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A computer-based daylight systems design tool

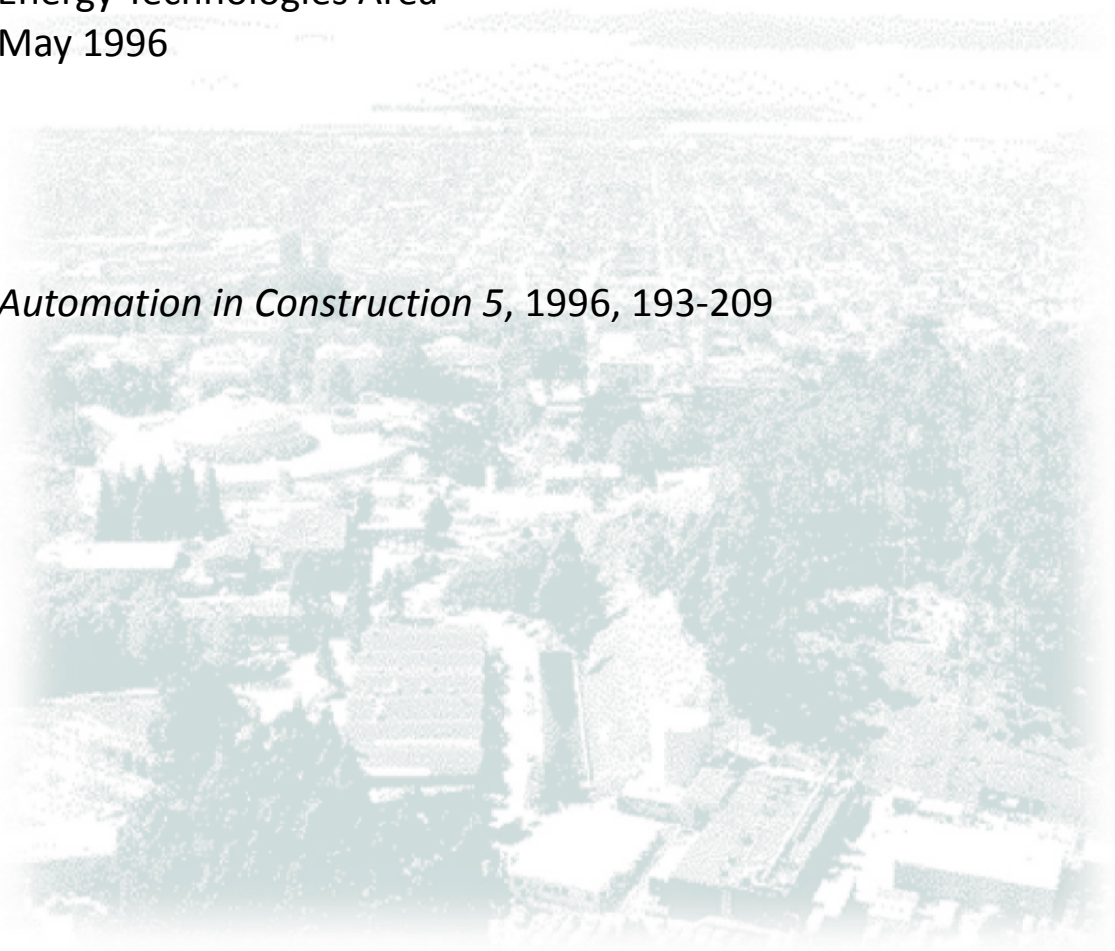
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A computer-based daylight systems design tool ¹

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Abstract

Currently numbers like illuminance or glare index are used for the evaluation of daylight system designs. We propose to use photorealistic pictures in addition to numbers as a way to assess the quality of a design solution. This is necessary since numbers-based performance criteria, that are currently in use, are either not sufficient to evaluate performance, or they require expert knowledge for interpretation. The paper discusses the implications and ramifications of this approach.

Keywords: Interactive simulation; Non-numerical performance criteria; Photorealism; Visual comfort; Performance based visualization; Indirect evaluation of performance

1. Introduction

Daylight systems in architecture are mostly designed to fulfill three different requirements: from many architects' point of view, they should be aesthetically pleasing, from the building owners' point of view they should be designed to reduce the energy bill, and from the occupant's point of view they should produce visual comfort. Some, but not all, of these conditions can be broken down into criteria that express the performance of a design solution with a particular daylight system in numbers such as daylight factor, glare index or equivalent sphere illumination [1]. These numbers are numerical performance criteria derived from specific formulae. They are established [2,3], changed or discarded by experts' associations for a particular design domain

[4–7]. The formulae are subject to change over time. In addition, numbers may be ambiguous since different designs can produce identical numerical performance values (for a definition of context, design and performance variables, see Rittel [8]).

Due to the changing, and sometimes incomplete, nature of formulae derived performance analysis, numbers are not always enough to describe the performance of a design solution. Human perception can detect patterns revealing underlying structure in visualizations more readily than by direct analysis of numbers, graphs and charts. Since computer-based simulations might be more meaningful to the architect and deliver information that is often very difficult or impossible to express as formulae, it is very helpful to refer to more complex representations of the performance of a particular design (e.g. a photorealistic picture showing reflected glare in a computer monitor due to glossy venetian blinds, or a picture showing how sunlight is reflected off an airport glass facade and might blind a pilot who maneuvers his aircraft). There are currently no for-

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¹ Discussion is open until March 1997 (please submit your discussion paper to the Editor of Architecture, Y.E. Kalay).

mulae for expressing these effects, especially if they are time dependent. However, given today's simulation algorithms and software, it is not only feasible to simulate these effects, but it is absolutely necessary since designs with flaws such as reflected glare will immediately lead to complaints once the solution is built. Therefore we need to rely on very extensive simulations in order to avoid these flaws. Computer-based design tools that incorporate these simulations need to fulfill the following requirements:

1. They must describe the behavior of light in a physically accurate way. Although this sounds trivial, it is difficult.
2. They need to take into account viewer sensation and perception.
3. They need to allow for consistent comparisons of photorealistic pictures (e.g. we are able to compare daylight factors of a room with different daylight systems).

4. They need to allow for interactive simulation — simulation speed is a vital issue.
5. They need to be user friendly in order to facilitate rapid input and to allow the user to generate a large variety of solutions in a short time.

