SIMULATION OF NATURAL LIGHTING : FROM GEOMETRICAL CONFIGURATION TO OCCUPANCY EVALUATION

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ABSTRACT

This paper summarizes the approach, method, and some results of an ongoing systematic study in simulation and evaluation of daylight factor distribution in rooms. The study aims to develop the basis for both critical investigation of simplified daylighting design guidelines and flexible fast response computational modules, which would enhance the CAAD systems towards preliminary design supporting lighting performance simulation.

Given the format restrictions of most commercially available lighting simulation software packages, the study was based on a specially developed and therefore adaptable simulation program (MB-3C) on the basis of the three component procedure. The input data can include the geometry of the room, position and size of the apertures, relevant photometric material properties, as well as data concerning possible obstructions. The simulation can potentially be based on different sky luminance distributions.

As a significant example for common preliminary design requirements, the aperture/floor area ratios were considered. The distribution of daylight factors were generated for a significant number of "virtual" rooms with different attributes (geometry, location and shape of openings, etc.) creating an extended data base for further statistical assessment. The results were analyzed with regard to their relevance for evaluation of existing and formulation of new daylight related design guidelines (tools, rules, requirements, etc.). Available empirical data concerning the inhabitants' response to the visual environment were taken into consideration in order to study the occupational relevance and consequences of the research findings.

1 INTRODUCTION

In the past, a number of simple rules have been developed to support the preliminary daylighting design process. Even the availability of highly sophisticated simulation programs has not eliminated the role of simple generic design guidelines because extensive input data (in terms of detailed material and geometry specifications as well as external environmental context) are usually not available at a preliminary design stage. To account for this fact and the associated needs, the following parallel measures are suggested:

* As part of a new conception for CAAD systems, "intelligent" and fast response estimation modules can be developed, which would provide "magnitude of order" information derived from a small set of data.

* The "conventional" set of simple daylighting design rules must be studied critically, using the increased computational capacities of the current simulation models.

The study presented here is part of a research effort in the development of a simulation program as a flexible tool for the analysis and evaluation of the validity and limitations of some common preliminary design rules for architectural daylighting.

As a typical example of simple generic rules for minimum daylight quality assurance in residential buildings, suggested ratios of glazing to floor area in habitable rooms are studied and discussed in detail, considering various proportional configurations of rooms as well as shape and locations of apertures. Some national or federal codes require certain minimum percentages of fenestration area to the room floor area (e.g. BOCA 1984: 8%, Bauordnung 1976: 10%, ΦEK 1989: 10%). The question is, if and to what extent, single indicators can describe and guarantee adequate natural lighting. Through computer-aided simulation of daylight conditions for typical rooms, a statistically significant data set was generated to examine the validity and limitations of such requirements. The simulation results were expressed mainly in terms of daylight factor based specifiers (minimum and maximum daylight factor, room average daylight factor, 2-point daylight factor, uniformity factor, etc.), since these are commonly used to describe and evaluate the quality of natural lighting in indoor rooms. At the same time, available empirical studies of the correlation between occupational evaluation of daylight quality and daylight factor based indicators were applied to support the interpretation of the results.

2 MODEL DESCRIPTION

Due to the format restrictions of most commercially available lighting simulation software packages (e.g. rigid input structures, limited output flexibility), an adaptable simulation program (MB-3C) was developed on the basis of the three component procedure (sky, externally reflected, internally reflected). Since the main features of this method are sufficiently documented in related literature (Hopkinson et al. 1966, Bryan and Clear 1980, Fischer 1982, Mahdavi 1989), only some specific technical aspects are mentioned here.

For the calculation of the sky component, a combined analytical-geometrical procedure is implemented. Based on explicit solutions for solid angle integral equations, the sky contribution for a model rectangular aperture can be derived for points perpendicular to arbitrary corners of the opening. For all other relevant points of the reference level and for all other rectangular aperture configurations, the sky component can be specified by application of appropriate geometric manipulations of this basic module. The currently implemented procedure is based on the analytical solution of the basic solid angle integral equations for the uniform and standardized overcast sky (CIE sky). However, based on numeric calculation procedures, other isotropic sky models can be realized. For the case of non-isotropic sky conditions, an extensive data set including discrete values for the distribution of relative luminances must be applied. An empirically modified "split flux" method was implemented for the calculation of the internally reflected component, implying a slight linear reduction of the internally reflected contribution at the deeper portion of the room.

