THE USE AND EVALUATION OF A COMPUTER PROGRAM FOR THE INVESTIGATION OF THE DAYLIGHT AND SUNLIGHT PERFORMANCE OF BUILDINGS

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ABSTRACT

This paper discusses the use of the computer program DAYLIGHT, as a method of analysing and evaluating the natural lighting in buildings. The computer's design parameters and outputs are discussed in some detail, and the program is then used to examine some of the standard design criteria. The paper concludes with a case study of a primary school building to evaluate the accuracy and usefulness of the program. In this study, the output from the computer is compared with measurements taken in a model of the school tested under an artificial sky, and both these results are judged against measurements taken in the real building.

INTRODUCTION

Daylight, which is a computer program created to simulate and display the daylight and sunlight performance of buildings, has been designed and developed over a number of years by the Construction Systems Development Group at Anglia Higher Education College. The program analyses the daylight behaviour within internal architectural spaces, and the interactions between a building, or set of buildings, and sunlight for any given geographical position. This information can then be displayed on a number of diagrams, contours maps, graphs and tables to provide a comprehensive package of graphical illustrations of the building's natural lighting behaviour.

The program was originally designed as an educational aid for students concerned with the environmental performance of buildings, but has now been developed into a useful design tool for practising architects.

Daylight and sunlight behaviour in and around buildings can, of course, be simulated by a number of other methods. An architect or engineer has access to an array of design charts, diagrams, tables, protractors and nonograms, all of which can be used to aid the design process. In addition, mathematical and physical models can be used to investigate the natural lighting performance of buildings. Whilst all these methods do have their merits, they all have one disadvantage in common - they are very time consuming to use. In addition, apart from physical modelling which can provide useful photographical information as well as numerical data, they usually provide little return for a great deal of work. Architects simply do not have the time, nor, in some cases, the required scientific background to work with such design tools. Computers can, however, provide this scientific information, and, of course, in a fraction of the time.

If a designer requires a knowledge of such daylight criteria as the average daylight factor or the uniformity ratio for a given room, twenty to thirty points, evenly spread over the working plane, may need to be considered to obtain a reasonably accurate estimate. If, as a result of such investigations, the fenestration needs to be altered, these values would have to be recalculated. It is not difficult to see that this iterative process would become intolerably slow by any of the traditional methods.

This is where computer simulation can come into its own. The operator can quickly alter the design at the touch of a button, generating a new set of data to analyse which can be of great value to the user particularly if this information is in graphical form as illustrated in Figure 1.

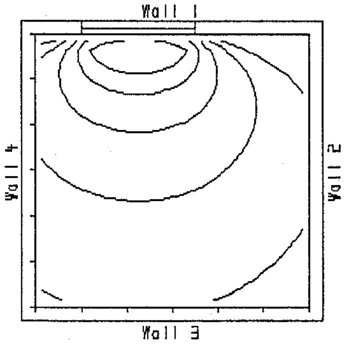


Figure 1. Plan showing daylight contours produced by the program.

Computers are not just design tools however. Students of daylight design can make better use of their time with the computer, studying building performance rather than learning to use lighting design aids.

Another important aspect of computer simulations is that the rapid analysis enables the user to critically examine the usefulness and accuracy of standard design criteria. One can quickly investigate how many points are required to give an accurate estimate of the average daylight factor and the uniformity ratio for a room, and how these will vary with the number of points chosen.

Table 1 illustrates an answer to these questions. It shows the criteria estimated by a number of different points for a room perceived to be well day-lit. Inspection shows that the criteria are virtually independent of the number of points chosen.

Table 1. Daylight criteria for a room

No of points	Average	Min	Max	UR
2 X 2	4.5	2.04	6.95	0.45
4 X 4	4.97	1.8	16.36	0.36
6 X 6	5.09	1.74	20.97	0.34
10 X 10	5.15	1.71	24.95	0.33
20 X 20	5.16	1.53	27.60	0.30

SCIENTIFIC BASIS OF THE PROGRAM

The program divides the room into a grid of rectangles and the daylight factor is calculated for a reference point at the centre of each rectangle at a height determined by the working plane.

