Dynamic link of light- and thermal simulation: on the way to integrated planning tools

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Abstract

A method to evaluate the energy demand for lighting on an hourly basis is presented. The method is based on a raytracer and a dynamic modelling of the sky's luminance distribution. The link to the thermal building simulation is shown by examples.

Introduction

The optimisation of the building envelope in order to use a high amount of passive solar energy while simultaneously minimising the heat transmission losses is a step in the planning process where dynamic building simulation is important. The criteria to evaluate the facades from an energetically point of view are:

- minimise transmission losses by low U-values
- achieve high solar gains in winter through high total energy transmittance values
- avoid thermal loads by reducing the total energy transmittance value in summer
- achieve a high amount of daylight in order to reduce the electrical demand for light and in order to reduce the thermal loads
- to avoid glare for a high visual comfort

From this criteria the planning tools should have the following capabilities:

- angle dependant modelling of the total energy transmittance TSET
- control of the TSET
- modelling of heat transfer in complex optical structures
- dynamic modelling of lighting

The first three criteria are met by several modelling techniques. They are used in different software tools, which are available at the market. In the following a method used to model the dynamic behaviour of lighting is described.

Dynamic lighting simulation

A method of dynamic lighting simulations must be able to cope with the total illuminance level which varies over time as well as the variations in the different sky luminance distributions. Apart from this, the building use patterns (i.e., working hours, weekend schedule) and the specific lighting demands have to be taken into account. Furthermore, this methodology should enable the simulation of complex daylighting systems.

Simulation programs using the method of raytracing are the only synthetic imaging programs which are capable of accurately modelling daylighting elements having non-lambertian reflective surfaces (mirrors, lightshelves, etc.). One disadvantage of the raytracing method is that it can be time consuming. For example, the computing time needed to evaluate the illuminance for a simple office room can take up to 8 minutes for one time step. Assuming a 9 hour working day and a 5 day work week, an office operates 2400 h a year. Therefore 320 h in real time are needed to compute the annual time series of the electrical energy demand for light. This is obviously too long. Therefore a method is needed, which reduces the number of time steps required for the simulations without losing too much information.

Data for the sky illuminance and the sky luminance distribution are often not available for use with lighting calculations. Therefore Perez et al. developed a model of the illuminance and the luminance distribution for intermediate skies based on a normally available data base: the direct and diffuse irradiance [Per90]. They are often given as time series in standard meteorological years on a hourly basis. With this sky model sky distributions from dark overcast skies to bright overcast skies and clear skies can be modelled with Perez model. The skies luminance distribution and the illuminance can be more precisely modelled then with the CIE sky model for overcast or a clear sky (which are in fact just two special cases of the Perez model).

The raytracer RADIANCE is used to evaluate the illuminance distribution in buildings, and thus structures with non-lambertian reflective properties can be calculated [war94]. The Perez model was designed so that the direct and diffuse irradiance can be used as input for daylight simulations. Within the International Daylight Measurement Program (IDMP) of the IEA this program, called gendaylit, was written and the results of the calculations were compared with measured sky distributions [Del95]. Fig.1 shows the comparison of the measured and simulated sky distributions.

