

# INTERACTIVE THREE-DIMENSIONAL VISUALISATION OF THERMAL COMFORT

Sebastian Herkel<sup>\*</sup>, Frank Schöffle<sup>\*\*</sup>, José Dionísio<sup>\*\*\*</sup>

<sup>\*</sup>Fraunhofer Institute for Solar Energy Systems (ISE), Solar Building Design Group  
Oltmannsstr. 5, D-79100 Freiburg, Germany, herkel@ise.fhg.de, Fax +49 761 4588 132

<sup>\*\*</sup>Fraunhofer Institute for Computer Graphics (IGD), D-64283 Darmstadt, Germany,  
schoeffe@igd.fhg.de

<sup>\*\*\*</sup>STA/DEM, Instituto Superior Técnico, 1096 Lisboa Codex, Portugal,  
dionisio@malhoa.ist.utl.pt

## Abstract

For improving feedback about thermal simulation results from engineers to architects, it is desirable to present them in the three-dimensional context of the building. In this paper, we present a system for improved thermal simulation and interactive 3D visualisation of the results. We describe extensions of the physically-based rendering system GENESIS-2 towards

- interactive reduction of complex CAD-models for use in building simulation (tessellation/decimation techniques).
- calculation of thermal comfort
- user-friendly interfaces for results exchange and their display within interactive Virtual Environments.

A highlight goes to the fact that the reduced thermal model is exported in STEP language, following a new technical notice of the German Engineers Society (VDI) 6021 "Data Exchange for Thermal Load Simulations". Also, radiation onto walls is simulated by the radiosity method within GENESIS-2. The thermal simulations are then performed by TRNSYS, using an import filter for VDI 6021.

The results of this simulation are transferred back to the GENESIS-2 system, where the thermal comfort is calculated according to Fanger's rule. Finally, the simulation results are visualised in the context of the original CAD-model of the building, enabling the user to interactively walk through the building and examine in real-time the simulated results. Thus, location-dependent comfort temperatures can be displayed even with a single zone model.

## Introduction

Thermal building simulation can give a detailed knowledge about the thermal behaviour of buildings. The results usually are presented as so called „fever curves“ which allows only experts to get a detailed insight on the thermal behaviour of a building. The

transport of the results to clients is more difficult: There is a need for visualisation. In order to transfer the feedback about these results from engineers to architects, it is helpful to present them in the three-dimensional context of the building.

On the other hand, radiosity-based techniques can simulate illumination in 3D environments, resulting in very realistic models. They are physically-based and rely upon the radiative transfer principles. Moreover, since the geometry stands for the basis of the form factor (view factor) computation, if there is no change of objects' position it can be applied for interactive visualisation. The mentioned techniques were applied as an innovative integrated architecture for the computation and interactive visualisation of radiation exchange within a room.

In the following sections, we briefly review the basics of the radiosity method and extensions of this method for daylight simulation. We then describe our approach for the reduction of complex architectural models for suitability in thermal simulations and interactive tools for setting up a Product Data Model (PDM) description of the model. We then present the data flow within our system, and describe our method for improved thermal comfort calculation and interactive visualisation. Example applications are shown and, finally, conclusions are drawn.

## The Radiosity Method

The radiosity method, which originated from thermal engineering, has been introduced in computer graphics in 1984 for solving the problem of global illumination simulation [Goral84]. In contrast to local illumination, where only the local properties of the regarded surface element and the light sources are taken into account, global illumination considers the complete scene geometry when simulating the irradiance onto a surface element, and thus can simulate shadows and inter-reflections. Restricted to only lambertian reflectors, this method simulates radiant energy transfers on a discretized finite element basis within an

environment, and thus solves the rendering equation [Kajiya86] in computer generated imagery. Since this method is view-independent, the results can be examined by the user by interactive walk-through. Several improvements, like progressive refinement radiosity [Cohen88] and hierarchical approaches [Hanrahan91], made the method applicable to complex environments. Further enhancements were made to enable sun and sky light simulation using the radiosity method.