The daylight factor is a measure of the total daylight illuminance reaching the reference point expressed as a percentage of total daylight illuminance from an unobstructed sky. The program divides this into a sky component, externally reflected component, and internally reflected component. (BRE Digest 309, 1986)

The sky component is a measure of direct daylight from the sky. The program has first to determine that area of sky which is visible from the reference point, taking into account internal obstructions, overhangs, the depth of window reveal and the size and position of the window frame. The effective window is then broken down into component parts (Hopkinson, Petherbridge and Longmore 1966) such that the line joining the reference point and a lower corner of the window is perpendicular to the window plane. The sky components due to these component windows are then calculated and added or subtracted accordingly to derive the total sky component due to the window.

The actual formulae used depend on the sky type being considered. For example, the following formulae are for the CIE Standard Overcast Sky:

Sky component due to a vertical window (Hopkinson, Petherbridge and Longmore 1966)

$$= \frac{3}{14\pi} (\phi - \phi_1 \cos\theta) + \frac{2}{7\pi} \sin^{-1}(\sin\phi \sin\theta) - \frac{1}{7\pi} (\sin 2\theta \sin\phi_1)$$

where θ, ϕ_1 and ϕ are the angles shown in Figure 2.

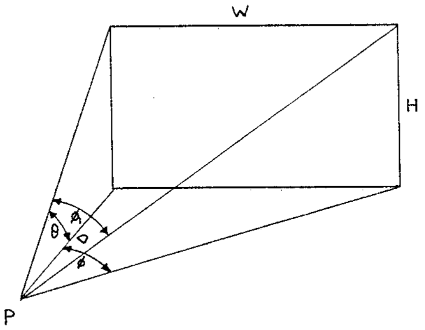


Figure 2. Diagram showing angles used for vertical windows.

Sky component due to a rooflight (Seshadri 1960)

$$= \frac{3}{14\pi} (\beta^1 \sin\gamma + \gamma^1 \sin\beta) + \frac{1}{7} + \frac{1}{7\pi} (\sin 2\beta \sin\gamma^1 + \sin 2\gamma \sin\beta^1) - \frac{2}{7\pi} \sin^{-1}(\sin\alpha \cos\beta) - \frac{2}{7\pi} \sin^{-1}(\cos\alpha \cos\gamma)$$

where $\tan\alpha = \frac{\tan\gamma}{\tan\beta}$ and

β, β^1, γ and γ^1 are the angles shown in Figure 3.

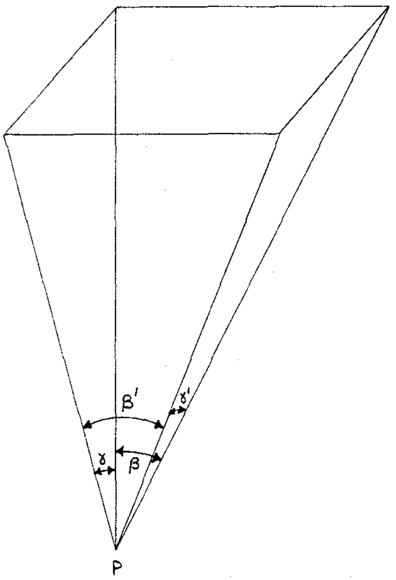


Figure 3. Diagram showing angles used for rooflights.

The resultant sky component is modified according to the transmission factor of the glass and the angle of incident light. A correction value is obtained by interpolating between values in the published table "Effective transmission factors for 6mm clear glass". (Littlefair 1982)

The externally reflected component is a measure of light reflected from external obstructions and into the room through a window. This is calculated in a similar way to the sky component. The program determines which part or parts of the window are affected by external obstructions. The equivalent sky component is calculated for each section affected and modified according to the reflectance of the external obstruction.

