SIMULATION OF SKY LUMINANCE DISTRIBUTION FOR DAYLIGHTING STUDIES

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ABSTRACT

This paper reports on a project carried out at Delft University of Technology, for improvement of daylighting simulation tools. Earlier work involved the development of SIBE2, a prototype daylight simulation program using new computational concepts for daylighting simulation in order to overcome a number of well known disadvantages of present daylighting simulation tools. This project was concerned with the importance of realistic description of the sky luminance used in the simulation. Methods of representing sky luminance distributions were surveyed, including both currently accepted and alternative methods. From this survey a computer program was developed to provide the sky representation for SIBE2. The model selected for implementation in the computer program. was; developed by Perez et al., and is based on CIE formulae. The work described in this paper illustrates the importance of the sky representation in daylighting simulation. The exploration of accuracy and realism as carried out in the program development recounted here suggests issues for future research in this field.

INTRODUCTION

In daylight simulation, as in any simulation, accuracy and realism are major goals. Present daylighting tools have a number of well known disavantages which limit the achievement of these goals. These include unacceptable inaccuracy in cases of small daylighting quantities, limited representation of building forms, the necessity of repeating all computational steps when even small changes are made to the building design, and large processing times. These disadvantages have all been addressed in the development at Delft University of Technology of the protoype program SIBE2. To further improve the performance of SIBE2, a project was undertaken to improve the way in which the sky is modelled, to provide a realistic description of sky luminance distributions.

The atmospherical conditions considered by models of sky luminance distribution generally fall into four categories: completely overcast; partly cloudy; clear sky; and all conditions. Commonly, simplistic models are used, which represent sky types with either no clouds[1,2] or with total cloud cover[3]. Some are slightly more general, such as Kittler[4] which provides for sky types ranging from completely overcast to clear, providing the conditions in all cases are homogeneous. Current research in the area of daylight luminance distribution is concentrating on the development of more realistic sky representations. The use of different sets of formulae to model different atmospherical conditions is a feature of the older models. In more recent models the aim is to develop general formulae that encompass a range of sky types. Parameters such as turbidity, sky clearness, sky brightness, cloud cover and percentage of clear sky are used to provide for the continuum of sky types.

SIBE2

Within the group Building Physics, Faculty of Architecture at Delft University of Technology, new computational concepts have been developed for daylighting calculation. Based on these concepts a prototype computer program, SIBE2, has been developed which enables the user to predict accurately the sky component on arbitrary tilted surfaces in any given situation. SIBE2 allows the user to model the building envelope and surrounding obstacles without the necessity of simplifying assumptions regarding geometry and orientation. This is important as factors such as small variations from the vertical plane of a window opening, and depth of window openings, have been shown to cause significant errors in computed daylighting quantities[5,6]. For each intercepting area in a space SIBE2 generates a number of points of measurement, all of which are positioned on straight parallel lines at regular distances, in order to get an impression of the variation of illuminance values over the area. The illuminance value for each point can be calculated by means of the luminance value of a given sky element, multiplied by the corresponding view factor. The variation in view factor values over an area is invariable, since the view factor is a purely geometric factor and independent of variations in luminance distribution of the sky during the day. Although SIBE2 imposes no limitations concerning the assumed luminance distribution of the sky, so far only the "uniform sky" and CIE overcast sky incorporated into the program. For a program designed to improve accuracy of calculations, it is obviously limiting to use sky descriptions which are only applicable to particular sky conditions.

SELECTION OF MODEL

To identify a model of sky luminance distribution that was flexible, accurate, and suited to use with SIBE2, a survey of literature was conducted. Based on this survey, all described models were divided into four categories:

- Models developed from illuminance measurements (usually measured on a horizontal plane, also vertical plane measurements in some models). The sky type is characterised by the total amount of light coming from it (given by unobstructed horizontal illuminance), and a formula developed to describe the characterisation [7].

- Models based on irradiance. These are similar to those using illuminance, with the difference that a luminance efficacy factor, either explicit or implicit, is required to calculate the proportion of available radiance which is visible. Some papers concerned entirely with luminous efficacy have been examined, and are included in this category[8].

- Model based on statistical distribution. These are generally used for cloud pattern simulation and calculation, and may be used in conjunction with a model which provides the background sky luminance[9].

- Algorithms which consider only zenith luminance were examined with the possibility that they could be used with luminance distribution algorithms which provided data relative to the zenith luminance[10].

The method selected for implementation was developed by Perez et al.[11,12], and is hereafter referred to as the Perez method. This is an irradiance based model, which uses the three CIE standard skies (overcast, intermediate, clear) and a high turbidity version of the clear sky.

Whilst these CIE formulae are widely accepted and provide for variations in sky conditions, they represent only four discrete points on a continuum of sky conditions. Even when there appears to be good agreement between the actual sky conditions and the ideal as represented by a CIE formula, a considerable difference may be measured[13]. The Perez method interpolates between these four sky definitions to provide a closer representation of sky conditions, allowing more accurate calculation of luminance distribution. The factors on which the interpolation is based are sky brightness and sky clearness. These are calculated from values of horizontal diffuse irradiance and direct normal irradiance, with extraterrestrial irradiance and optical airmass. The values used may be measured or simulated data. The common availability of both types of these data was one of the perceived advantages of the Perez method. Many meteorological measurement stations include irradiation among the data measured, and numerous methods exist for the calculation of these values.