2. Need for physically accurate simulation

It is essential to have a software tool that can describe the physical behavior of the most commonly found elements for a particular design domain. This requires physically accurate modeling. In the lighting context, it means that the software can accurately calculate the behavior of light for the most commonly found building materials, forms and design elements. Daylight system components such as screens, blinds and light shelves must be modeled, and various sky conditions, site parameters and common building materials must be shown. In addition,

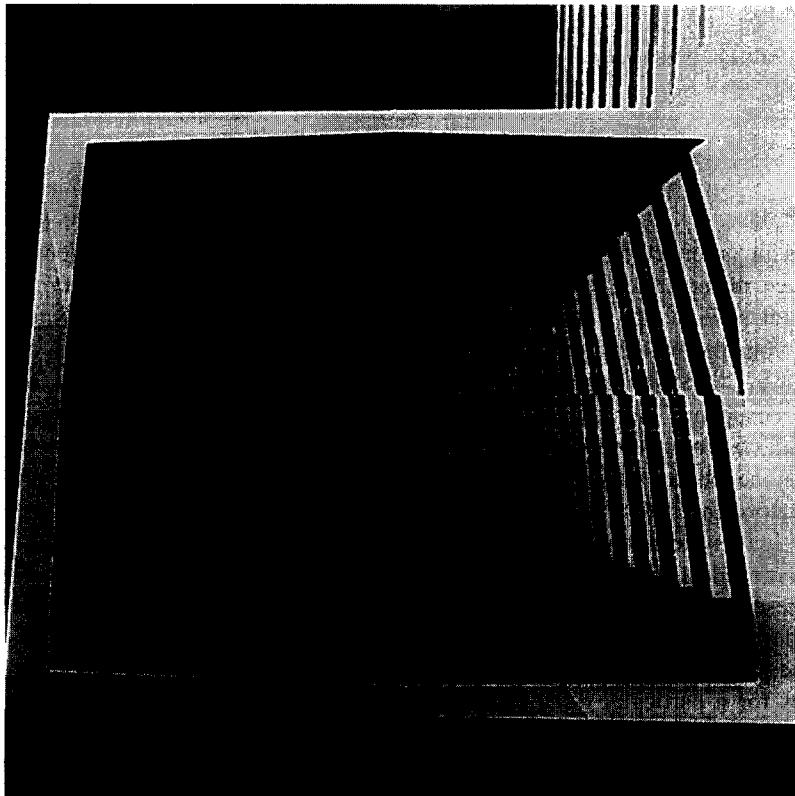


Fig. 1. Photorealistic simulation of reflected glare in a computer monitor. The screen pixel luminance ranges from 0 to 150 cd m^{-2} . Although the average luminance of the daylight system is within the specification of lighting codes, some letters are barely legible.

we might want to display effects such as reflected glare on a computer monitor, etc. For the daylight systems (e.g. light shelves) and context variables (e.g. location or time), we are interested in simulating the behavior of daylight for the purpose of adjusting a known set of design parameters (e.g. daylight system geometry, material properties like surface gloss or room shape).

The complex geometry of environments with vari-

ous daylight systems makes closed-form solutions hopeless, since it involves two or more dimensions or nonlinear effects, thereby yielding nonlinear differential equations. If we are interested in simple spaces with one daylight system limited to a few attributes, closed form solutions could be used [9,10]. However, the systems to be considered include venetian blinds, lightshelves and screens, and any combination thereof (these are the daylight systems com-

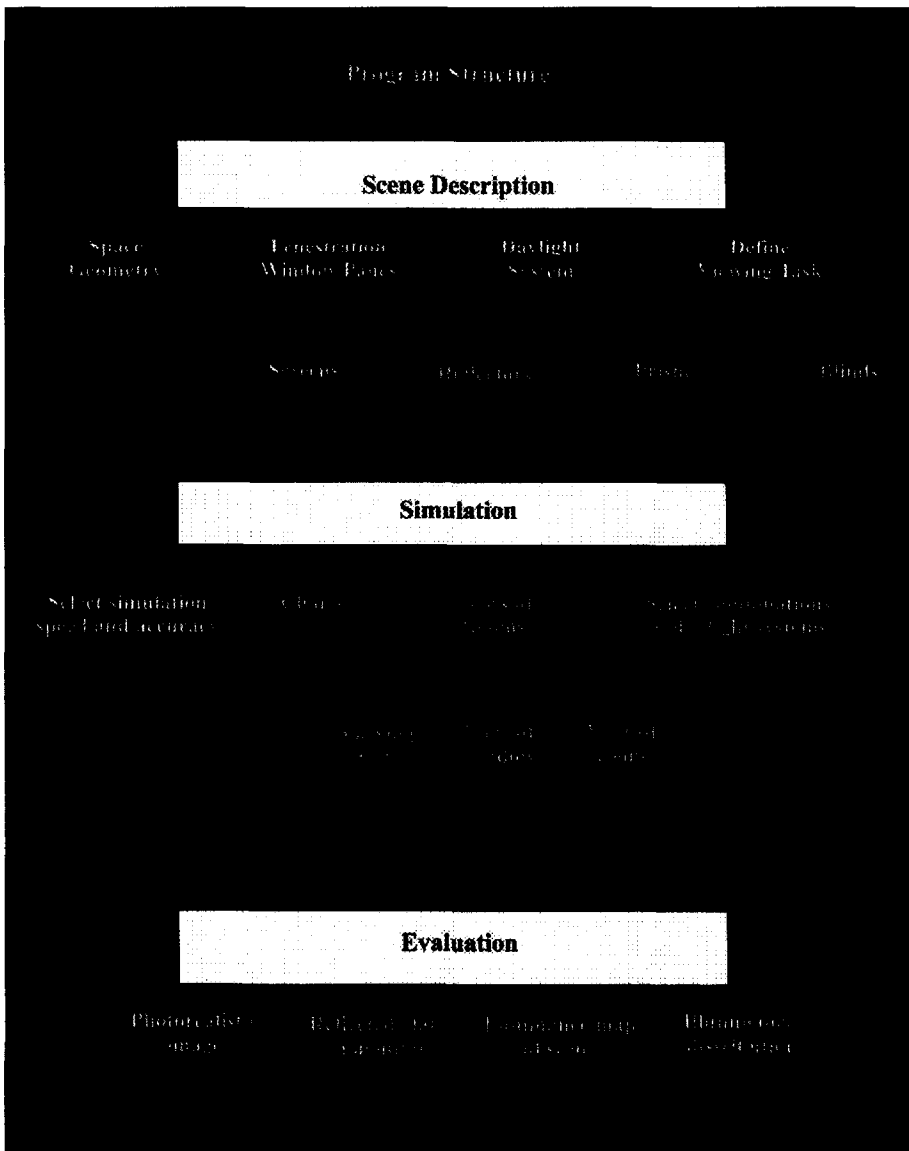


Plate 1. Flowchart with the program structure.

mon in the US). In addition, in order to model window panes and daylight systems with clear to totally diffuse reflectance and transmittance, various materials like clear glazing, translucent panes and opaque surfaces with glossy, matte and rough or smooth surface reflection properties need to be considered. Therefore, we need to rely upon numerical methods. A large assortment of numerical techniques exists for solving integral equations [11–14]. In lighting, Monte Carlo methods are used scenes with arbitrary complexity, where the radiance function is a function of four variables (surface position and direction) and where finite element methods would be too cumbersome. They can model effects like shadows with fuzzy or crisp edges, interreflections, surface gloss, transparency and translucency, thus making the rendered scenes highly realistic [15–17].

The software package Radiance, a ray tracing program employing Monte Carlo methods, is suited for these lighting simulations and has also been verified against field measurements and other lighting simulation software [18,19].

