NATURAL-LIGHTING DESIGN IN ARCHITECTURE: FILLING IN THE BLANKS

Benjamin Geebelen and Herman Neuckermans
Dept. of Architecture, K.U.Leuven
Leuven 3001, Belgium

ABSTRACT

This paper discusses the first full version of IDEA-l, a new natural-lighting design tool for the early stages of the architectural design process. This computer program, which is part of the larger IDEA+ research project, allows the user to judge the impact of natural light on his architectural design. For this purpose a number of tests are provided, covering different aspects of natural lighting. This paper will discuss each of the tests and the involved algorithms. The paper will end with a reflection on the IDEA+ project, which aims at providing a new integrated design environment for architecture.

PURPOSES AND FEATURES

Lighting design in architecture

The past few decades an increasing number of research projects have illustrated a growing interest in natural lighting. Rising ecological awareness, combined with new insights into the psychological and physical effects of daylight and daylight deprivation, have sparked a number of research initiatives worldwide that study the potential of daylight for decreasing energy consumption, reducing carbon-dioxide emissions and improving the well-being of our buildings' inhabitants.

These projects have resulted in the definition of the daylight factor, in the introduction of standard skies and of design guidelines, in a few "manual" computation methods and, more recently, in the development of a number of computer tools. Most of these computers tools aim at an in-depth simulation of the light propagation in a building, sometimes even combined with a full thermal simulation. Examples include Radiance, Adeline, DOE2, and ESP-r. Most of these programs can produce amazing results when operated carefully, i.e. by a skilled and knowledgeable user and based on elaborate and accurate input. Because of their nature these applications are best suited for the later stages in the architectural design process. Not only is their use labor-intensive and therefore expensive, they also require a level of detail that is not available in earlier stages. Typically consultancy firms use this kind of software.

As for the early stages of the architectural design process, a number of tools have been developed to compute the daylight factor, including protractors, tables, dot charts and diagrams. None of these require a high level of expertise or a high level of detail. They seem therefore excellently suited for the conceptual design stage. However, their use is not nearly as widespread as one would expect. A number of reasons can be found: their result, the daylight factor, is not very informative; the fact that all calculations have to made by hand makes them rather cumbersome to use; many designers feel they can rely upon their intuition when it comes to lighting…

What does this mean for the component of lighting in architectural design? Lighting, if at all treated, is in most cases reduced to the very last stages. For artificial lighting this can seem completely justified. However, natural lighting includes a wide range of aspects that can affect design decisions as early as conceptual design. Research has shown that often very important conceptual decisions are taken based on assumptions without any form of prior assessment (de Wilde et al. 1999)(Saelens & Hens 2000). Too often poorly chosen design options are optimized, options that might have been abandoned in the conceptual design stage when looked at closely. This situation, which is not limited to lighting, cannot be justified, considering that early design decisions tend to have the greatest impact.

Changing this situation is not an uncomplicated task. It involves a change in mentality on behalf of the designer, perhaps a change in the education of architects, it requires the careful study of conceptual design decisions and the availability of appropriate assessment tools. Providing one of these tools is what we aim at with the development of IDEA-l (read "idea-ell"). This program, which is part of the larger IDEA+ research project at K.U.Leuven, aims at providing a means for the designer of judging the impact of natural lighting on his design right at the beginning of the design process.

General requirements

The development of IDEA-l is governed by one basic principle: it has to be easily accessible in an early design stage. This entails ensuring ease-of-use, requiring only a low level of expertise and avoiding excessive work. A great deal of the program's structure, features and functionality is determined by this principle: data input is kept to a minimum, and throughout the program the user is offered assistance in choosing appropriate tests, in performing them, in interpreting results and in making decisions based upon these results.

Aspects, quantities and criteria

Lighting is a complex amalgam of different aspects. They can roughly be categorized into three groups: functional requirements, visual comfort and aesthetic quality. Depending on the functional brief of a building or a room one or more of these aspects will become important and will require assessment.

Not only do the aspects depend upon the function of a building, the same applies to the criteria that have to be met. Direct sunlight can be pleasant in a residential context; it rarely is in a museum.

After the user has provided the functional brief, IDEA-l suggests a selection of aspects to be tested. The user can always broaden or narrow this selection to his liking. For each of the chosen aspects the program automatically chooses the fitting criteria.

