, and
- the calculation of the electrical performance of shaded, interconnected PV cells.

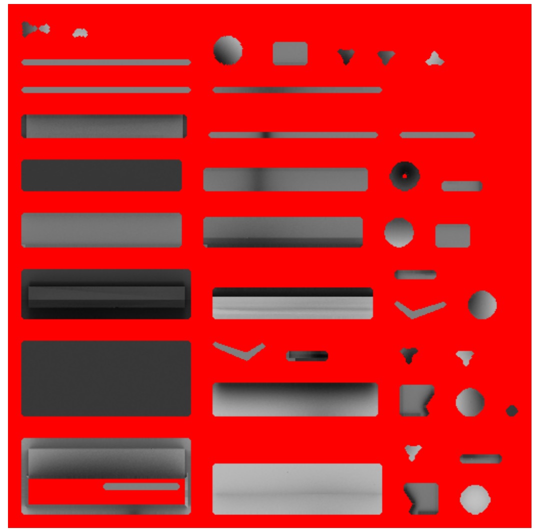


Figure 9: Bitmap of flattened elements of dwelling with tree as shown in Figure 8.

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