3. Consider viewer sensation and perception

It is necessary to take into account the perception of the human observer when simulating the results. The image display should match, as closely as possible, the sensation in the actual scene when perceived by a sample of human observers. In the visualization of illuminated scenes, methods for image synthesis calculate the ‘real world’ radiance instead of the monitor radiance values. The perceived visual sensa-

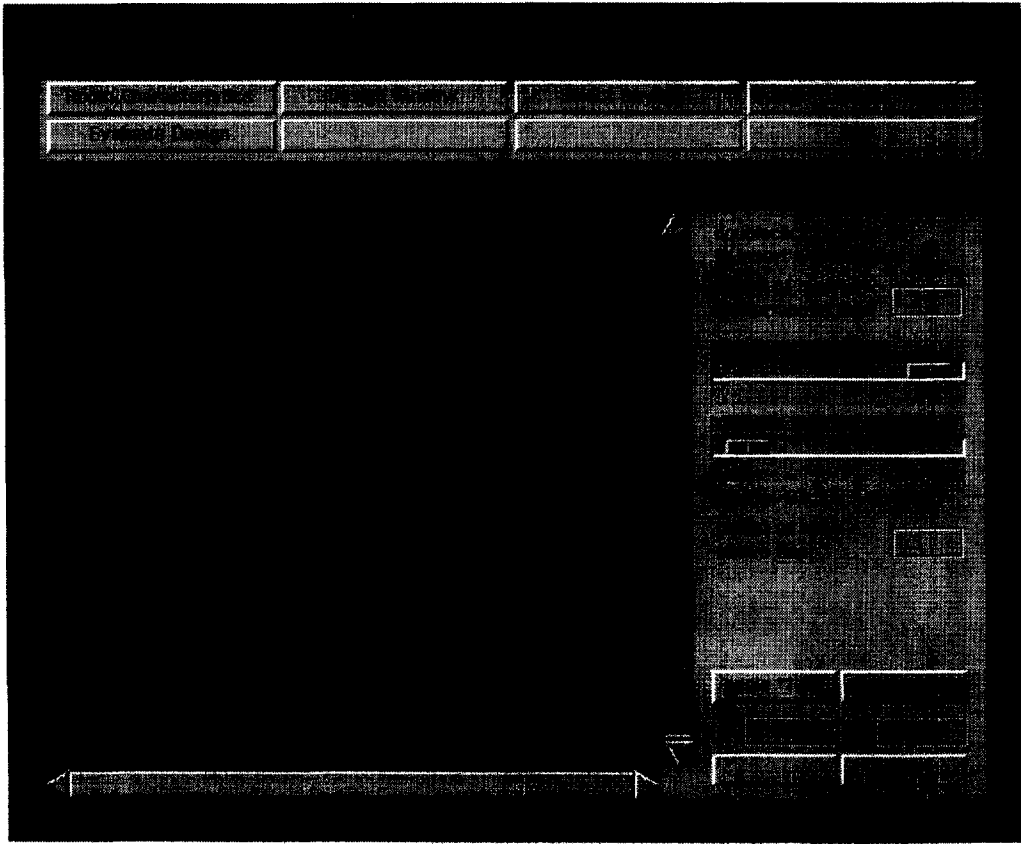


Fig. 2. Interactive input of the computer monitor location and viewpoint characteristics on a 2D plan. The monitor can be placed anywhere and tilted and rotated to any desired location.

tions are not truly equivalent. Tone reproduction is a problem in computer graphics as well as in photography. In photography, corrections are usually limited by the chemical restrictions of the film. In computer graphics, the wide ranging scene radiances have to be converted to a very small range of display radiances on a monitor or another display device. These conversions can be dubious or aphysical since they may ignore light dependent changes in the way we see [20,21]. This means that scene context parameters such as adaptation have to be considered. In the lighting context, several proposals have been made to translate scene luminance into screen luminance as well as to consider viewer adaptation for a particular view. The proposals have not yet been experimentally validated, but their results appear to be promising. We use such a model to display pictures scaled to a particular viewer adaptation [22]. This

makes it possible to display a picture of, for example, a monitor showing letters in a very bright room in a way such that the monitor appears very dark on the picture, and the letters on it are barely legible.

4. How to compare photorealistic pictures when they are used as performance evaluation

It is necessary to find consistent ways to compare design solutions based on complex simulations. Performance values based on numbers such as daylight factors are ready for comparison, but simulations like pictures or sound may not be since we do not know what to compare when the result is complex [23]. Different pictures showing various daylight systems in the same room do not tell us much about the actual performance of the solutions, and they do not

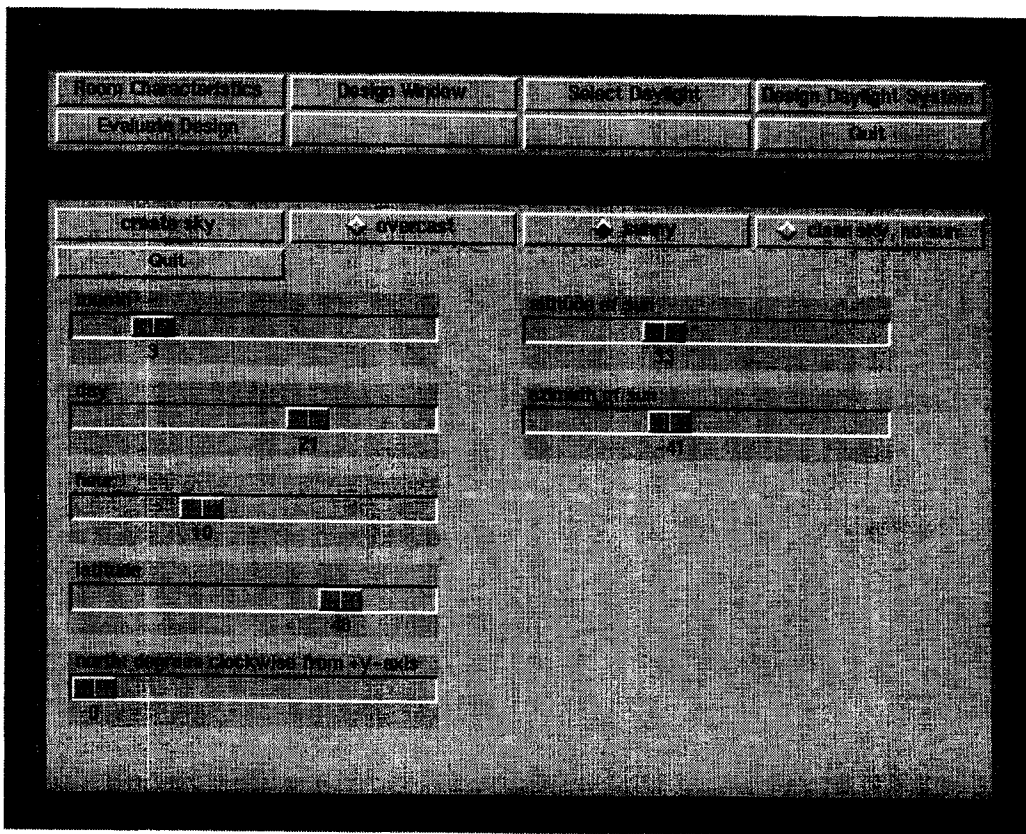


Fig. 3. Definition of the daylight characteristics such as time and location. Azimuth and altitude angles of the sun are updated automatically according to the specified location.