The internally reflected component is light which, having once entered the room, is reflected and inter-reflected at the surfaces of the room before it reaches the reference point. Although, in practice, the amount of inter-reflected light varies according to the distance of the reference point from the window, it is generally considered adequate to use an average or minimum internally reflected component for the whole room. The formulae used are obtained from BRE Digest 310 (1986) and are given as follows:

Average internally reflected component for side-lit rooms

$$= \frac{0.85W}{A(1-R)} \qquad X\ (CR_{fw} + 5R_{cw})\ \%$$

where W = Area of window
A = Total area of ceiling, floor and walls including area of window
R = Average reflectance of ceiling, floor and all walls, including window, expressed as a fraction
R_{fw} = Average reflectance of the floor and those parts of the walls below the plane of the mid-height of the window (excluding the window wall)
R_{cw} = Average reflectance of the ceiling and those parts of the walls above the plane of the mid-height of the window (excluding the window wall)
C = A coefficient having values dependent on obstructions outside the window

Average internally reflected component for rooflit interiors

$$= \frac{KWR}{A(1-R)}\ \%$$

where W = Glazed area of rooflight
A = Total area of floor, all walls and ceiling, including area of rooflight
R = Average reflectance of floor, all walls and ceiling, including rooflight, expressed as a fraction
K = A coefficient having values dependent on the type of rooflight and obstructions outside

The minimum internally reflected component is obtained by applying a conversion factor to the average internally reflected component. This is derived from the average relectance R and is given in BRE Digest 310 (1986).

DESIGN PARAMETERS AND OUTPUTS

The user starts by defining the length, width and ceiling height of a simple rectangular room. This basic room may then be modified to take account of a number of factors which influence the magnitude of the daylight factor. Many of these variables have default values for convenience.

The room itself may be modified to include internal obstructions enabling the user to simulate internal walls and irregular shaped rooms. The reflectances of internal surfaces may be defined, and window recesses can be modelled by specifying the thickness of the walls and ceiling.

The program takes account of the position and size of vertical windows and rooflights and in both cases, framing and window bars can be included.

The room is then positioned on a site of known orientation and geographical position. Individual external obstructions such as other buildings, can be detailed on this site in terms of position, size and reflectance. A typical site plan is shown in Figure 4.

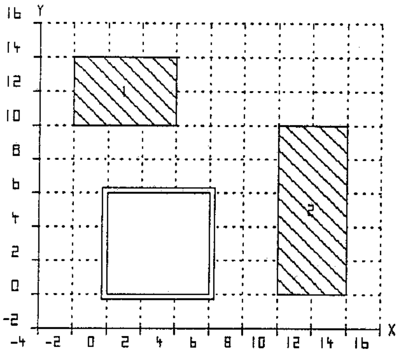


Figure 4. Plan showing typical site information.

Outputs may be modified to take account of such variables as dirt on windows and deterioration of room surfaces. They may be displayed in a number of different ways giving, for example, a choice between daylight factors(%) and illuminance levels, or up to 10 contour levels of the user's choice. Graphs may also be displayed showing daylight levels through a cross section of the room.

All outputs may be printed to a simple dot matrix printer or a postscript laser printer or may be plotted on an HPGL format plotter.

THE CASE STUDY

An evaluation of Daylight

This section describes the results of research work carried out to evaluate the accuracy of the program compared to predictions using a model tested in an artificial sky and actual measurements taken in a real building. The building is Maylandsea County Primary School in Essex, which was designed in the later part of the 1980s by the Architects Department of Essex County Council and has been occupied since April of 1990.

Output from the program is compared with measurements taken from a model tested in a flat top artificial sky which approximates the standard CIE overcast sky conditions. These results are then evaluated against measurements taken in the actual school when the sky was judged to approximate the same overcast condition.

Figure 5 shows a part of the building under consideration. It comprises three typical classrooms in one corner of the building.