For each of the aspects that can be quantified we examined the currently used quantities. More precisely we wanted to explore the possibilities of more informative and more intuitive quantities. The daylight factor, for instance, is a straightforward way of eliminating the effect of changing sky luminance and quantifying light levels, but to a designer its lack of informative value greatly reduces its appeal. However, linked to functional requirements, we can deduce far more informative quantities from it, such as daylight autonomy. Traditional quantities and criteria are still incorporated, but supplemented with a few new quantities. The performances for each quantity are not only compared with possible criteria, but also graded on an intuitive scale, ranging from "very poor" to "excellent".

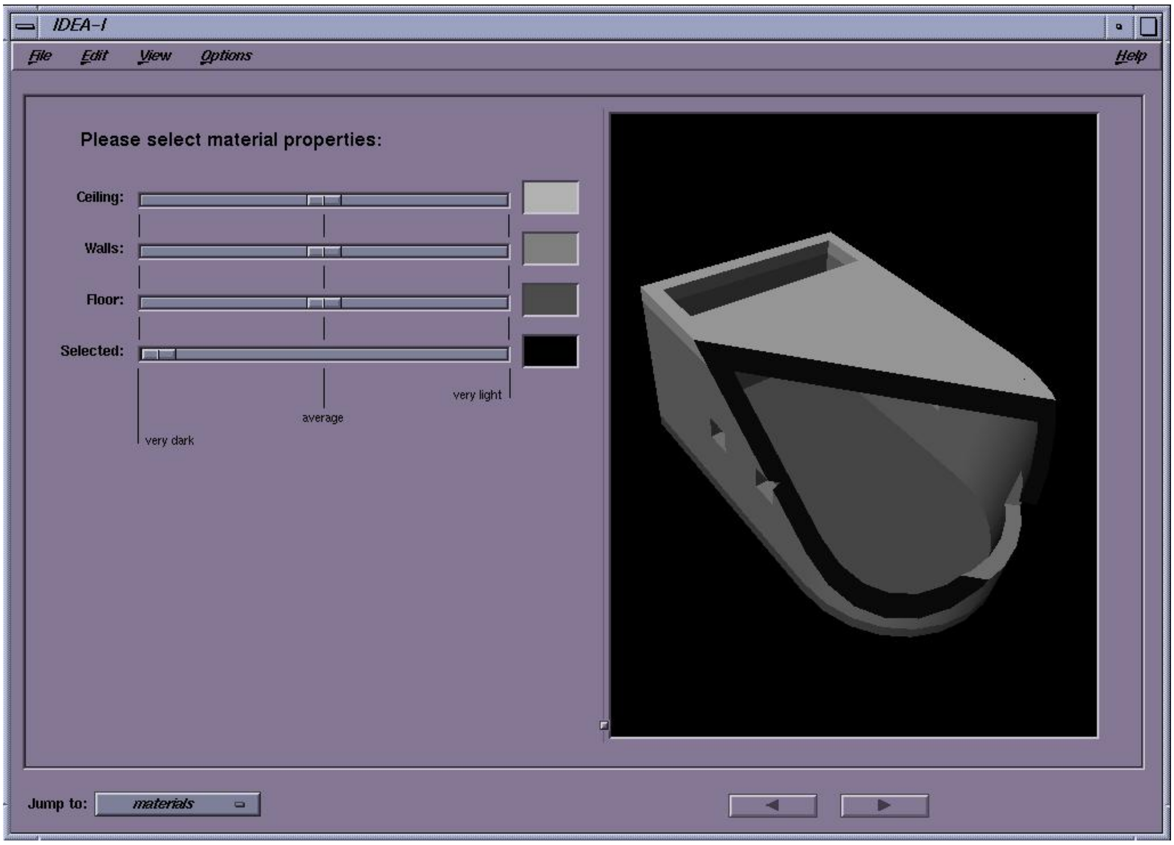

Figure 1: Screen shot from first partial version (September 2000). Data input is intuitive rather than quantitative.

Tests

The provided tests follow the aforementioned aspect categories. For each category one or more tests can be run.

For functional requirements, the program offers the daylight factor, daylight autonomy, illuminance levels based on statistical weather data, insolation time, heat gains from direct sunlight and the solar envelope.

Visual comfort is more complex as a performance. It cannot be easily quantified, and the appreciation of a lighting situation strongly depends on the observer. After a few decades of research a fitting answer to this problem is yet to be found (Velds 1999). We have chosen to include the glare index as a measure for comfort.