tell us what an occupant living and working in that space would actually perceive. However, we are interested in both aspects. Therefore, we suggest to define realistic tasks for a given context with a given design as an indication for performance [24], and simulate these realistic tasks for varying design solutions. By realistic task we mean a typical work or activity which the occupant is performing in that space (e.g. reading letters on a monitor or on a glossy page). The ease or difficulty with which this task can be fulfilled complements the computed performance values such as glare index or contrast. It is defined as a measure of the ‘goodness’ of the design solution and operates on a semantic scale (i.e. ‘difficult — easy’). For the design domain daylighting, one realistic visual task for rooms with daylight systems might be the viewing of a monitor. The common visual task of viewing a monitor display

has actually influenced lighting codes [25–27]. The German lighting code, for example, demands a luminance limit [28,29] (this is a number-based performance criterion) for interior surfaces and light sources that is based on the visibility of a typical display unit [30]. However, it does not state the direct requirement that characters on the screen must be clearly legible, but rather poses the indirect requirement that any luminance in the interior must be limited to a maximum value, based on experiments conducted with particular equipment [31,32]. However, visual contexts and products may change as new technology and new visual tasks come along. In this regard it is not so important to state that a certain numerical performance criterion has to be met. It is much more important to simulate the latest equipment and procedures under a particular task typical for the chosen setting, and let the designers and users decide whether

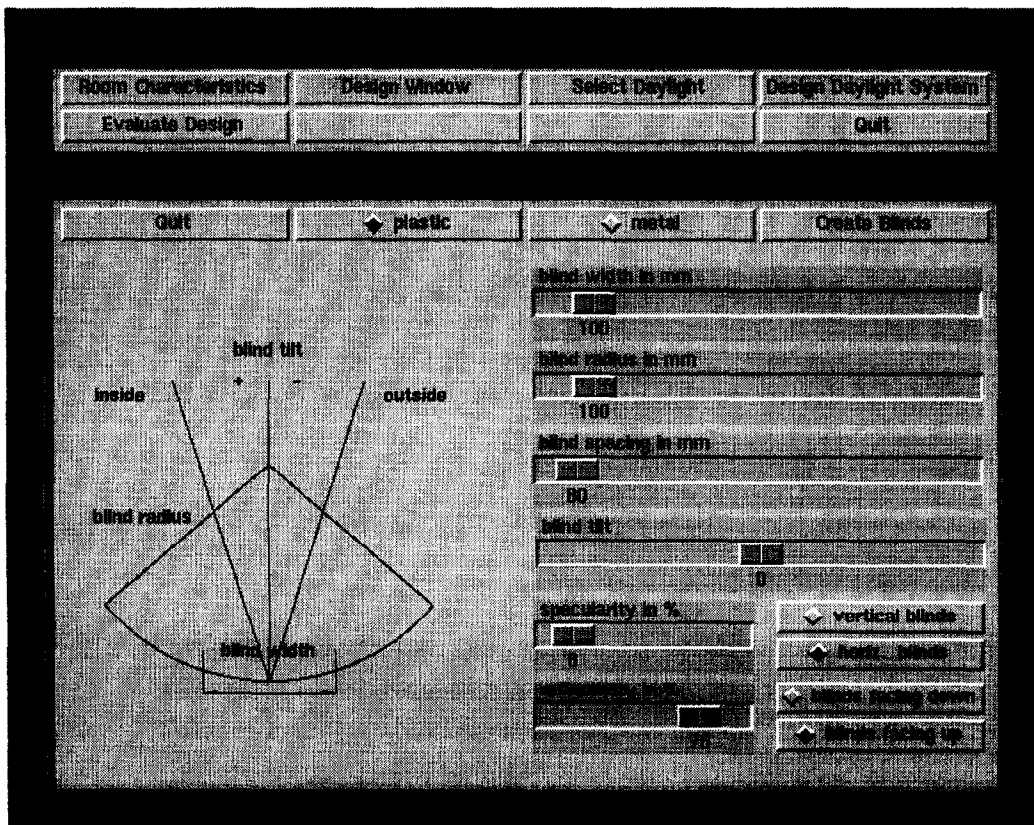


Fig. 4. Description of a daylight system: venetian blinds serve as one example. The design variables include geometry and material attributes.

this is an acceptable situation. Therefore, we simulate a monitor with a commonly found display showing text and pictures, from a close up view typical for office work (see Fig. 1). The luminance of the simulated monitor display ranges from 0 to approximately 150 cd m^{-2} (these values are standard for today's common visual display units). The monitor location and orientation as well as the view point are variables which can be controlled in the design tool, in order to accommodate for a wide range of viewing conditions. The resultant output can then be evaluated in terms of the visibility of the display seen on the monitor (i.e. in the way the occupant would perceive these). Are the colors and letters on the display clearly visible, given a specific viewer adaptation and a particular daylight system? This is an indirect evaluation of a design via the ability of the

human observer to perform a certain task in a certain environment. Our approach overcomes the problem that people, if they are not lighting experts, are often not able to observe the difference between two different lighting patterns. Rather, they immediately will complain about performing a certain task if it can only be carried out with difficulty. Therefore, it is highly useful to evaluate the performance of a system indirectly, via the visibility of realistic tasks or objects found in a particular design domain. This is achieved by taking the appearance of a 3D object like a monitor for the purpose of displaying the performance of a daylight system. We call this performance-based simulation. Performance based simulation can also cure the problem that people initially perceive that a solution is a beautiful design, but only until they start to work in that space. If the