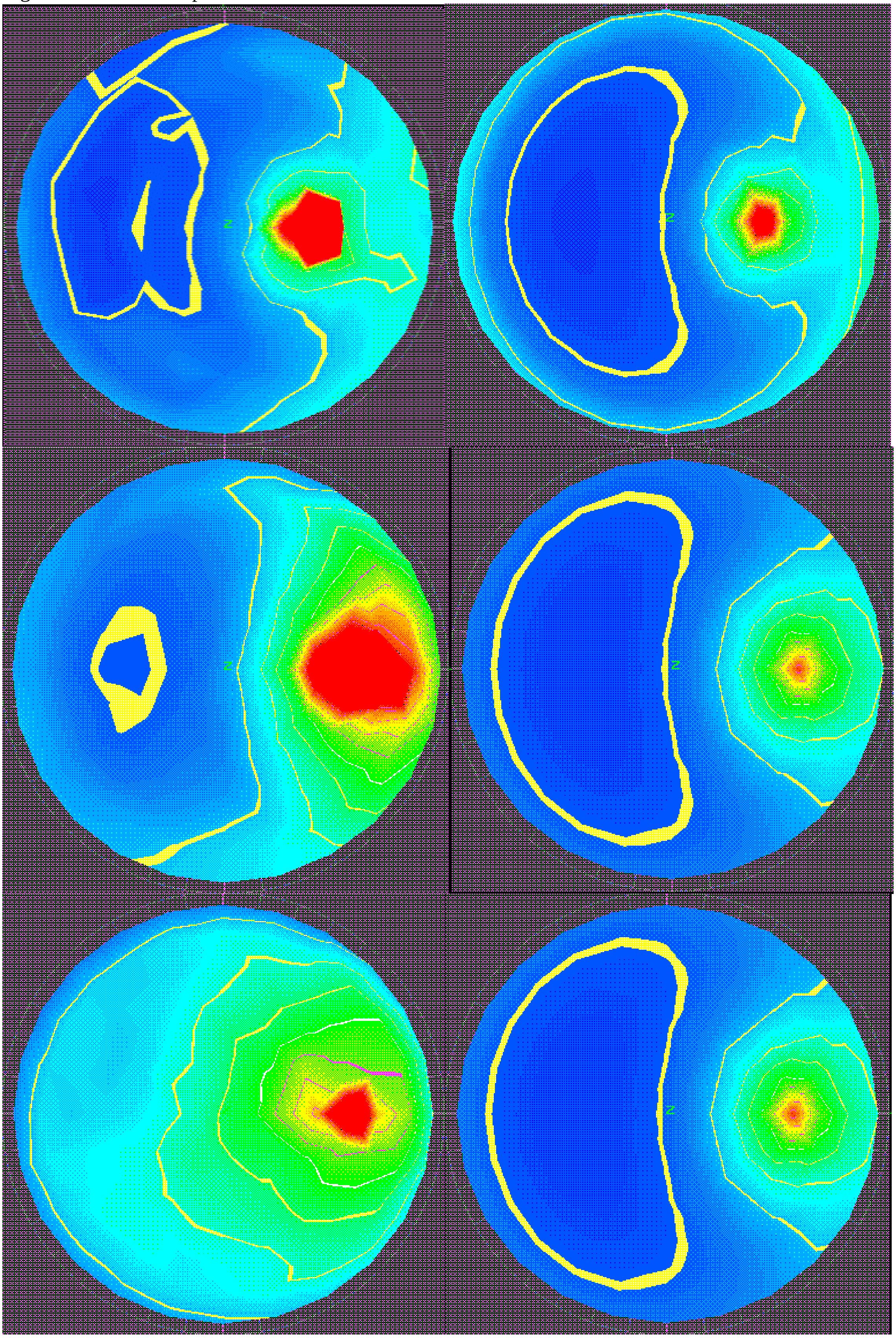

Fig. 1: Comparison of measured and simulated sky distributions according to the Perez model. Top: clear sky, middle: intermediate sky, bottom: overcast sky

To reduce the run time of the simulations, hours with similar sky distributions, similar positions of the sun and similar irradiance levels are calculated only once. Therefore the direct irradiance, diffuse irradiance and sun's zenith angle are grouped into classes for each time step of the day. The standard deviation of the global irradiance is used as criteria for the quality of the classification. There is no bias in the mean value after classification. The classes have an equal amount of pairs. The coupling of the classes for the possible cases with different radiance values and for the different angles gives mathematically a higher amount of cases as existing. For example, dividing the direct irradiance in 6 classes, the diffuse irradiance in 3 classes and the zenith angle in 35 classes a number of 6 x 3 x 35 = 630 cases are expected. Using this methodology, the number of different classifications (or time steps to be calculated) clearly depends on climate. For example, for Freiburg, Germany using values from the German Test Reference Year, a total number of 355 different classes exist when using the above mentioned number of classes for irradiance and the angles.