Only the designer can judge aesthetic quality. IDEA-l offers him the possibility of making semi-realistic renderings, walkthroughs and timeframe animations. Important here is that the user gets a general idea of the light distribution in his design, and that the process doesn't become too time consuming. Elements like the fine-tuning of material properties and texture maps are therefore deliberately omitted.

Additional features

Extensive help functions assist the user in every stage, including help files, "tooltip help", message fields in dialog boxes and an online glossary. They explain the relevance of different aspects, the corresponding tested quantities and help interpreting the test results. In conflicting situations the program helps the user in finding a solution by suggesting a range of possible design options to explore. This last feature is deliberately kept rather general: it is not the computer's task to produce a limited set of alternatives from which to choose, but to steer the designer in the right direction. Creativity is in no way jeopardized.

User interface and input

The design of the user interface has been greatly governed by the underlying principle discussed above. In order not to overwhelm the user with screen-filling dialog boxes we have opted for the structure of a wizard, a program that guides the user through the process one step at a time.

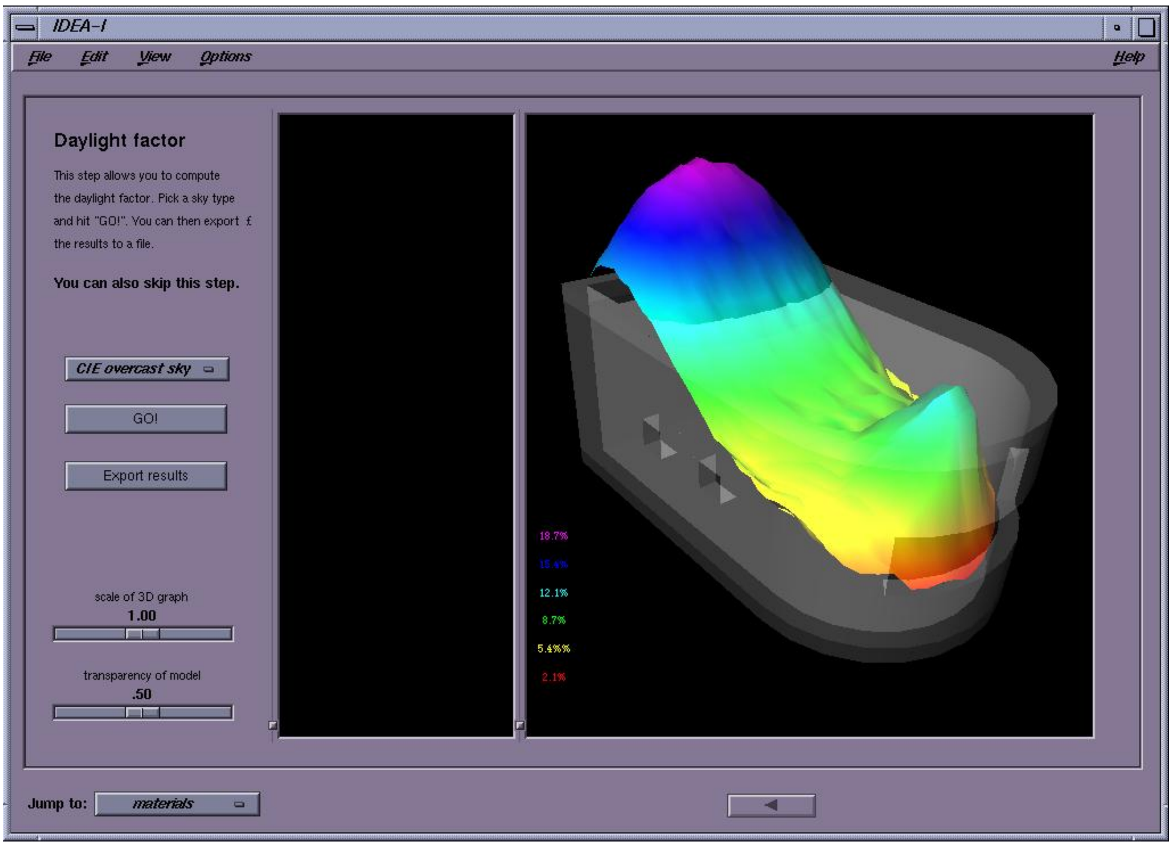

Figure 2: Screen shot from the first partial version (September 2000). The daylight factor is one of the quantities that can be computed.

In order to lower the required level of expertise, most quantitative data input has been replaced by qualitative statements, which are then translated into appropriate values by the program. Of course more expert users have the choice to manipulate the numerical values.