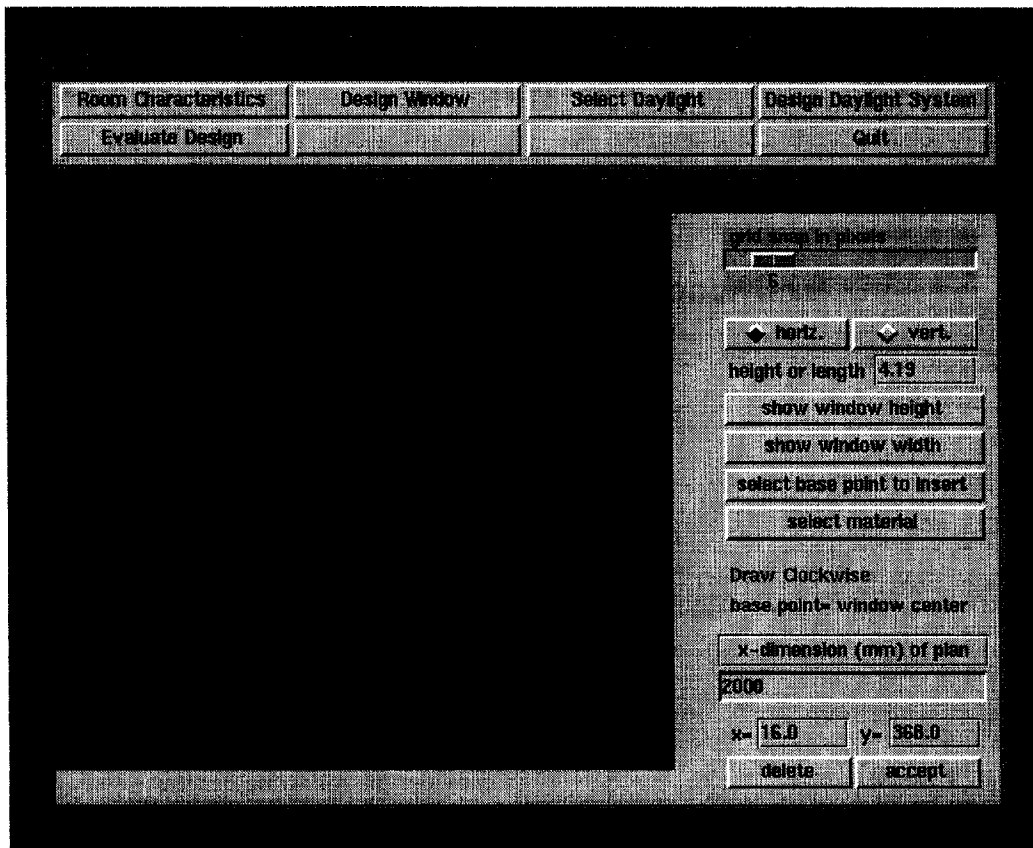


Fig. 5. User created drawing of a lightshelf. Arbitrary shapes can be created for maximum flexibility. The shelf can be oriented either horizontally or vertically.

simulation result is not acceptable, the solution has to be rejected. The ‘good’ case, however, does not mean that this is necessarily a ‘good’ solution — it only means that the solution doesn’t have a particular flaw. We propose to introduce and simulate as many important and typical tasks for a particular design context as possible and feasible, since experience tells the designer that too many flaws may show up once the design is built. This explains the preference of many designers to rely only on full-scale mockups [33]. This method of evaluating performance does not substitute for the numbers-based performance criteria. It adds more constraints, which are not numbers-based, to complement the numbers in as many ways as is economical and to exclude as many unwanted surprises as possible. This method relies on the simulation of a variety of many typical occupant activities, as well as on the ability to consider adaptation of the occupants. For this design tool, we chose a relatively simple task (the viewing of a monitor). Future simulations and design tools will bring more complex evaluation methods, like simulating rotating elements under lamp flicker in industrial manufacturing work and evaluating their subsequent visibility.

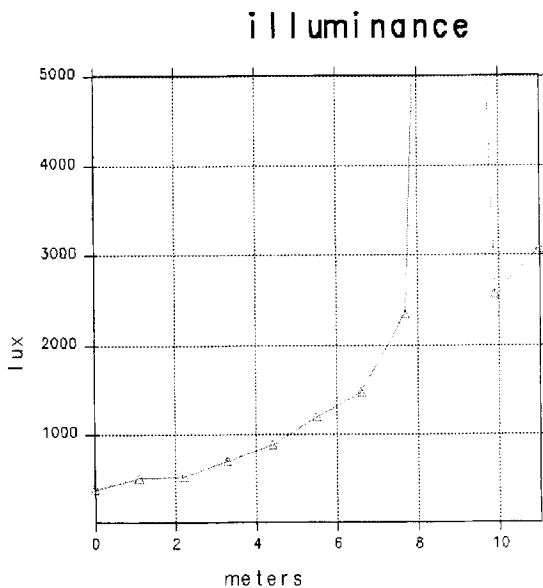


Fig. 6. Output option: Graph showing illuminance values along the center line of the room.

5. Interactive simulation makes computation time an issue

Computation time should allow for interactive simulation in order to obtain simulation results quickly. Unfortunately, the computational requirements for the simulation of complex scenes may still be prohibitive. In lighting simulation, the computation time for a scene consisting of 1 000 000 elements can yield a computation time of 6 days on a fast workstation running radiosity software and a time of two days for some ray tracing software [34]. In our case, however, we are dealing with up to 500 polygons at the most. This allows rendering times from 10 s up to 1 h, depending on the accuracy desired. This is now within reach of interactive simulation, given a user friendly interface that allows rapid input and selection of various daylight systems.

6. Need for a user-friendly interface

Powerful accurate simulation tools like Radiance are not widely used, mainly due to their cryptic command line input (which gives the program user maximum flexibility in generating whatever the tool can do) and the required input that many designers do not care or know about (e.g. precise color, gloss or roughness specifications). Also, the many output options in terms of pictures and graphs (i.e. illuminance distributions, etc.) are confusing to the novice user. Therefore, it is essential to develop a mouse driven graphical user interface that allows easy and rapid input of all important context variables (e.g. room dimensions and material, daylight conditions, exterior ground) and design variables (e.g. window material and type, material and geometry of various daylight system(s)), while hiding all input that does not affect the results from the user (i.e. “what color should the ceiling be?”). It is also essential to let the user choose the output options in terms of output type (pictures and/or numbers) as well as rendering speed and accuracy desired. Such a user interface provides the following benefits:

1. It drastically decreases input time by offering the user a manageable quantity of input variables specifically out of the daylight systems design context.

- Given quick input and output, it allows the user to generate many solutions and a variety of solutions in a short time, since she will start to ‘play’ with design and context variables. In this way she will generate many solutions, and some of them might be very valuable.

Starting to ‘play’ with parameters like daylight system specularity, ground reflectance, venetian blind tilt or light shelf size helps the user to develop an understanding for the way in which context variables (i.e. wall reflectivity or window sill depth) and design variables (i.e. screen tilt or specularly transmitted light) interact. It also allows for parametric studies, where the user chooses one particular daylight system and starts to vary its material properties in order to find out how sensitive the daylight factor at

a point or veiling reflections on the screen will be to various design variable changes. This is the well-known synthesis and analysis cycle [35]. In this context, design becomes a ‘patient search’ [36] through an almost infinitely large set of possibilities. This tool offers the designer the simulation methods and the computation speed to make this search possible and economical. It is not a quick ‘expert’ knowledge shortcut aimed at novices, but rather is an aid for designers who want to generate and refine many solutions. This assumes they already have a basic knowledge about material properties and daylight systems. (This reminds the authors of learning an art like computer programming — most of it is learned by trial and error as well. That’s why there are debuggers.)



Fig. 7. A view showing the space as seen from the window.

7. Description of the program

The program was developed on a UNIX platform using the tool command language tcl/tk and the ray tracing software Radiance. The UNIX platform is necessary to allow for simultaneous multiple renderings showing different views of a solution, and pipelines. The program consists of pop-up menus that allow the user to interactively select room properties, daylight conditions and daylight system variables with scales and buttons via the mouse. It also has a 2D-CAD interface that allows the user to view the room plan, place the viewpoint and the monitor interactively on this plan and to draw custom-tailored reflectors of arbitrary shape and size.

Plate 1 shows an overview of the program structure.