The other main advantage of the Perez method, for the purposes of this project, is that it allows implementation not only of the interpolation method but also includes the four CIE standard skies. These may be preferred in some situations, for example; to use in comparison of SIBE2 results with other daylighting calculation methods, using standard sky descriptions.

IMPLEMENTATION

At this stage of the project, the program to calculate luminance distribution has been created independent of SIBE2, using a similar design philosophy to allow later integration. The program calculates the luminance value for each azimuth and orientation angle and stores the information in a data structure compatible with that used in SIBE2.

The luminance distribution data may be viewed using a graphical package utilised in the implementation. As with SIBE2, a rectangular representation is available, with azimuth and orientation angles as the x and y axes. In addition, a polar representation has been provided, for a more intuitive visualisation of the sky dome. These representations take the form of contour diagrams showing variations in luminance values over the hemisphere.

Four levels of accuracy may be used in the calculations. As in SIBE2, the accuracy factor determines the discretisation of the sky dome, and allows 10°, 5°, 2.5° or 1° increments between sky points. Thus for a less accurate calculation, a 10° increment may be used, requiring fewer calculation steps and so less processing time and reduced storage requirements, or for a high accuracy calculation, a 1° increment may be used, with corresponding increases in processing time and memory required.

To allow the user to receive output according to the data available, three options are provided for the format of the output. Where a value for zenith luminance is available, data may be output in the form of absolute luminance values calculated with measured zenith luminance. If irradiance data is available, a value for zenith luminance may be calculated, and data may be output in the form of absolute luminance values using this calculated value. If none of this information is available, data will be output in the form of luminance values relative to the zenith luminance.

In order that the effects of sky conditions may be studied over significant periods or even a whole day, the program allows calculation of a series of times for a particular day. The user selects start and finish times and a time step interval. The luminance distribution is then calculated for each point of time.

COMPARISON WITH MEASURED DATA

Although the literature on the Perez method sets out previous validation and verification using measured data, further comparison was carried out to check the application of the formulae to Dutch conditions. Using data collected in Eindhoven by the Building Physics group, Faculty of Architecture at Eindhoven University of Technology (not yet published) calculations were made using CIE formulae appropriate for the local sky conditions, and using the Perez interpolation method. An example is shown for 09/05/93 showing: actual sky description (Fig. 1a), CIE clear (Fig. 1b), CIE intermediate (Fig. 1c) and the Perez method (Fig. 1d). As seen in the example, the Perez method provides a reasonable approximation of the actual values, and in this case is better than the CIE models. Where the sky type corresponds with the conditions of a particular CIE sky description, the Perez interpolation provides that sky description. The value of the Perez method is evident since for the majority of conditions the sky luminance distribution will fall outside the CIE descriptions.

ACCURACY AND SKY DISCRETISATION

In SIBE2, the ability to vary sky discretisation was introduced to explore accuracy of results[5,14] and to allow flexibility in the time required to carry out calculations. To maintain a common structure, the sky luminance distribution calculations also included this option. The accuracy differential for the various discretisation densities was of great interest in the development of this project. A first approach was to calculate sky luminance distributions for each level of discretisation (1°, 2.5°, 5° and 10° elements) for various sky types, and to compare the flat plane illuminance resulting from the sky descriptions. These proved very similar, with a maximum difference found of 2%, and in most cases the difference was much less.

To further examine the discretisation effects on the accuracy of computational results, the luminance value in the centre of two specific sky elements of 10° x 10° and 5° x 5° were compared with the average luminance value over the same area when subdivided into 1° x 1° elements. An example is given showing a 5° x 5° square (Fig. 2a), compared with a 5 x 5 array of 1° x 1° squares (Fig.2b). The average over the array of 1° x 1° squares differs by only 1.3% from the value for the 5° x 5° square; the range of luminance values over the area is however much larger at 15.8%.

Thus the difference involved can be seen to be negligible when large areas of sky are involved, but the difference may become important in illuminance calculations where a window opening "views" only a small part of an element. The portion of the sky element relevant to the calculation may be at the extreme end of the range within that element and for large elements may differ considerably from the value used.

CONCLUSIONS

A program to model luminance distribution has been developed for incorporation into SIBE2. This program utilised the Perez model, which proved to be a valuable method to use in this project. It is based on well established formulae, uses as input data that are widely available, and provides accurate output.