### Daylight Simulation with the Radiosity Method

Early methods for daylight simulation [Nishita86][Dobashi94][Tadamura93] had several drawbacks - some are prone to artifacts or cannot catch all shadow boundaries, and they all require very expensive recalculations when sky conditions change. A powerful approach which can handle changing sky conditions efficiently has been presented by Müller et al. [Müller95]. This method uses a large sky dome placed around the scene. The sky dome is subdivided into patches according to [Tregenza87]. Each of the sky patches acts as a light source during lighting simulation, thus simulating sky light. The sun is represented by an additional point light source. Several sky models can be applied to calculate the initial luminance distribution on the sky dome patches - CIE overcast and clear sky models [CIE73] as well as the Perez sky model [Perez93] and measured data sets.

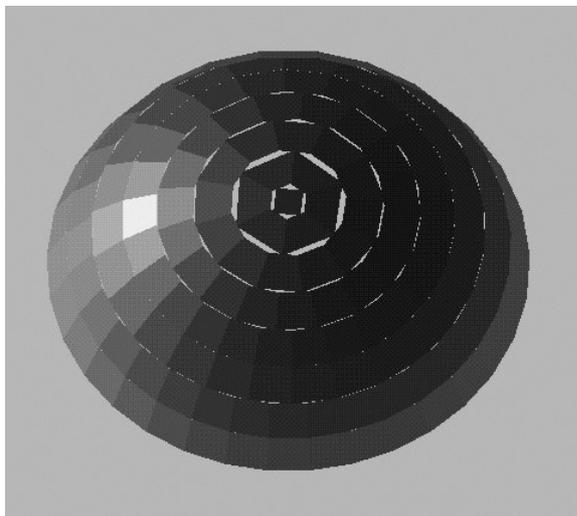


Fig. 1: Sky model of GENESIS-2 according to Tregenza's model.

### Simulating Solar Irradiance onto the Building Shape Using the Radiosity Method

We choose this approach to simulate solar Irradiance onto buildings. The radiosity method is independent of the wavelength of the radiant energy, and so the

algorithms developed for simulating visible light can be applied directly to simulate solar radiant exchange. The radiosity approach has the immediate advantage opposed to most thermal simulation packages that it considers occlusion correctly. Thus, not only orientation of facades is taken into account when simulating irradiance, but also shadows due to surrounding buildings. We feel this effect to be a significant step forward to more exact simulation of the direct irradiance reaching building facades.

For initialisation of sky patch emission, we use measured horizontal diffuse irradiance values, and for sun emission the normal diffuse irradiance is used. Thus, we have to calculate visibility and form factors in a pre-process only once for each sky patch and we can re-use it whenever a new simulation is to be performed for another place on earth or another time, e.g. - since geometric relationships between sky patches and the scene do not change. Moreover, visibility data can be stored on disk and re-used in later sessions, as long as the scene geometry remains unchanged. This allows very fast simulations for a huge amount of different points in time, like, e.g., a whole year in one-hour steps.

### Data Preparation and Product Data Modelling

There is a long discussion on shared data bases and product modelling in the field of planning tools [Bazjanac97]. The approach is to have consistent data when performing consultancy in building physics.

In 1997, a new technical notice of the German Engineers Society (VDI) 6021 "Data Exchange for Thermal Load Simulations" has been established [VDI97]. In this technical notice, an interface between CAD data and simulation tools is defined. The EXPRESS language is used using the STEP physical file format [ISO10303]. This Exchange format was available at the moment of the tool's specification and fits especially to the demands of TRNSYS [Klein et. al].

In order to create such a data file containing the specific information needed by thermal simulation programs, the huge amount of information included in a CAD-drawing has to be reduced. Within GENESIS-2, an interactive model reduction tool has been implemented. Architectural CAD data can be imported in the system in several formats (e.g., DXF and others) for interactive modification and reduction. Not used elements within the CAD-model like furniture can be neglected when performing building simulation. The system furthermore includes powerful mechanisms for scene

simplification, which is essential when preparing a model for thermal simulation. We extended these scene manipulation tools by user interfaces for

applying thermal material descriptions, defining thermal zones, and, finally, creating a product data model (PDM) description of a building.