A summary of how the program works is as follows (user input is accepted in any sequence): The user defines the context like space geometry and space materials. She then adds the window description and defines its width, height and depth as well as the window sill height. Automatic checking is performed for all geometry parameters to make sure that the window fits into the wall (note: It is possible to divide the window into a lower and an upper pane with different glazing materials, as this is typical for fenestration with advanced daylight systems). The glazing material can be clear or translucent, and its transmission and reflection properties for both diffuse and specularly transmitted and reflected components can be defined. The user can then insert a monitor into the scene and define a viewpoint (see Fig. 2).



Fig. 8. Output option: View of a window with a lightshelf.

For this program, the monitor itself is still a default monitor — future developments of this program will bring the simulation of performance tasks whose values can be changed, like variable luminance of the monitor or different glass types for the screen. The monitor is placed with the mouse into the 2D plan of the scene. It can be rotated to any desired horizontal and vertical tilt. The viewpoint is selected via the mouse as well.

The user then defines the daylight characteristics of the site (see Fig. 3). This includes month, day and hour as well as latitude and cloudiness. If any of the parameters are not selected (no matter if they are sky or room or material descriptors), the program provides typical default values to avoid to give lengthy input or forcing the user to give values he does not know or understand.

Currently, up to three daylight system types can

be selected and their combined and/or single effect can be evaluated. The three systems are venetian blinds, light shelves and screens, which are the most commonly found systems in the US. The daylight systems have material parameters (material type and diffuse and specular reflection and transmission properties) and geometry and location parameters. For a venetian blind, for example, the user can define depth, width and height of the system, the curvature of the slats, the tilt and spacing of the slats and the vertical or horizontal orientation of the slats (see Fig. 4). The other daylight systems include similar parameters which are of primary interest to architects and consultants. Since there is no such thing as the typical light shelf shape, the light shelf is drawn by the user on the 2D CAD interface (see Fig. 5).

The user has several options for output of simula-

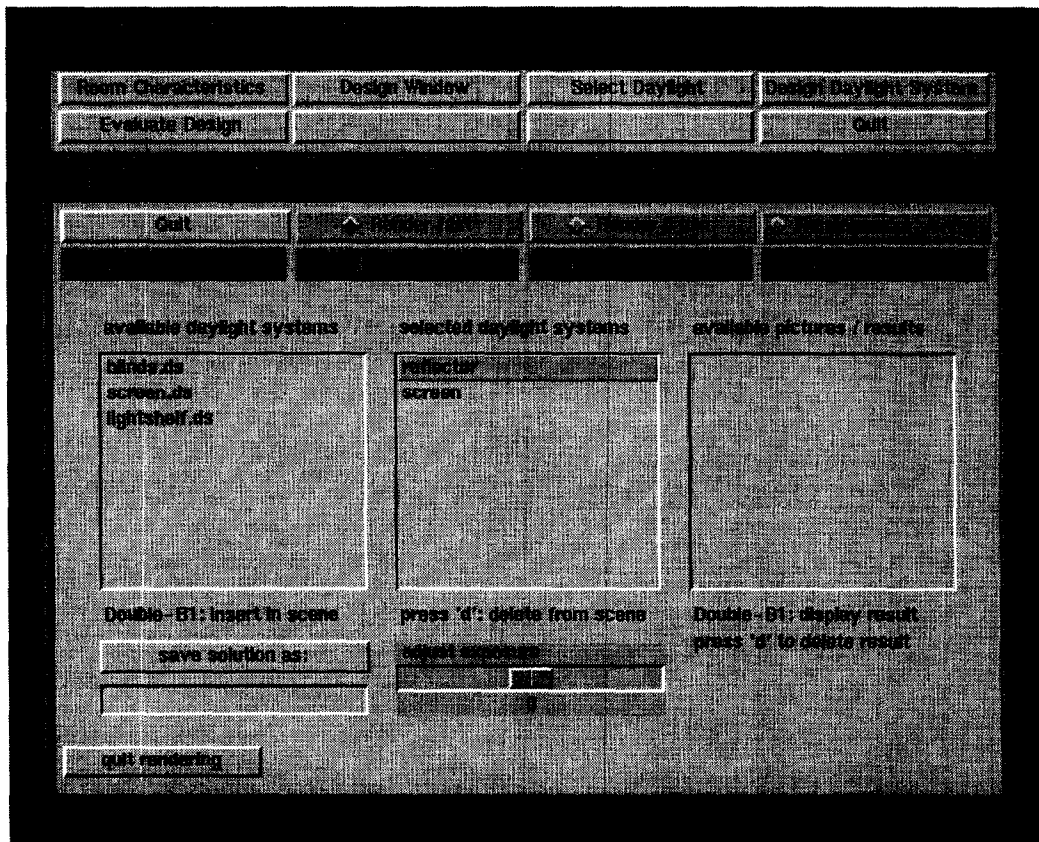


Fig. 9. Menu of the daylight design tool showing output options: The user determines speed/accuracy and desired views.

tion results. These are an illuminance plot showing graphical information (illuminance values in the space — see Fig. 6), and pictures providing up to three different views: the selected close up view of the monitor (see Fig. 1), a view showing the space from the window (see Fig. 7) and a view showing

the space to the window (see Fig. 8). The options can be selected with checkbuttons, which means that all or some or none of them can be selected simultaneously (see Fig. 9). The second set of options pertain to the accuracy and speed of the results obtained. A very accurate simulation can take up to