The flexible input data include the geometry of the room, position and size of the apertures, and relevant photometric material properties. The output format is adaptable and provides data concerning local and average daylight factors (based on user-defined grid definitions) as well as a number of relevant statistical specifiers (minimum/maximum values, uniformity factors, etc.).

3 OCCUPATIONAL EVALUATION

For the description of daylight conditions in rooms in residential buildings, the reference points P_1 and P_2 (cp. Fig. 3.1) have been suggested (DIN 5034).

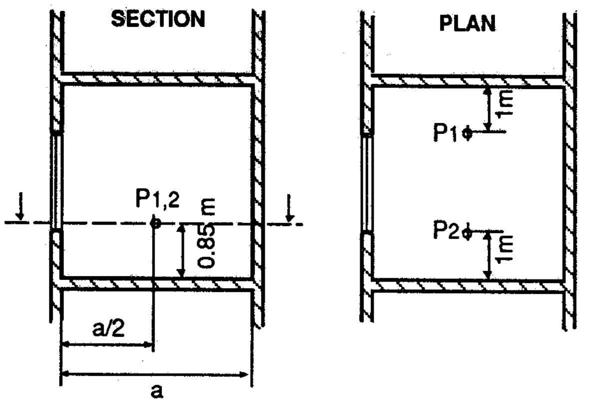

Fig. 3.1 Reference Points for Daylighting in Residential Buildings (after DIN 5034)

Following the results of extensive statistical analysis, the following correlation between the average value of the daylight factors at these two points (DF_{2P}) and the subjective evaluation of the daylighting conditions (expressed in terms of a U-scale) was derived (Seidl 1986):

$$U = 3.2 \cdot \log DF_{2P} + 6.6 \qquad \text{(eq. 3.1).}$$

The results for U can be interpreted according to the following table (Table 3.1):

U=	-2	-1	0	1	2
"Subjective" evaluation	very poor	poor	neutral	good	very good

Table 3.1 "Subjective" Evaluation of daylight conditions in residential rooms for different values of U (cp. eq. 3.1)

It is clear from Table 3.1, that a minimum value of 0 is required for U. This corresponds to a DF_{2P} value of 0.9%. As an additional requirement based on some other studies, a minimum daylight factor of 0.75% must be maintained at both reference points.

Being involved in the human ecological study of environmental relationships (Mahdavi 1990, 1986/a, 1986/b, 1986/c), the authors are not convinced that the complexity of occupants' responses to the environmental factors can be reduced to a simple psycho-physical function such as eq. 3.1. However, as a hypothetical model for quantitative assessment of one aspect of the visual environment (horizontal illuminance distribution), the suggested correlation can be temporarily implemented to establish a format for the investigation of the potential occupational relevance of variations in related room parameters.

4 SIMULATION STRATEGY

Focusing on the issue of glazing/floor area ratio, numerous configurational variations of room and window shapes (locations) were generated. The specification formats (data base structure) of these configurations are listed in Tables 4.1 and 4.2. The floor area of the test room was assumed to be 16 m^2. Based on a glazing/floor area ratio of 10%, this gives a glazing area of 1.6 m^2. The d/w-ratio (room depth to room width) was varied from 0.48 to 2.07 (in this study room width = width of the window wall). The room height was assumed to be constant (2.6 m) for all room configurations. The glazing area was realized in terms of 3 proportional variations of a rectangular window (covering a width to height ratio of 0.75 to 1.33) as well as a combination of 2 rectangular windows of the same size (width/height ratio = 0.67). These windows were then relocated in several discrete steps in order to study the effects of various levels of eccentricity of window locations in the exterior wall of rooms. The impact of vertical window displacement was studied in terms of 3 different sill heights.