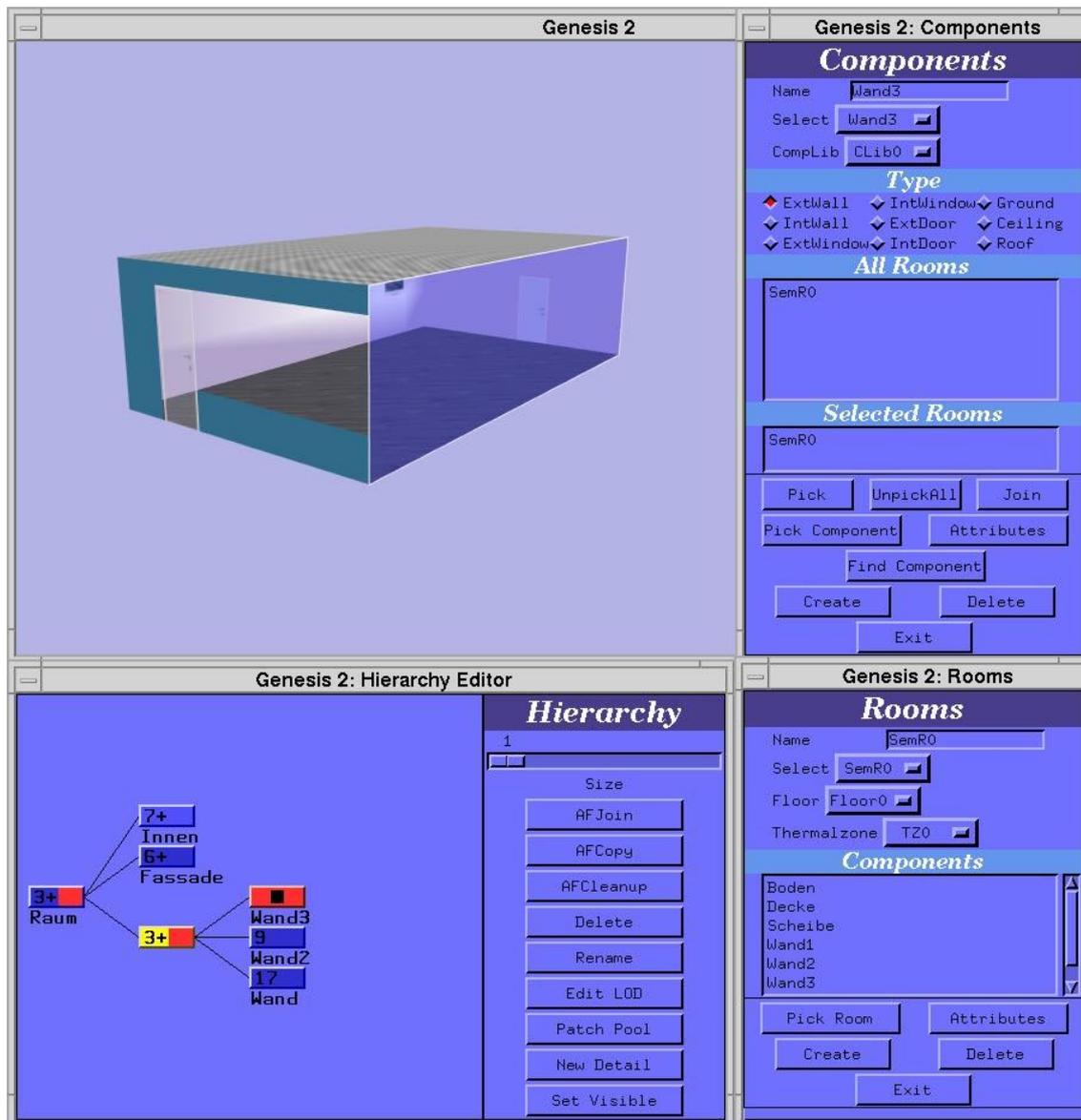


Fig 2. Interactive selection of thermal zone elements within a GENESIS -2 scene.