The next stage of the project is the integration with SIBE2 that will allow accurate illuminance calculation within a space, based on actual sky data for time and location. In a project of this nature, the importance of sky discretisation as a factor in accuracy of results can not be underestimated. When flat plane illuminance resulting from a sky luminance distribution is considered, the difference between 1° and 10° discretisation steps appears negligible. However, the luminance distribution may differ widely from the central value of a sky segment, which becomes very important when only a portion of that segment is visible within a space. In a program like SIBE2, which is aimed at defining particularly the less well lit areas of a space, this issue is central to the performance of the program. While fewer sky segments allows reduced processing time and memory requirements, the corresponding drop in accuracy may nullify the value of the calculation.

Future work using this program involves the previously mentioned integration with SIBE2 to create a daylight simulation program which will calculate illuminance values for internal spaces based on actual sky measurements for the location and orientation. This will involve further comparison with actual measurements to test how close a relationship may be achieved between measured and modelled results.

TABLES AND FIGURES

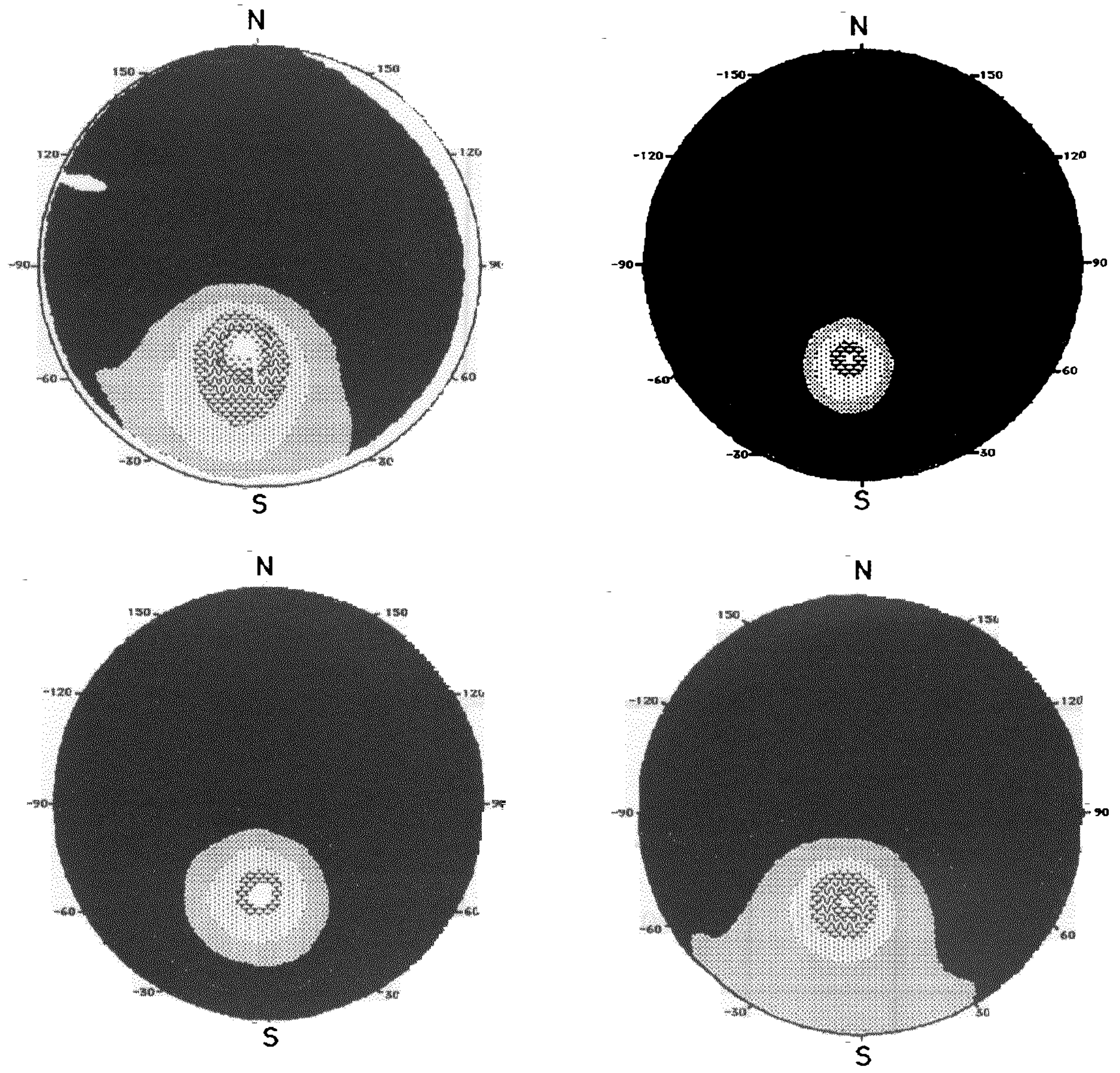

Figure 1 a Sky representation from measured data
b CIB clear sky formula
c CIB intermediate sky formula
d Perez model representation

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Figure 2a Luminance value over 5°x5° element

23387	24197	25030	25741	25059
23379	24063	24630	24880	24645
23037	23555	23924	24064	23933
22535	22930	23194	23290	23201
21969	22282	22484	22555	22488

Figure 2b Luminance values over 5x5 1°x1° elements

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