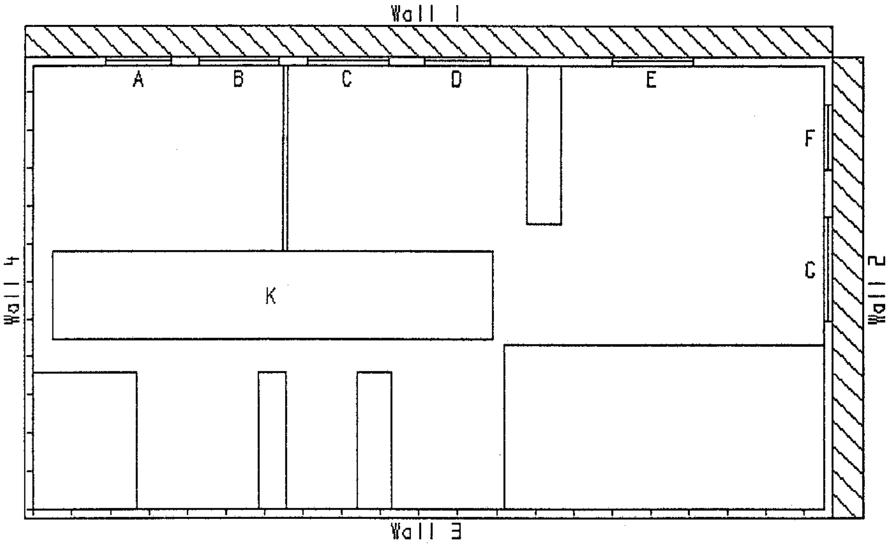
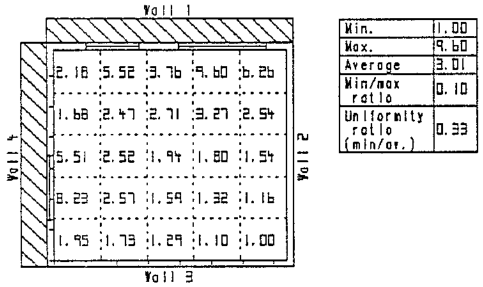


Figure 5. Plan showing part of Maylandsea County Primary School

The comparison

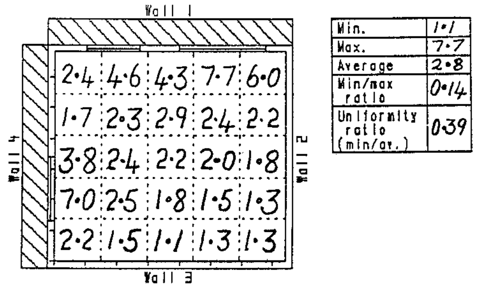
The daylight factors predicted on the computer for classroom 3 are illustrated in Figure 6. Figure 7 details the measurements taken in the model, and Figure 8 shows the real building data. Table 2 can be used to compare some of the daylight criteria.



2.18	5.52	3.76	9.60	6.26
1.68	2.47	2.71	3.27	2.54
5.51	2.52	1.94	1.80	1.54
8.23	2.57	1.59	1.32	1.16
1.95	1.73	1.29	1.10	1.00

Min.	1.00
Max.	9.60
Average	3.01
Min/max ratio	0.10
Uniformity ratio (min/av.)	0.33

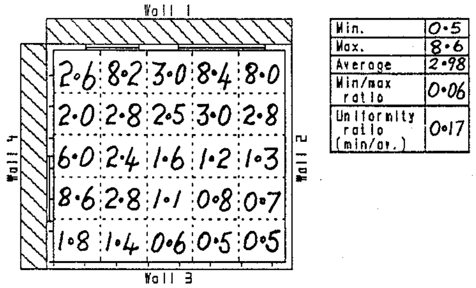
Figure 6. Plan showing daylight factors (%) for classroom 3 produced by the program.



2·4	4·6	4·3	7·7	6·0
1·7	2·3	2·9	2·4	2·2
3·8	2·4	2·2	2·0	1·8
7·0	2·5	1·8	1·5	1·3
2·2	1·5	1·1	1·3	1·3

Min.	1·1
Max.	7·7
Average	2·8
Min/max ratio	0·14
Uniformity ratio (min/av.)	0·39

Figure 7. Plan showing daylight factors (%) for classroom 3 measured in the model.



2·6	8·2	3·0	8·4	8·0
2·0	2·8	2·5	3·0	2·8
6·0	2·4	1·6	1·2	1·3
8·6	2·8	1·1	0·8	0·7
1·8	1·4	0·6	0·5	0·5

Min.	0·5
Max.	8·6
Average	2·98
Min/max ratio	0·06
Uniformity ratio (min/av.)	0·17

Figure 8. Plan showing daylight factors (%) for classroom 3 measured in the real building.