### System Architecture and Data Flow

When the thermal model of the building thus has been set up, the building simulation is to be performed in the next step. For this, at first a simulation of the solar irradiance onto the building shape is performed within the GENESIS-2 system. This data then is handed for further thermal simulations to a thermal simulation package. Thus even complex obstructions in a inner city context can be handled. A newly implemented filter converts the PDM into TRNSYS Input file format. For performing the thermal simulation, we use the TRNSYS package [KLEIN96] The results of the simulation (wall temperature, room air temperature,

convective heat fluxes from walls, etc.) are passed back to GENESIS-2. There, the resulting data is assigned to the associated parts of the original geometrical model, and thermal comfort is calculated taking into account the complete scene geometry and solar radiation. Finally, the results are displayed for analysis and can be examined by the user interactively in the context of the original building geometry. Fig. 3 gives a flow chart of the whole data structure and shows the overall architecture of our system.

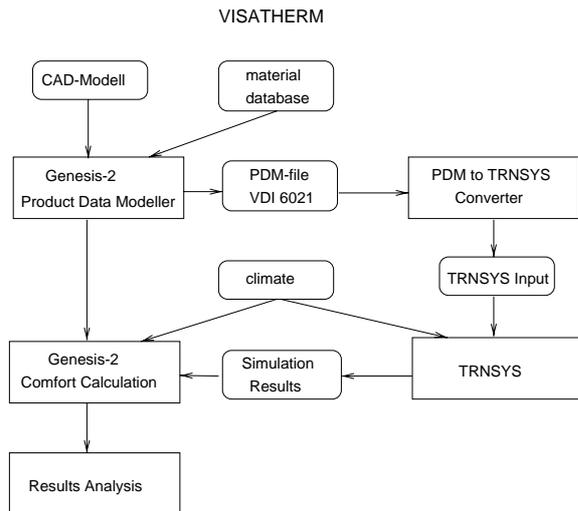


Fig. 3. Flow chart of the program structure

The current platform of the system is SGI's IRIX.

### Calculation of Thermal Comfort Using Radiosity

Within Fanger's theory of thermal comfort, the calculation of the radiation exchange between the surrounding and the human body is of high interest [Fanger82]. In thermal simulation programs, the calculation of the mean radiative temperature (MRT) often is done very roughly, not having a geometric model or a rather simple one. Knowing the surface temperatures calculated within the thermal simulation, the radiative temperature at every location in a room can be calculated correctly [ISO7730], when considering correct view factors.

Since with GENESIS-2 [Müller93] we already had a powerful radiosity system available which gives us the view factors, we implemented the algorithms described above in that system, and modified it in order to be able to simulate thermal radiant exchange. This system serves as a testing environment for novel radiosity algorithms, and therefore it provided us with efficient visibility calculation tools and several form factor calculation methods to choose from.

The thermal comfort, described by the predicted mean vote (PMV), is calculated using default values for clothing and the air velocity. For the MRT, which contributes to the PMV calculation, we decided to increase accuracy by taking into account direct irradiation by the sun and shadowing, as described in the next section.

We calculate the MRT values on a uniformly subdivided grid laid in the room of interest. The grid resolution can be specified by the user and may be

different for the three coordinate axis - the finer the grid is, the more exact the results will be, but the longer the calculation takes. MRT (and PMV) values are simulated on all grid vertices *before* visualisation and stored throughout the session.

### Adding Direct Sun Light to Thermal Comfort Calculations

When calculating the MRT and PMV values using temperatures resulting from the thermal energy simulation package, we can improve these values by adding the direct irradiation due to sun light. The influence of the direct irradiation by the sun onto the comfort level is included as well. In this calculation the sun is considered as a hot infrared source.