We feel the user has to be able to perform tests on the design he is working on, instead of abstract box-like rooms. We have therefore provided import facilities from known file formats, .dxf and .rad. More ideally the geometric data comes from the IDEA+ database, which is explained below.

ALGORITHMS

Making the program suited for early design stages implies minimal waiting times. However, with ever-increasing processor performance, speed becomes less of an issue. The computing power at our disposal allows us to make use of more complex calculation algorithms and thus improve accuracy.

Diffuse sky radiation

Diffuse sky radiation or skylight[1] can be divided into a direct and an indirect part. The indirect part can then be divided further into an internally reflected and an externally reflected component.

Direct component
IDEA-l computes the direct sky component analytically for the uniform and standard overcast skies and for polygonal window openings. Other window shapes are approximated with polygons. Other sky types will be added in the near future.

The direct sky component is the only one that can be computed analytically. It was never done before, because the complexity does not allow for calculations by hand. However, with the computer at our disposal, there is no need to settle for less.

The principle is fairly straightforward. In order to compute the light coming from the sky dome through a polygonal window, we regard the solid angle that is described by that window as the composition of the solid angles below each of the sides of the polygon (Figure 3).

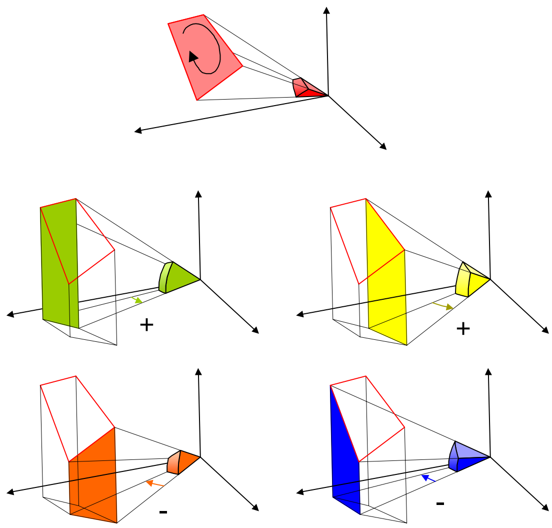

Figure 3: The decomposition of the solid angle described by a polygonal window.

In order to obtain the irradiance in a point on a horizontal plane, we have to solve the following equation for each of the partial solid angles:

$$E_h = \int_\Omega L(\vartheta,\varphi).\cos(\vartheta).d\omega$$

For the Moon and Spencer sky this results in:

$$E_h = \frac{L_z}{6}\left(\varphi_1 - \frac{t_0.t_1.s_1}{D}.\left(\arctan\left(\frac{D}{t_0.t_1.c_1+1}\right)+C\right)\right)$$
$$+\frac{2.L_z}{9}.\left(\begin{array}{l}\frac{|\varphi_1|}{\varphi_1}.\left(\arcsin\left(\frac{t_0-t_1.c_1}{D}\right)+\arcsin\left(\frac{t_1-t_0.c_1}{D}\right)\right)\\ -\frac{t_0^2.t_1^2.s_1}{D^2}.\left(\frac{t_0-t_1.c_1}{t_1.\sqrt{t_0^2+1}}+\frac{t_1-c_1.t_0}{t_0.\sqrt{t_1^2+1}}\right)\end{array}\right)$$

where

$$\begin{aligned}
L_z &= \text{Radiance of the zenith}\\
t_0 &= \tan(\vartheta_0)\\
t_1 &= \tan(\vartheta_1)\\
s_1 &= \sin(\varphi_1)\\
c_1 &= \cos(\varphi_1)\\
D &= \sqrt{t_0^2.t_1^2.s_1^2+t_0^2+t_1^2-2.t_0.t_1.c_1}\\
C &= 0, -\pi \text{ or } \pi
\end{aligned}$$

and ϑ_0, ϑ_1 and φ_1 can be found in Figure 4.

[1] We use the terminology as proposed by CEC

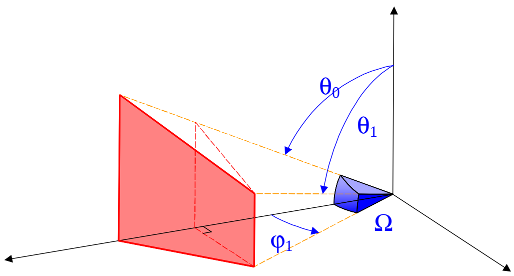

Figure 4: The solid angle below a line.