Table 2. Daylight criteria for classroom 3.

	Average daylight factor	Min	Max	Uniformity ratio
Computer	3.01	1.00	9.6	0.33
Model	2.8	1.1	7.7	0.39
Real building	2.98	0.5	8.6	0.17

If one assumes that a side-lit room is perceived to be well day-lit if the average daylight factor is 5% and the uniformity ratio is 0.3, then the computer program predicts that for classroom 3, although the daylight is reasonably uniform, the overall average is too small. These predictions are largely confirmed by the model study except that the model suggests the lighting will be even more uniform with a ratio of 0.39.

The average daylight factor as measured in the real building at 2.98 compares very well with both the modelling techniques and the maximum values are also acceptably close. However, the minimum daylight factor in the real building was measured at half that predicted by the modelling techniques, reducing the actual uniformity to 0.17.

Thus both the computer program and the physical model accurately estimated the average and maximum daylight factors, but failed to predict how uniform the daylight was in the actual school.

Of course, real buildings do generally contain a great deal of what might be described as "general clutter" which is difficult to simulate in a physical or computer model. Real classrooms contain desks and cupboards and coats hung against the wall, not to mention children and their output which tends to cling to every available vertical surface. This may account for the real building's lack of ability to distribute the available daylight as predicted by the two models.

Figure 9 illustrates the variation in the daylight factor with distance from the window in wall 4 of classroom 3. Again, the computer and the model compare favourably with each other, with the school measurements showing slightly more variation. However, the general shape of all three curves is what one would expect and is encouraging.

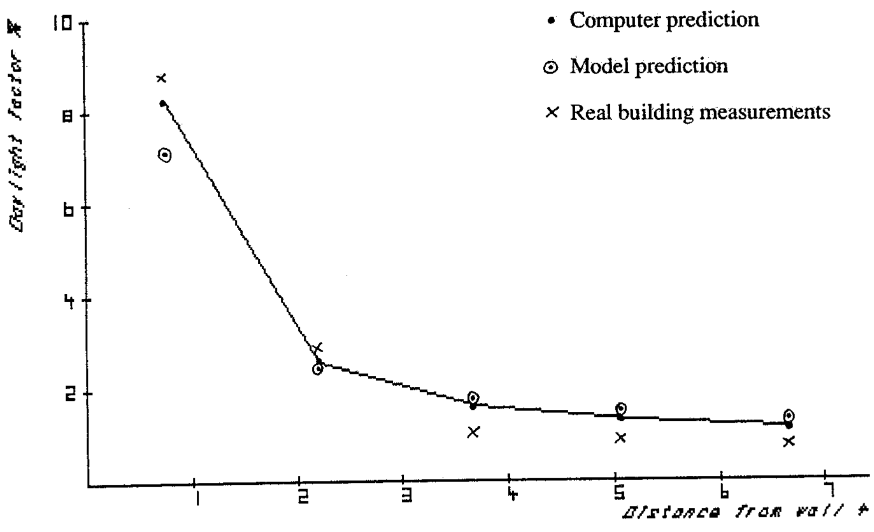


Figure 9. Graph showing daylight factor v. distance from wall 4 taken from a point 2.04 metres from left corner of wall 4

CURRENT DEVELOPMENT

The current research involves modifications to the program to simulate daylighting conditions within buildings for a number of different sky conditions. Sunlight behaviour in and around buildings is being investigated and the sky factor and associated right to light problems are being explored.

CONCLUSION

This paper has discussed the need and usefulness of a computer generated analysis of the daylight performance of buildings. It has examined the consistency of daylight criteria for a number of different shaped rooms, and has suggested that the consistency of these criteria over a range of points may be a measure of daylighting design quality.

Details of the scientific basis of the program has been given together with some typical outputs.

A casestudy was used to illustrate the accuracy of the modelling technique compared with physical modelling and real building measurements. Good correlation was found between the maximum and average daylight factors for all three sets of data. The lighting in the real building, however, was found to be less uniform than both the modelling techniques predicted.

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