Table 1 gives the accuracy of the calculated global irradiance as a function of the number of classes. The standard deviation of the calculated global irradiance with respect to the measured values must remain below a given value. It is shown that a reduction of the calculated cases down to 350 leads to acceptable standard deviations. This methodology allows different sky luminance distributions based on the Perez model to be simulated. It is climate dependent and a function of the measured hourly diffuse and direct irradiation values for a given location.

Table 1: Standard deviation of the hourly global irradiation after classification

classification				standard deviation			
classes			cases after reduction	direct irradiance [W/m^{2}K]	diffuse irradiance [W/m^2]	zenith-angle	global irradiance [W/m^2]
direct irradiance	diffuse irradiance	zenith-angle					
10	5	55	831	17,9	13,2	2	21,4
8	4	45	596	23,4	16,1	2,6	26
6	3	35	355	35,1	20,8	3,4	36,3
6	3	23	253	36,2	23,1	5,2	41,9
4	2	23	148	49	30,2	5,2	55,5

In Fig 2 and 3 the German Test Reference year for Freiburg is classified according to the method described.

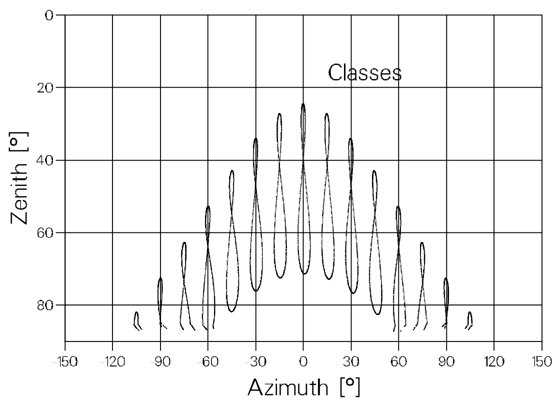

Fig. 2: Classifying the zenith angle.

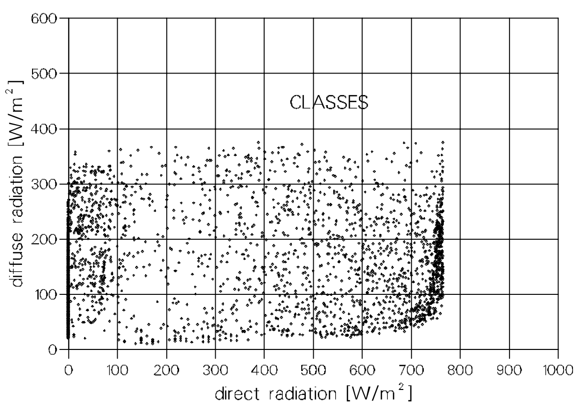

Fig. 3: Classifying the direct and diffuse radiation

A review of the existing programs was undertaken to determine the best simulation tool for this work. The most well-known program which calculates coupled daylighting and thermal scenarios over time is ADELINE, a software developed within Task 12 of the Solar Heating and Cooling programme of the International Energy Agency - IEA. In ADELINE, the sky luminance distribution is modelled according to the CIE distribution model for a cloudy sky, a clear sky without the sun and a clear sky with the sun. These sky distributions are calculated on an hourly basis for one day per month over a year. A so-called intermediate sky can be calculated by combining a clear and cloudy sky, whereby the degree of cloudiness/clearness depends on a factor called the effective sunshine probability. The effective sunshine probability is defined as the ratio of the direct illuminance at a certain time step to the theoretical maximum of the direct illuminance for this month. In this procedure in ADELINE, only the hourly direct irradiance values and the mean monthly turbidity are considered for the analysis of the different sky distributions. Variations in the brightness for the cloudy sky distribution for each time step are modelled as a Gaussian distribution and are not normalised, for example, with values for the measured hourly diffuse radiation. This can lead to less accurate results.