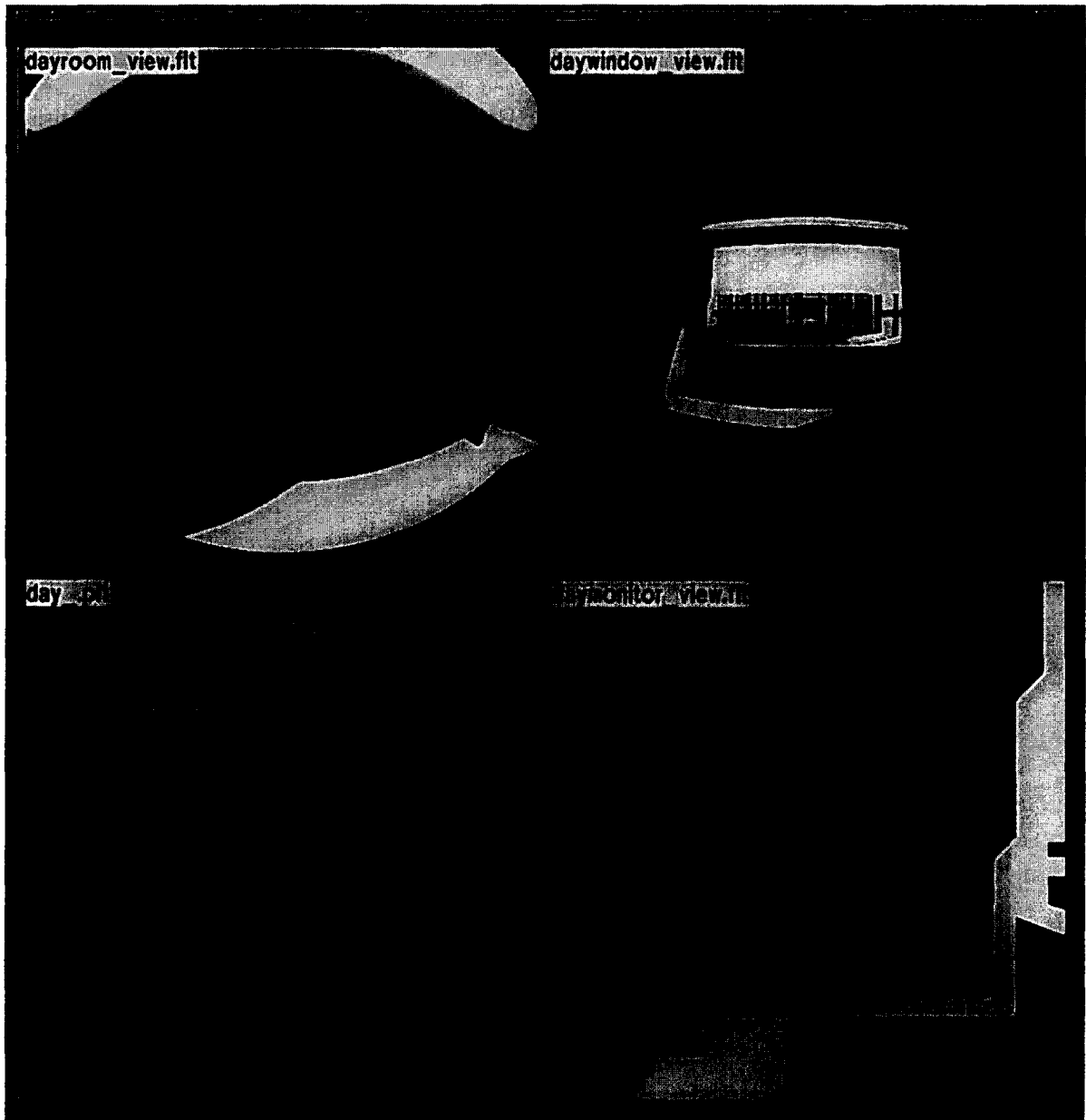


Fig. 10. A 'design story': An array of pictures and a graph describes the performance of the clear glazing solution. The pictures are saved as one file.

50 min, therefore it is desirable to let the user select from four different speeds/accuracies depending on how much time he has and how much accuracy is really necessary. The first option gives graphical output in charts only (that is illuminance values on a line from the window to the rear wall). The second

to fourth selections generate photorealistic visualizations. The second option shows almost immediate results (the interreflected light component is not calculated here, however, reflected glare on the screen will be shown). The third and fourth selection take into account multiple interreflections and differ

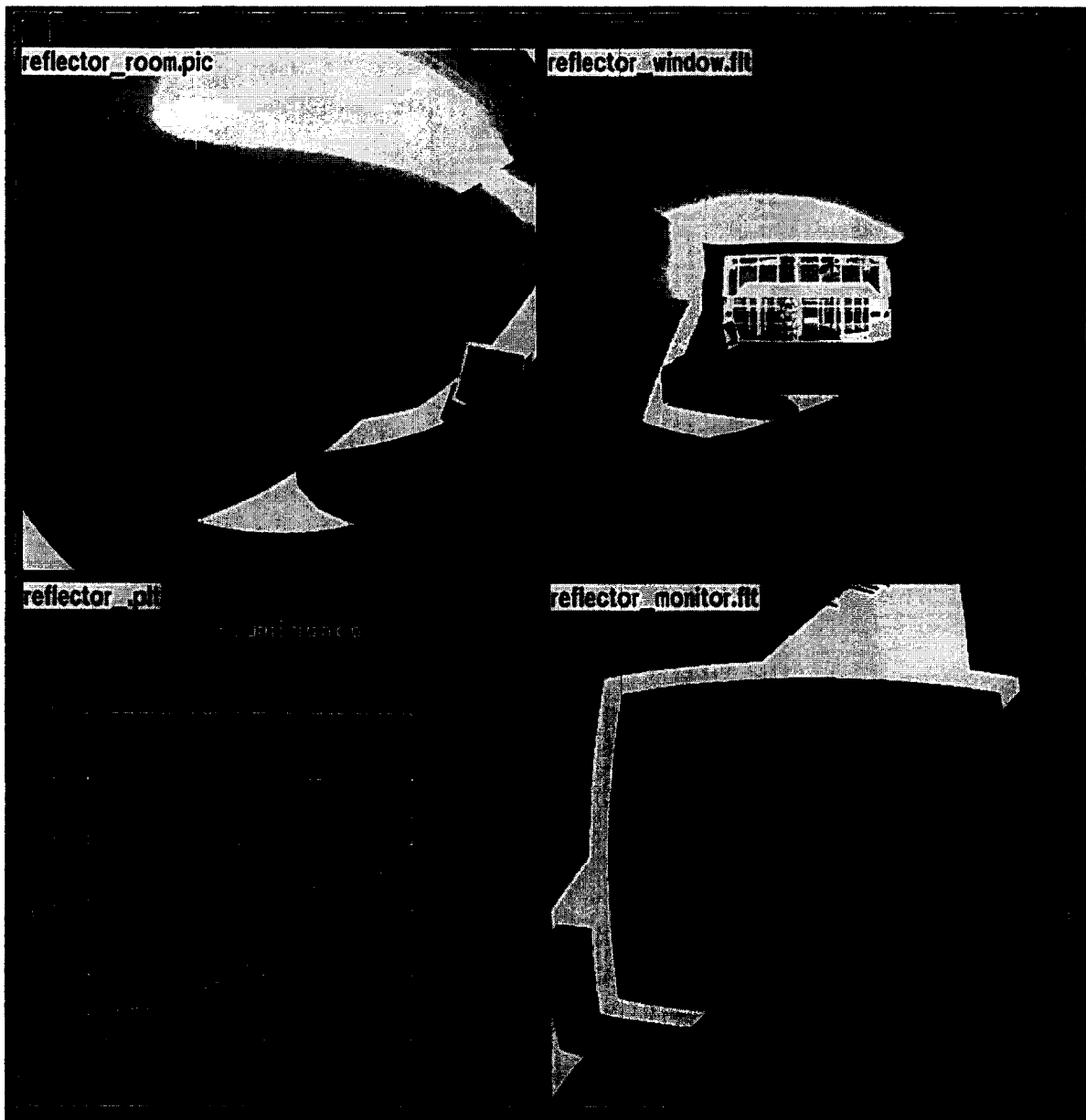
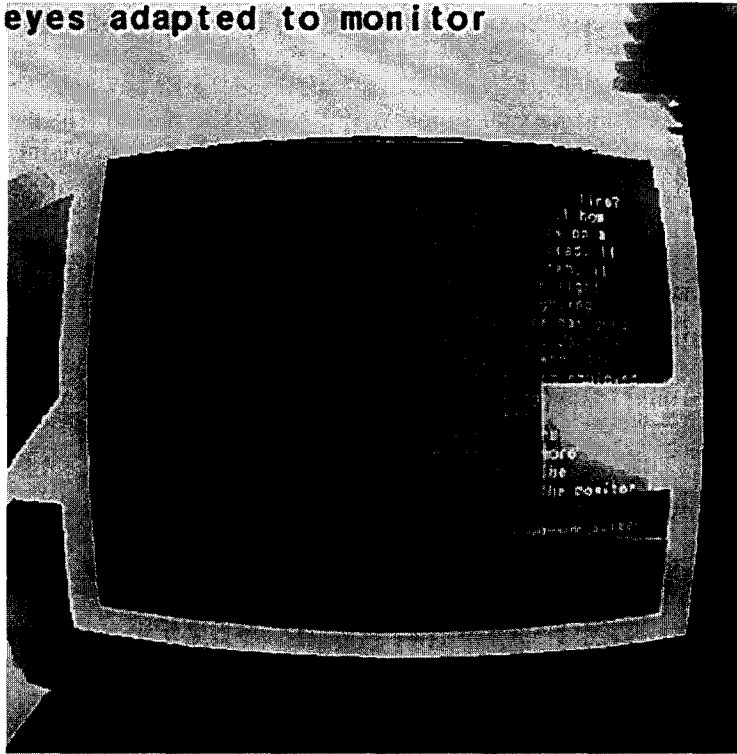
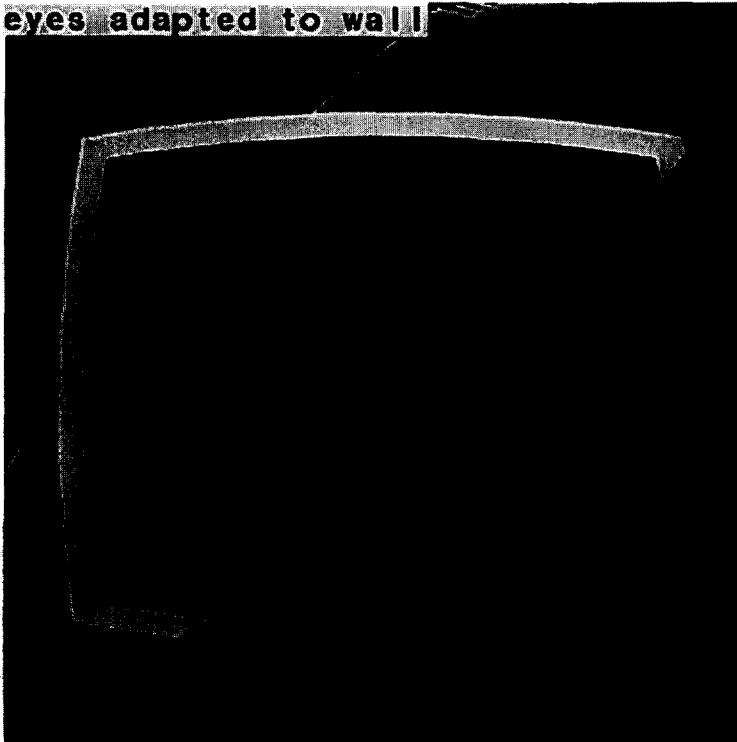