		Window Configurations			
		W1	W2	...	Wn
Room Configurations	R1	R1 - W1	R1 - W2	...	R1 - Wn
	R2	R2 - W1	R2 - W2	...	R2 - Wn
	...	...	...	...	...
	Rm	Rm - W1	Rm - W2	...	Rm - Wn

Table 4.1 The specification format (database structure) for considered room configurations (defined by discrete room d/w-ratios R_1 ... R_m) and window configurations (defined by discrete window width/height-ratios W_1 ... W_n)

The assumed photometric properties of the selected building elements are listed in Table 4.3. A maintenance factor of 0.8 was assumed for the windows. A total number of approximately 400 configurational cases were simulated based on the CIE overcast sky model. External obstructions were not considered. The daylight factor distribution was derived in terms of an orthogonal grid for a receiver plane at a height of 85 cm. The output format includes 2-point, minimum/maximum and room average daylight factors as well as the uniformity factors.

		Window Configuration Wj			
		V1	V2	...	Vq
Room Configuration Ri	H1	H1 - V1	H1 - V2	...	H1 - Vq
	H2	H2 - V1	H2 - V2	...	H2 - Vq
	...	...	...	...	...
	Hp	Hp - V1	Hp - V2	...	Hp - Vq

Table 4.2 The specification format (database structure) for horizontal and vertical variations (H_p, V_q) of the window location for a specific room Ri and a specific window shape Wj

Element	Reflectance [%]	Transmittance [%]
Glazing	10	75
Walls	50	-
Floor	40	-
Ceiling	70	-

Table 4.3 Photometric element properties of the simulated rooms

5 RESULTS

The simulations provided some 160,000 daylight factors. The statistical operations performed on this large data set cannot be described here in an exhaustive manner. Thus, only two major manipulations with significant implications for the problem statement will be considered:

- calculation of the 2-point daylight factor, the room average daylight factor and the uniformity factor for each case (specified by the room d/w-ratio as well as shape and location of the window);
- calculation of average values of the 2-point daylight factors, the room average daylight factors and the uniformity factors for each room geometry (including all variations of window shapes and locations in that room).

The numeric summary of the results is given in Table

5.1. A graphic illustration of the results is given in Fig. 5.1.

Statistical Results	2-Point Average [%]	Room Average [%]	Uniformity Factor [-]
Room 1	1.31 ± 0.22	1.72 ± 0.18	0.35 ± 0.05
Room 2	1.30 ± 0.17	1.73 ± 0.18	0.35 ± 0.04
Room 3	1.30 ± 0.14	1.73 ± 0.19	0.36 ± 0.04
Room 4	1.26 ± 0.13	1.73 ± 0.19	0.36 ± 0.03
Room 5	1.19 ± 0.12	1.70 ± 0.17	0.35 ± 0.02
Room 6	1.12 ± 0.11	1.68 ± 0.15	0.34 ± 0.02
Room 7	1.00 ± 0.09	1.60 ± 0.15	0.34 ± 0.02
Room 8	0.93 ± 0.08	1.57 ± 0.13	0.33 ± 0.02
Room 9	0.86 ± 0.07	1.52 ± 0.12	0.33 ± 0.02

Table 5.1 Numeric listing of the calculated average values of the 2-point daylight factors, the room average daylight factors and the uniformity factors for each room geometry (including all variations of window shapes and locations in that room)