Coupled Daylighting and Thermal Energy Simulations

The coupling of the dynamic daylight calculations and the thermal building simulation is performed on the level of the operating system UNIX. If there is no control on the daylighting systems, the results of the daylighting calculations are directly input into the thermal simulations. In case of a controlled system (venetian blinds e.g.) an iterative solution is recommended as shown in Fig. 4.

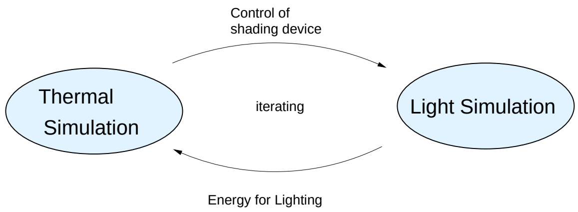

Fig. 4: Schematic view of the interaction between the light and the thermal calculations

An Example: the city hall ofHennef

The city hall in Hennef planned by Böhm & Partner in Cologne is a typical example for office buildings planned in the last years. The job of the integrated planning process was to optimise the construction of the facade and their effect as well on the temperatures in summer as on the energy demand for heating and light. The areas and the kind of glazing has been varied during the planning process. In Table 2 the electrical energy used for lighting is given for a south oriented office dependent on the amount of classes used for reduction of the climate data. The installed light sources are dimmed in groups so that an illuminance level of 500 lux was continually available. The installed power was 12.5 W/m². When the lighting was always on, the annual energy demand was 32.6 kWh/m². When the light were switched on only when the illuminance level was below 500 lux, the electrical energy demand was reduced to 5 kWh/m². The reduction potential due to dimming of the light sources is 1.8 kWh/m² for this building. In Table 2 the error due to the reduction of the time steps calculated is given as well. When the amount of hours calculated is reduced from 2610 to 331 hours, an error of 10% exists, when the number of calculated hours is even further reduced the error will increase rapidly.

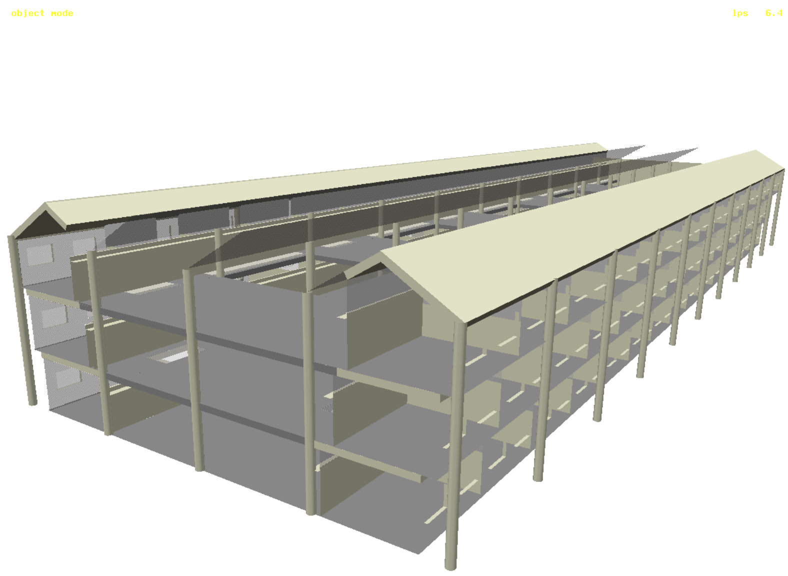

Fig.5: RADIANCE model of the city hall at Hennef

Table 2: specific annual energy demand for lighting in a south orientated office with a facade which have 2/3 transparent parts (τ_{vis}=0,7)

calculated hours		2412	331	234	157
classification	direct irradiance	-	6	6	5
	diffuse irradiance	-	3	3	2
	zenith angle	-	35	23	23
control of the lighting		annual energy demand $_{electric}$ kWh/m^2			
always switched on		32,6	32,6	32,6	32,6
switched in one group		4,95	5,12	2,83	2,81
in two groups		4,93	5,11	2,82	2,79
in one group and dimmed		3,29	3,01	2,58	2,57
in two groups and dimmed		3,22	2,92	2,57	2,56
in four groups and dimmed		3,15	2,84	2,56	2,56
max. deviation		-	9,8%	42,7%	43,4%

The above mentioned example shows that the energy demand for lighting from a primarily energetic point of view can be in the same range as the energy demand for heating of a building which meets the criteria of the German building code. But when the light gaining areas of the building are dimensioned in the right way and the light is switched on only when lighting level fall below 500 lux, the saving potential due to additional measures in the field of daylight - i.e. light redirection - is small. Fig. 6 gives the thermal energy balance of the city hall: The annual demand for heat is around 50 kWh/m².