Indirect component
The indirect sky component can only be computed analytically for a very limited set of ideal situations. We have therefore chosen a new approach, which is a mix between a simple radiosity method and an empirical solution. The externally reflected component is approximated empirically. For the internal reflections all polygons in a scene are first regrouped into larger surfaces, based upon the information in the IDEA+ database. The irradiances on these surfaces are then computed with a crude radiosity step, which treats each surface as a uniform emitter.

This procedure is still in the experimental stage. Test results will provide validation data in the coming months.

Insolation

Depending on the test the user asks for, insolation is computed by means of a forward (i.e. as seen from the position of the sun) or a backward (i.e. as seen from within the model) projection.

For a forward projection, all obstructions, whether building elements, parts of the surroundings or shading devices, are projected on the model. This can be useful when the user wishes to see how shadows are formed throughout a day of the year.

When examining a single point or a single surface, it can be far more interesting to use a backward projection. Here the obstructions are projected on the sun trajectories. This allows us to analytically determine the exact times at which each obstruction blocks the sun for the examined point. We can thus compute for each point the number of hours of direct sunlight for each day of the year or the average number of hours of direct sunlight for each month of the year. For each surface, we can compute the percentage of area that is struck by direct sunlight for any time of day and any day of the year.

Rendering

As mentioned before, it is more important that our program provides a good idea of the light distribution in a short amount of time than that it can produce spectacular images with hyper-realistic texture mapping and flashy reflections. Our goals do not correspond with those of most commercial rendering packages. The objective of IDEA-l is not to produce images for presentation purposes, but only to allow the designer to check whether his design corresponds with what he intended. For this we need a fast and yet reliable algorithm.

We believe to have found a good compromise in the hierarchical stochastic radiosity method developed at the Computer Science departments of K.U.Leuven

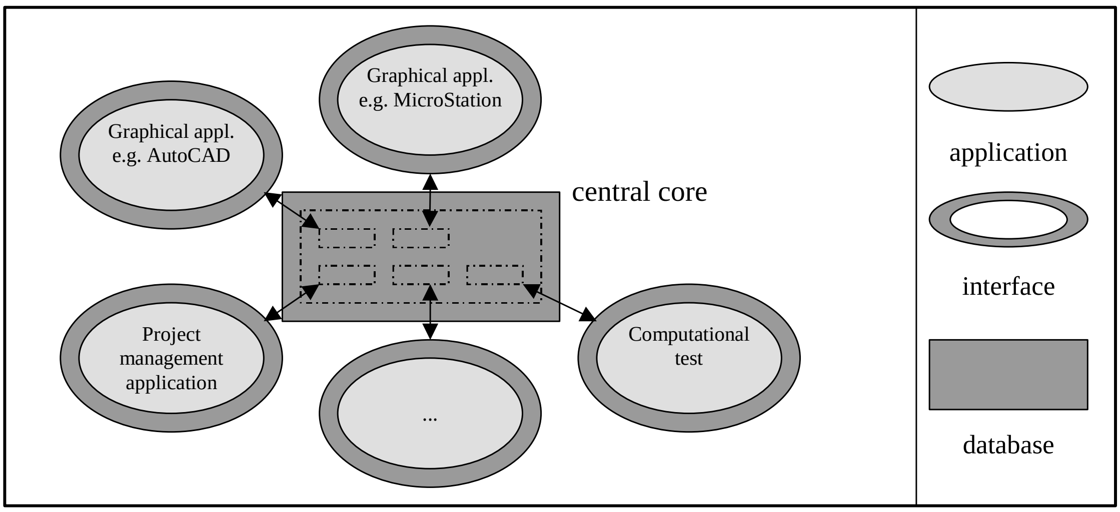

Figure 5: The central-core model

and the Universitat di Girona (Prikryl 2000). This bi-directional algorithm is view-importance driven and uses weighted importance sampling techniques for Monte Carlo form factor computation (Bekaert et al. 2000b) and stochastic Jacobi iterations for the radiosity system solution (Bekaert et al. 2000a). The result is a very fast and progressive technique. Fairly good results are produced in a very small amount of time and are then gradually refined. The user can immediately decide whether to kill the rendering and start over, or to wait for a more accurate result.

Further testing will have to point out the applicability, reliability and accuracy of this method.

DEVELOPMENT STATUS

A first partial version of IDEA-l was finished in September of 2000. Since then, development has continued and a first fully functional version is due for July 2001. It should then contain most of the features described in this paper. These versions run on IRIX 6.5, but will be ported to Windows2000 in the future. Before that time our attention will focus on further development, thorough testing and validation of the used algorithms.