We compute MRT values on the 3D grid in the room we are interested in by simply gathering energy from the surrounding walls, *and*, additionally, from the sun, if visible from the grid vertex regarded. We hereby consider again occlusion due to walls and nearby buildings as well as the orientation of the test surface. The MRT value at a given point thus is calculated as

$$T_{mrt} = (T_{umrt}^4 + T_{sun}^4)^{(1/4)}$$

with  $T_{umrt}^4$  being gathered onto the test element  $p$  from all  $i$  surrounding walls according to their temperatures  $T_i$  and the view factors  $F_{(p-i)}$ :

$$T_{umrt}^4 = \sum ((T_i)^4 * F_{(p-i)})$$

$T_{sun}^4$  is calculated as

$$T_{sun}^4 = \tau * \cos(\alpha) * I_{direct\ normal} / \sigma$$

Here, occlusion is taken into account with  $\tau$ , the transparency coefficient, which is zero when the sun is not visible from the point of interest, and one if the sun is visible. Values between 0 and 1 indicate that some medium between the sun and that point attenuates the irradiance, like a window, for example. The calculations are based on the local climate data. Finally, the face's orientation towards the sun is being considered by  $\cos(\alpha)$ . Using this formula, we can compute the values for separate sides of an object within the room, and obtain different results, depending on the irradiance on the sides from the surrounding walls and the sun. At each grid vertex, we calculate and store six values, for the six sides of a cube-shaped 'proof element' (see below).

### Three-Dimensional Visualisation

For visualisation, two methods have been implemented:

- false colour representations on virtual planes in the room
- a ‘proof element’ representing the human body, realised in the form of a small cube with its six sides coloured in false colours

The planes can be placed at arbitrary positions (but parallel to the coordinate system) within the room, and the user may decide whether to visualise only one, two or three planes (oriented perpendicular to each other) at a time. For the plane visualisation, we interpolate the six values stored at the grid vertices for the six directions. The resulting values are furthermore interpolated if a plane does not lie exactly on the grid vertices, and then they are mapped to false colours. Between vertices there is also an interpolation performed within a plane, resulting in smooth colour transitions across the planes. Note that the colour of a specific point on a plane thus always represents an interpolated value of (a) the six values for the six considered directions and (b) the surrounding vertices, for which exact values have been computed.

Similar to the planes, colours are mapped onto the sides of the proof element, which can be placed arbitrarily in the room - independent from the planes. Since energy is gathered onto each side of the cube from the visible walls and the sun, they may obtain different resulting temperatures - depending on their distance from the walls, their orientation and whether this point is being directly illuminated by the sun or not, resulting in different colours for the cube’s sides.

Values which can be visualised in the described manner are MRT and PMV. Additionally, temperature and energy flux from walls can be represented by false colours directly on the walls.

Furthermore, a possibility has been realised to visualise temperature and energy flux in complete time-rows, which can be animated within the context of the 3D model. The user thus can easily ‘step through time’ or look at an animation and see how the values change while time goes by.

### Example: A Conference Room

Figures 4 to 6 show a part of a conference room, looking outside. The MRT and PMV values in this example are calculated on a 10 x 10 x 10 grid. Additionally, for a proof element, the mean radiant

temperatures are calculated. On a grid point close to a window through which the sun is shining, for example, we get a higher temperature value on the side facing outwards the window than on the other sides of the cube. At night, it will be the other way round due to the cold surface of the window.

Fig. 7 shows the energy flux from different walls within the conference room in false colour representation.

### Conclusions And Outlook

A tool for interactive simplification of complex CAD-models for use in building simulation has been implemented, which additionally allows to assign thermal properties to its components. The proposed system architecture supports improved mechanisms for thermal simulation through combination of a radiosity-based simulation tool and a thermal simulation package. Data exchange between the system components is done by exchange file formats compatible to national standards.

Using the results of a thermal simulation, the mean radiative temperature is calculated taking into account solar irradiation. Therefore, the capabilities of GENESIS-2 for fast radiosity calculations are used.

The results of the thermal simulation as well as the comfort indices are displayed within the context of the three-dimensional building in interactive Virtual Environments, enabling an easy understanding and analysis of the simulation results.

Further development will make the tool available on other platforms. The integration of other features like air flows will be done. The compatibility with other data exchange formats like the IFC will be realised.