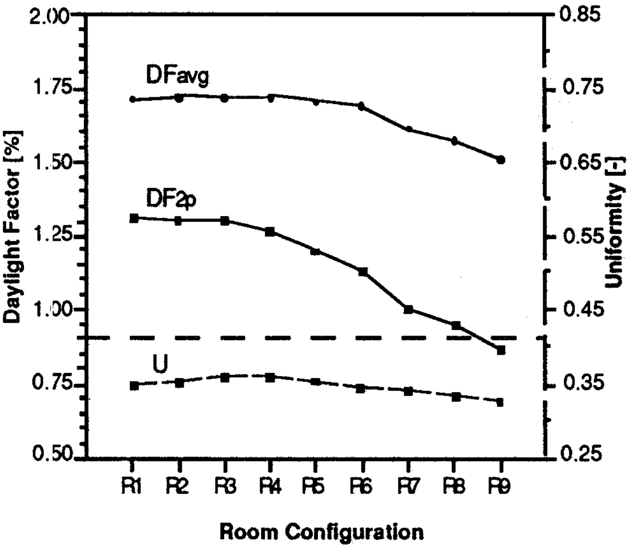

Fig. 5.1 Graphic presentation of the calculated average values of the 2-point daylight factors, the room average daylight factors and the uniformity factors for each room geometry (including all variations of window shapes and locations in that room)

6 DISCUSSION

As it can be seen from Fig. 5.1, there is an obvious trend with regard to both room average daylight factors and 2-point daylight factors within the considered range of room proportions. The following statistical operations are based on the significance of this trend, especially in the case of the 2-point daylight factors. They offer an original framework for developing applicable graphic design methods and augmenting CAAD systems in terms of performance simulation.

As a first step, a regression analysis was performed to study the relation between the average values for 2-point daylight factors and the room d/w-ratios (Fig. 6.1). Within the considered proportional range, a highly significant correlation can be implied ($r^2 = 0.992$). The general mathematical function for this relation is:

$$DF_{2P} = c_1 + c_2 \cdot \frac{d}{w} \qquad [\%] \qquad \text{(eq. 6.1)},$$

with $c_1 = 1.479$ and $c_2 = -0.302$ (for the set of conditions specified in Table 4.3).

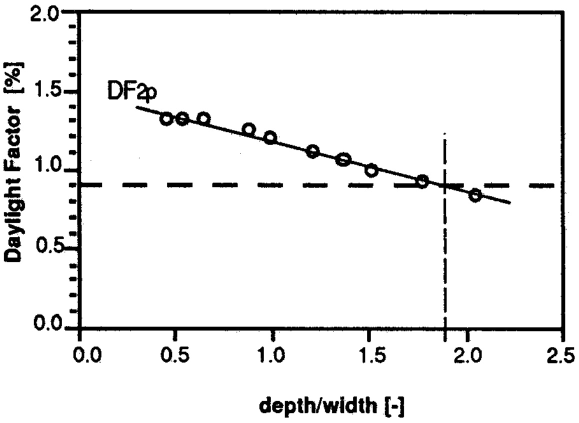

Fig. 6.1 Correlation between the average values for the 2-point daylight factors and the room d/w-ratios

Equation 6.1 gives the lower level of d/w-ratios for acceptable DF_{2P} values. However, it does not consider the additional requirement of a minimum daylight factor of 0.75% at both reference points. Thus, the percentage of cases with factors at one of the reference points below 0.75% ($P_{0.75}$), was calculated. The result of this calculation is added as a second regression line in Fig. 6.2 (with $r^2 = 0.943$). The corresponding general form of this relation is:

$$P_{0.75} = c_3 + c_4 \cdot \frac{d}{w} \qquad [\%] \qquad \text{(eq. 6.2)},$$

with $c_3 = 74.672$ and $c_4 = -78.961$ (for the set of conditions specified in Table 4.3).

Equation 6.2 gives the lower level of acceptable d/w-ratios depending on the desired statistical confidence. For example, for a $P_{0.75}$ value of 0%, the corresponding d/w-ratio would be 0.95.