CONTEXT

IDEA+

The IDEA+ research project aims at the development of a new *I*ntegrated *D*esign *E*nvironment for *A*rchitects that is meant to correspond better with the needs and practices of architect/designers. If we look at architectural design software today, we can discern two major flaws: it is not suited for all different stages in the design process, and it causes the design team to create a host of redundant models and files.

Central Core Model

The latter problem is easily recognized: by the time a project reaches the construction phase, it has been described in sketches, preliminary plans, construction plans, facade drawings, sections, etc. To top this heap of information off, every additional member of the design team, whether building physicist, lighting designer or constructional engineer, produces at least one extra digital model to perform his tests on. The production of all those models of what is essentially one single design is an obvious waste of time and manpower, and in the end leads to the impossible task of keeping these different models consistent.

Several research teams around the world have acknowledged this problem (Eastman et al. 1997)(Hendricx 1997a/b)(Khemlani et al. 1997) and are simultaneously working on conceptual object models for architectural databases. In this approach, as illustrated in Figure 5, all software should be built around one central database that contains all possible relevant data. This way consistency of data is guaranteed, and redundancy is avoided. Each separate program, whether modeller, stability test, lighting test or acoustical test, can then be linked with this database through its own interface and address only the set of data fields it needs. When provided with appropriate interfaces, existing software can remain in use.

CONCLUSION

We have presented the specifications for a new design tool for natural lighting, a prototype of which is currently under development at K.U.Leuven, specifically devised for use by architects in the early stages of the design process. This tool is meant to fill a void in the architects' toolbox by offering a quick estimate of the impact of their design choices on the lighting quality of their projects. With it, architects will be able to get a grip on every-day daylighting problems for which, until today, they have had to rely upon their intuition. Our aim is to allow for conceptual design decisions to be made based upon knowledge instead of guess. Though this is merely one step in a series of many, we feel confident that this is a step in the right direction.

REFERENCES

Bekaert, Ph., M. Sbert and Y.D. Willems, "The Computation of Higher-Order Radiosity Approximations with a Stochastic Jacobi Iterative Method", in: proceedings of the Spring Conference on Computer Graphics (SCCG) 2000, Budmerice, Slovak Republic, May 3-6, 2000a.

Bekaert, Ph., M. Sbert and Y. D. Willems, "Weighted Importance Sampling Techniques for Monte Carlo Radiosity", in: proceedings of the 11th Eurographics Workshop on Rendering Brno, Czech Republic, June 26-28, 2000b.

de Wilde, P., G. Augenbroe and M. van der Voorden, "Invocation of Building Simulation Tools in Building Design Practice", in: proceedings of Building Simulation '99, Kyoto, September 13-15, 1999.

Eastman, C., T.S. Jeng, R. Chowdbury and K. Jacobsen, "Integration of Design Applications with Building Models", in: CAAD Futures 1997, Kluwer Academic Publ., Dordrecht, 1997.

Hendricx, A., "Shape, Space and Building Element: Development of a Conceptual Object Model for the Design Process", in: Challenges of the Future, Proceedings of the 15th European Conference on Education in Computer Aided Architectural Design, Vienna, Austria, September 17-20, 1997a (only available on CD-ROM).

Hendricx, A., “The Building Model Revisited: a Conceptual Object Model for Architectural Design in the Early Design Stage”, in: Computers in the Practice of Building and Civil Engineering, Proceedings of the Worldwide ECCE Symposium, Finland, September 3-5, 1997b.

Khemlani, L. and Y.E. Kalay, “An Integrated Computing Environment For Collaborative, Multi-Disciplinary Building Design”, in: CAAD Futures 1997, Kluwer Academic Publ., Dordrecht, 1997.

Prikryl, J., Ph. Bekaert, and W. Purgathofer, “Importance-Driven Hierarchical Stochastic Ray Radiosity”, in: proceedings of the 8-th International Conference in Central Europe on Computer Graphics, Visualization and Interactive Digital Media 2000 (WSCG 2000), Plzen, Czech Republic, February 7--11, 2000.

Saelens, D. and H. Hens, “Active Envelopes, The Future for Low-Energy Office Buildings?”, in: Tools for Design and Engineering of Buildings, proceedings of the International Building Physics Conference 2000, Eindhoven, September 18-21, 2000.

Velds, M, “Assessment of lighting quality in office rooms with daylighting systems”, T.U.Delft, Delft, 1999.