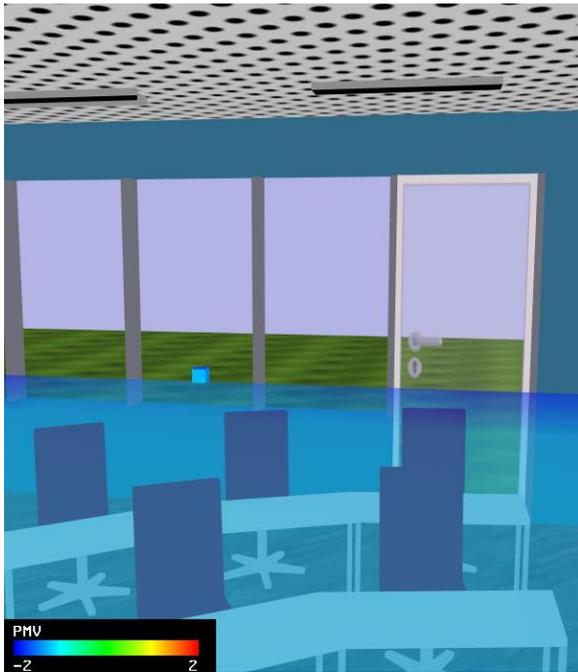


Fig 4. Distribution of PMV within a conference room at night. The area nearby the window has a low PMV value.

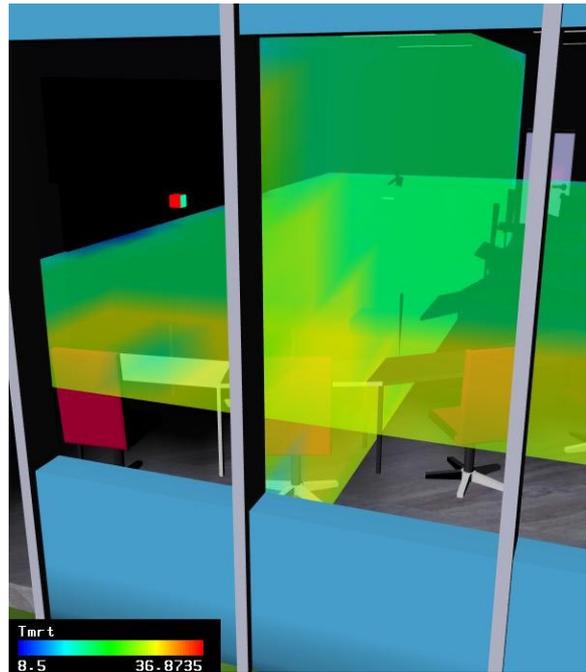
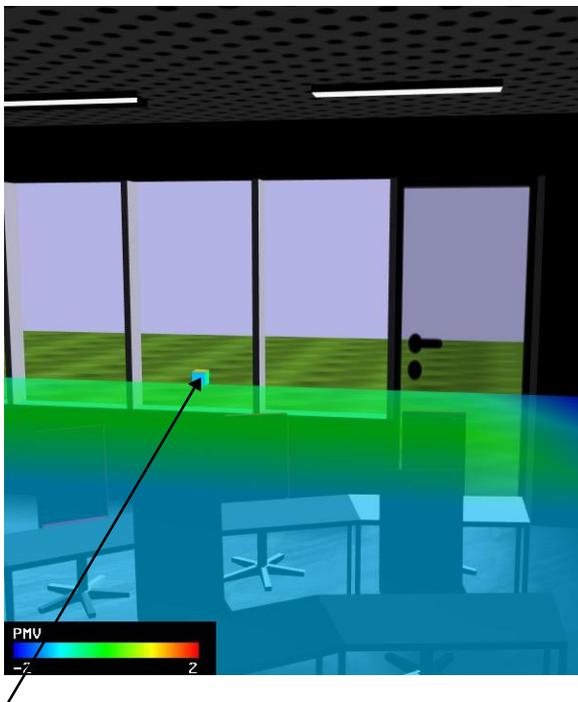


Fig 6. Distribution of the mean radiative temperature (MRT) within a conference room at noon. Due to the irradiation of the sun, the area nearby the window has higher temperatures. The MRT values are displayed on a semitransparent plane in a height of 1,2 m above the floor



proof-element

Fig. 5. Distribution of PMV within a conference room at noon. The area nearby the window has higher PMV values than the remaining regions.



Fig. 7. Energy flux from the walls within a conference room.