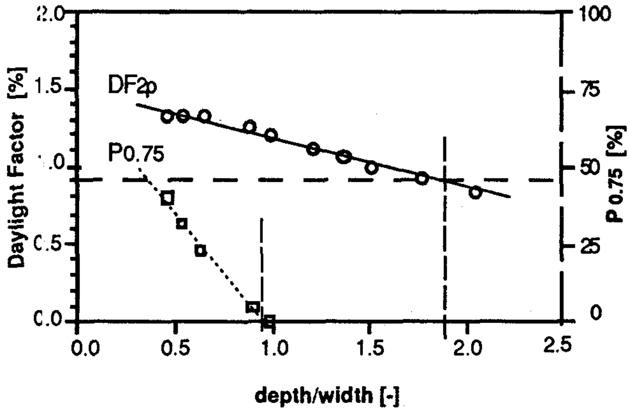

Fig. 6.2 The percentage of cases, where the daylight factor at one of the reference points is below 0.75% as a function of d/w-ratio (cp. also Fig. 6.1)

The first approximation for the highest acceptable d/w-ratio can be achieved by setting a value of 0.9% for DF_{2P} in eq. 6.1. This results in a value of 1.92 for the d/w-ratio. However, this upper level is valid only within the statistical deviation range of average DF_{2P} values obtained by eq. 6.1. In order to have a flexible level of confidence, a third regression line is added in Fig. 6.3 (with $r^2 = 0.96$). This line indicates the percentage of cases, were the DF_{2P} is less than 0.9% ($P_{0.9}$). The general form of the corresponding function is:

$$P_{0.9} = c_5 + c_6 \cdot \frac{d}{w} \qquad [\%] \qquad (\text{eq. } 6.3),$$

with $c_5 = -101.295$ and $c_6 = 78.531$ (for the set of conditions specified in Table 4.3).

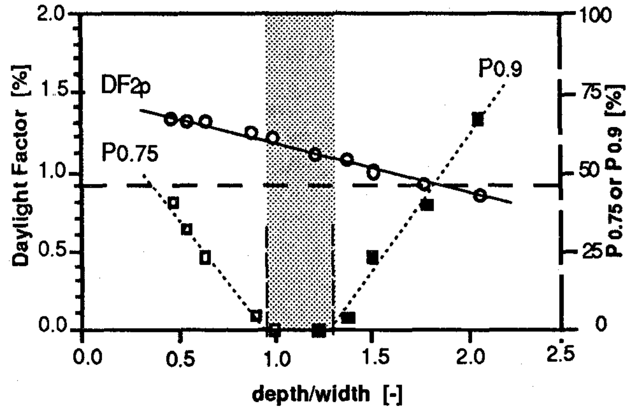

Fig. 6.3 The percentage of cases, where the DF_{2P} is less than 0.9% as a function of d/w-ratio (see also Figures 6.1 and 6.2)

From eq. 6.3, the highest acceptable d/w-ratio can be defined for various levels of confidence. For example, in case $P_{0.9} = 0\%$, the d/w-ratio would be given by 1.29.

Summarizing the steps 1 to 3 (cp Fig. 6.1 to 6.3), a range of 0.95 to 1.29 can be derived for the acceptable d/w-ratios for the mentioned levels of statistical confidence and the set of conditions specified in Table 4.3. Potentially, a table of $c_1, \ldots, c_6$ values can be obtained following the same procedure for other realistic geometrical room and window configurations/dimensions and other photometric material properties.

7 CONCLUSION

Since extensive daylighting related input data are usually not available at a preliminary design stage, flexible and effective estimation procedures are needed, which would provide "magnitude of order" information derived from a small set of data. As a major application, these rules could be realized in terms of "intelligent" modules within the CAAD systems to enhance their interactive design supporting capacities.

As a typical example of simple generic rules for minimum daylight quality assurance in residential buildings, suggested ratios of glazing to floor area in habitable rooms were discussed in detail, considering various proportional configurations of rooms as well as shape and locations of apertures. Through computer-aided simulation of daylight conditions for typical rooms, a statistically significant data set was generated to examine potentially significant correlations between gross scale preliminary design data and daylight factor based specifiers. To support the interpretation of the results, available studies of the correlation between occupational evaluation of daylight quality and daylight factor based indicators were considered.

A 3-step statistical analysis has manifested a highly significant correlation between configurational parameters (room d/w-ratios) and the 2-point daylight factors. Corresponding mathematical functions with variable levels of statistical confidence were derived, which, by proper extension, could offer an original framework for developing practical graphic design methods and performance simulation modules for CAAD application.

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