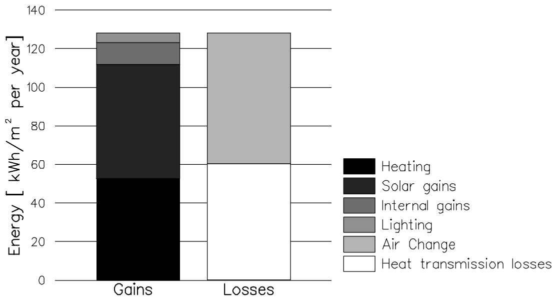

Fig. 6: Annual energy balance of the city hall in Hennef (all figures are in end energy)

A second example is an office building located in a central urban district in Hamburg, Germany. Fig. 7 gives the model of the office and it shading situation.

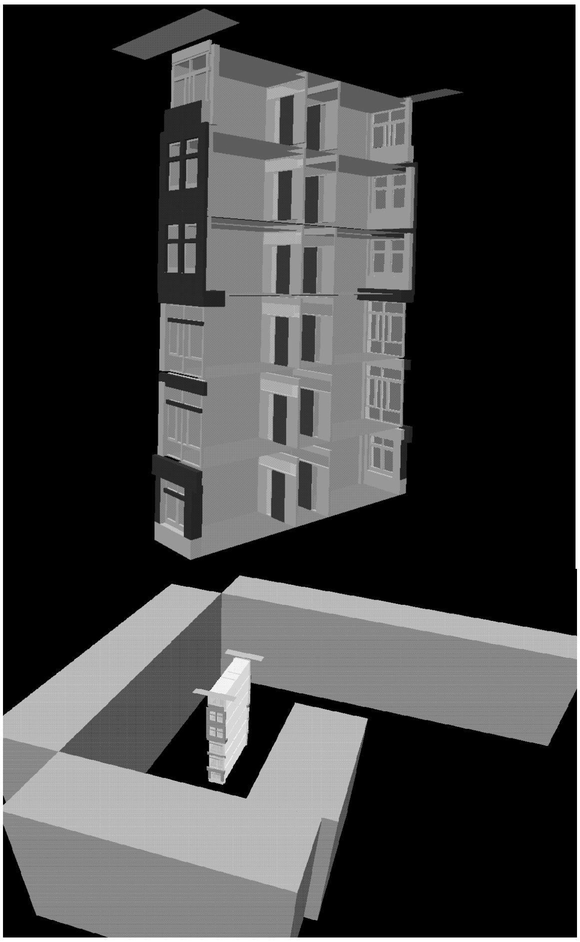

Fig. 7: Model of an office in an inner city location

The influence of two different design options for the upper part of the windows and different control strategies for the lighting on the electrical energy demand were the subjects of the investigations. In Fig 8. the annual distribution of the saving potential is given. Table 3 gives the results:

Table 3: Relative saving potential for different control strategies compared to an undimmed lighting equipment

control strategy	glass	Laser Cut Panel
1 zone dimmed	65,2 %	65,4%
2 zones, not dimmed	31,7 %	32,5%
2 zones dimmed	72,9 %	72,9%