Fig. 11. 'Design story': These images describe the lightsheLF solution.

eyes adapted to monitor



eyes adapted to wall



by the amount of light rays traced through the scene. By letting the user decide on the speed and output type, maximum flexibility is achieved. The result — a single graph or picture or multiple pictures or multiple pictures and one graph (see Figs. 10 and 11) — can be saved as a picture file containing all the graphs and/or pictures. This allows the user to establish a series of studies where the solutions might differ by daylight, room characteristics and daylight system characteristics (anything that is an input variable). An indefinite amount of solutions can be saved and compared to any new solution. This is very important, since we deal with mostly pictures as results, which rely on visual comparison with other pictures.

The viewer perception of the monitor can be taken into account by applying a linear scale factor to the image [22]. Thus the image displays visibility of characters on a computer monitor under known lighting and viewing conditions. This results in two consequences: firstly, brightly lit scenes will produce a bright display and very dark scenes will produce a dark display; secondly, the visibility level on the display is roughly the same as it would be in the real world, and if an object such as a letter on a monitor under a glary daylight system is not visible on the simulated result, it will also not be visible in the real setup, if the viewer adaptation is known (see Fig. 12).

It is immediately obvious whether the daylighting solution is acceptable from the monitor reflections point of view, since veiling reflections on the screen immediately show up on the simulation picture. The actual visibility of the pictures showing the computer monitor can be adjusted to take into account different viewer adaptations, such providing varying contrast on the pictures as the effect of varying visibility. Since the renderings can be created in a short time, it is possible to simulate a whole range of daylight systems. Ultimately such a system can provide menus of options to facilitate rapid selection of a design solution that meets the user's design goals.

8. Application possibilities in practice

Daylight design tools are generally useful for architects who shape building facades, as well as for engineers involved in lighting, heating, ventilation, and air conditioning of buildings. The type, shape and orientation of daylight systems determines the electric lighting loads as well as the cooling loads during the daytime. The irradiance due to daylight (in the visible range only) on a building facade facing south is on a sunny day in December, March, and June, at 15:00 h for a latitude of 50 degrees, is 311, 821 and 527 W m^{-2} , respectively. These numbers are significant for the energy consumption of a building. It is vital to decide what to do with this energy density.

From the perspective of energy conservation, it could be desirable to bring as much daylight as possible to the interior space, while at the same time reducing the cooling load imposed by daylight. This indicates that the design of daylight systems is a delicate balance between various factors, i.e. cooling loads and electric lighting loads.

Visual comfort is another issue. Typically, it is addressed using evaluation methods that compute visual comfort probability or glare indices. Most of these methods are based on windows or light sources in or around the line of sight. While the application of these methods is highly desirable, because they introduce psychophysiological comfort as another means of evaluation, there are two shortfalls: the methods are rarely used, because they are based on complex formulae and difficult to understand for building designers, and they do rarely express what an occupant working in a space would be likely to perceive at her workstation. An easy-to-understand evaluation from the occupant's perspective is his simulated workstation. That is the reason why this software simulates monitors under different daylight systems. This allows the architect and the non-lighting experts involved in the electrical and mechanical building systems design to understand the implica-

Fig. 12. These images show the visibility of the monitor display for a viewer who is either adapted to the bright patch of sunlight on the wall behind the monitor or to the image on the monitor.

tions of a particular daylight system clearly, and to use this software during the design of building facades.

9. Conclusion

We presented a first step in the development of performance based simulation, where realistic visual tasks are simulated in a particular design environment. A space with a daylight system is evaluated in both numerical values such as daylight factor as well as perception-based pictures taking into account visibility of a realistic visual task. This method assesses the performance of a design solution indirectly via the visibility of a visual display showing letters and pictures. This approach tackles the problem that numerical performance criteria are not enough to evaluate a design solution. The success of computer-based prediction and evaluation ultimately depends on methods that show the performance of a design from the occupant's point of view, thereby requiring the establishment of more sophisticated, perception-based evaluation methods for all design tools.

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