## Keywords

Thermal Simulation, Thermal Comfort, Radiosity, Product Data Modelling, Interactive 3D Visualisation

## Acknowledgements

Many thanks to our colleagues A. Topor, L. Marcelino, A. Pomi and T. Grosch in supporting us.

This work has been financially supported by the Fraunhofer society.

## Literature

Bazjanac V., Crawley D.: „The Implementation Of Industrial Foundation Classes In Simulation Tools For The Building Industry“, 5<sup>th</sup> IBPSA conference pp. I-203-I-210, 1997.

CIE Technical Committee 4.2. Standardisation of luminance on clear skies. CIE Publication No. 22, Commission International de l'Eclairage, Paris, 1973.

Cohen M.F., Chen S.E., Wallace J.R., Greenberg D.P.: “A Progressive Refinement Approach to Fast Radiosity Image Generation”, ACM Computer Graphics (SIGGRAPH '88 Proceedings), 22(4):75-84, 1988.

Dobashi Y., Kaneda K., Nakashima T., Yamashita H., Nishita T., Tadamura K.: “Skylight for Interior Lighting Design”, Computer Graphics Forum (EUROGRAPHICS '94), Vol. 13, No. 3, 1994, pp. C-85 -C-96.

Fanger P.O.: „Thermal Comfort“, Robert E. Krieger Publishing Company, Malabar, Florida, 1982.

Goral C.M., Torrance K.E., Greenberg, D.P., Battaille B.: “Modeling the Interaction of Light Between Diffuse Surfaces”, ACM Computer Graphics (SIGGRAPH '84 Proceedings), 18(3):213-222, 1984.

Hanrahan P., D. Salzman, L. Aupperle: “A Rapid Hierarchical Radiosity Algorithm”, ACM Computer Graphics (SIGGRAPH '91 Proceedings), Vol. 25, No. 4, July 1991, pp. 197-206.

ISO 7730 „Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort“, 1984.

ISO 10303 Part 11 „Industrial automation systems and integration - Product data representation and exchange“, 1994

Kajiya J.T.: “The Rendering Equation”, ACM Computer Graphics (SIGGRAPH '86 Proceedings), 20(4):143-150, 1986.

Klein S., Beckman W.A.: TRNSYS14.2 SEL University of Wisconsin, Madison, July 1996

Müller S., Kresse W., Gatenby N., Schöffel F.: “A Radiosity Approach for the Simulation of Daylight”, Sixth Eurographics Workshop on Rendering (1995). In: Hanrahan P.M., Purgathofer W. (eds.): Rendering Techniques '95. Springer Verlag, 1995, pp. 137-146.

Müller S., Unbescheiden M., Göbel M.: “GENESIS - Eine interaktive Forschungsumgebung zur Entwicklung parallelisierter Algorithmen für VR-Anwendungen”. In: Warnecke H.-J., Bullinger H.-J. (eds.): Virtual Reality - Anwendungen und Trends (Reihe 'Forschung und Praxis', Bd. T35). Springer Verlag, 1993, pp. 321-341.

Nishita T., Nakamae E.: “Continuous Tone Representation of Three-Dimensional Objects Illuminated by Sky Light”, ACM Computer Graphics (SIGGRAPH '86 Proceedings), Vol. 20, No. 4, August 1986, pp. 125-132.

Perez R., Seals R., Michalsky J.: “All-Weather Model for Sky Luminance Distribution - Preliminary Configuration and Validation”, Solar Energy, Vol. 50, No. 3, 1993, pp. 235-245.

Tadamura K., Nakamae E., Kaneda K., Baba M., Yamashita H., Nishita T.: “Modeling of Skylight and Rendering of Outdoor Scenes”, Computer Graphics Forum (EUROGRAPHICS '93), Vol. 12, No. 3, 1993, pp. C-189-C-200.

Tregenza P.R.: “Subdivision of the sky hemisphere for luminance measurements”, Lighting Research and Technology, Vol. 19, 1987, pp. 13-14.

VDI 6021 „Datenaustausch thermische Lastberechnungen“, Verein Deutscher Ingenieure, Düsseldorf, 1997.