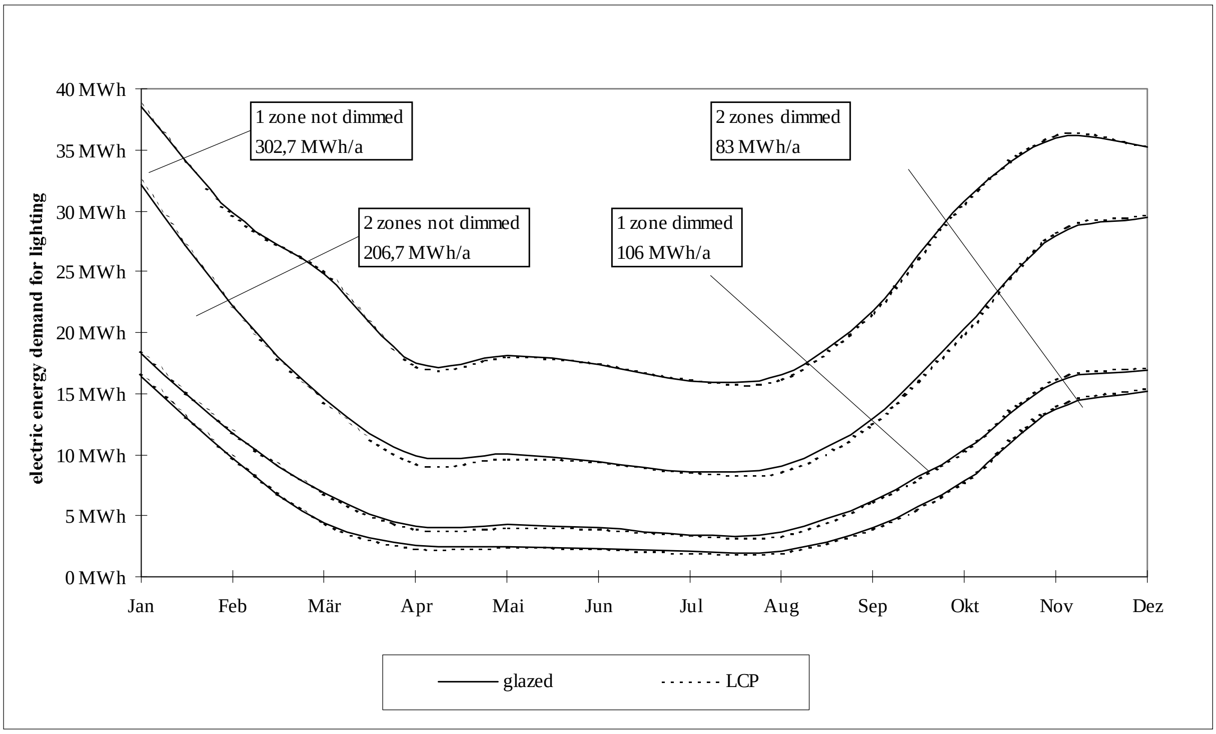

Fig. 8.: Influence of the dimming of light on the electrical energy demand for light. Two design options are considered: Glazing and Laser Cut Panels (LCP).

Conclusion

Using a dynamic lighting simulation and a link to the thermal building simulation, the energetical impact of different design options of a facade can be analysed in detail. This is important especially for buildings which already have a low energy demand.

Acknowledgements

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Literature

[Sic94] F. Sick, "Neue Chancen durch Neue Werkzeuge in der Gebäude-planung", 4. Symp. thermische Solarenergie, Staffelstein 1994

[Del95] J.J. Delaunay, "La lumiere naturelle: sa repartition direct-ionelle", Dissertation Université Strasbourg, 1995

[Api95] P. Apian-Benewitz," Messung und Modellierung von lichtstreuenden Materialien zur Computer-simulation von Tageslicht-beleuchtung", Dissertation Universität Freiburg 1995

[War94] G. Ward, "The RADIANCE 2.4 Synthetic Imaging System", University of California 1994

[Per90] R. Perez et Al., „Modelling Daylight Availability and Irradiance Components from direct and global irradiance“, Solar Energy Vol. 44. No. 5 pp. 271-289, 1990

[Ade96] M. Szerman, J. Stoffel „ADELINE 2.0, Radlink Technical Manual“ IEA Solar Heating and Cooling program, Task12