

# An intuitive daylighting performance analysis and optimization approach

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The effective integration of daylighting considerations into the design process requires many issues to be addressed simultaneously, such as daily and seasonal variations, illumination and thermal comfort. To address the need for early integration into the design process, a new approach called Lightsolve, has been developed. Its key objectives are to support the design process using a goal-oriented approach based on iterative design improvement suggestions; to provide climate-based annual metrics in a visual and synthesized format; and to relate quantitative and qualitative performance criteria using daylighting analysis data in various forms. This methodology includes the development of a time-segmentation process to represent weather and time in a condensed form, the adaptation of daylight metrics that encompass temporal and spatial considerations, and the creation of an interactive analysis interface to explore design options and design iterations. This system relies on optimization techniques to generate these suggestions. Lightsolve allows the designer to explore other design alternatives that may better fulfill his objectives and to learn about appropriate strategies to resolve daylight or sunlight penetration issues. It offers architects and building engineers support for daylighting design that can be employed interactively within the existing design process.

**Keywords:** daylighting, design process, design support, interactive optimization, energy, simulation, visualisation

## 1. Introduction

The modeling of daylight in buildings is a challenging problem of increasing importance. Careful management of daylighting in a building is crucial in minimizing the environmental impact of a structure (U.S Department of Energy, 2006). It also has the potential to produce positive effects on health (Veitch, 2005), (Webb, 2006), well-being and, possibly, productivity (Cuttle, 2002), (Heschong-Mahone Group, Inc., 2003), (Kim, et al., 2005). In addition to these benefits, it remains a predominant factor in how a space is revealed and perceived by its users (Lam, 1986), (Guzowski, 2000).

Therefore, a major challenge that designers face is to effectively combine the many performance parameters

involved in daylighting with aesthetic considerations. These parameters include daily and seasonal variations, the delicate balance between sufficient illumination and visual comfort, and the thermal aspects of incoming solar radiation, amongst others. Only if this integration happens early in the design process can it have a significant impact on energy savings and ultimate building performance.

One might argue that developments in design software should make this type of daylighting design accessible to the architect, reducing the need for expert design advice and providing for daylighting consideration early in the design process. Today's tools, however, have not fully facilitated this potential.

### 1.1 Supporting the design process

The architectural design process is usually described as a non-linear, non-quantifiable process of creating forms and spaces (Broadbent, 1988). Yet with an infinite number of variations, it usually includes the isolation of a general concept or “Form” and the development of this “Form” into a final proposal. This development phase almost always involves an iterative process, often based on trial-and-error albeit in a non-linear way because considerations as diverse as aesthetics, performance, structure and many others all have to be addressed simultaneously.

For spaces in which the management of sunlight and daylight penetration is critical, special attention has to be given to these aspects early on in the process because they are strongly affected by fundamental design decisions such as orientation, massing, and openings position or size. To explore a range of alternatives in an efficient way, the designer may choose to resort to some form of design support, which can consist of hiring a consultant or of using design tools such as calculations, scale model analyses or computer simulations. He will then start refining his concept according to certain goals (which may vary during the process) and within certain constraints (some of which may be more flexible than others).

Ideally, this should affect the continuity and seamlessness of the design process as little as possible. For example, if a significant amount of time or too high a number of steps are needed to produce the data he needs, or if the form in which these data are delivered cannot be easily interpreted, important information may be discarded and the resulting design be negatively affected. This critical issue in using computer simulation (or any form of design support) is one we decided to focus on in this work.

### 1.2 Available tools

Generally, tools intended for use in the early stage of design are either mostly quantitative in output (tables, illuminance maps) and highly restrictive in model complexity (Lehar, et al., 2007), (Hitchcock, et al., 2003), (Reinhart, et al., 2007), (Paule, et al., 1997), or they solely focus on direct shadows and sun course analyses, which restricts them to providing qualitative outputs (Google, 2007), (Bund, et al., 2005).

At the other end of the spectrum are rendering tools, which are usually based on CAD imports and allow practically any degree of complexity for the model at the expense of computation time (Altmann, et al., 2001), (Ashdown, 2004). The most widely adopted one for accurate daylight modelling is *Radiance* (Ward, et al., 1998) on which more than 50% of the daylighting software packages are based (Reinhart, et al., 2006). Two of these, Daysim (Reinhart, et al., 2001) and

S.P.O.T. (Architectural Energy Corporation, 2006), also produce climate-based, annual performance outputs in the form of Daylight Autonomy (DA), which represents the percentage of work hours were daylight is sufficient to perform a given task (Reinhart, et al., 2006). Finally, some existing software packages such as Ecotect (Marsh, 2008) rely on a combination of these advanced tools (Daysim and Radiance) and their own algorithms and modelling capabilities to become a central interface from which a range of daylighting analysis options are available.

Despite their sometimes remarkable capabilities, these tools typically display information on daylight performance in a sequential, sometimes tedious and often broken way: almost always one moment at a time (except for the few ones that produce annual calculations) and the generation of renderings is usually separated from the calculation of daylight metrics (illuminance, daylight factor etc). One can easily see how a more seamless data visualisation platform, that could display data on an annual basis and in connection with qualitative renderings, would become powerful in providing comprehensive information while minimizing disturbance of the design process. How the proposed approach intends to achieve these goals is explained in the following sections.

### 1.3 Objectives of an expert design support system

In addition to evaluating the performances that can be expected for a given design (analytic approach), computer models have been used – although not extensively yet for daylighting design – either to produce a diagnostic about the current performance using comfort or energy criteria (Paule, et al., 1997), or to seek for a more “optimal” design through an objective solution-finding process based on target values (Caldas, et al., 2002), (Chutarat, 2001), (Fernandes, 2006).

However, as discussed earlier, the very nature of architectural design prevents traditional optimization from being effective; it is very unlikely that the designer will accept an offline, computer-generated optimum (or even a set of optima) as his final design choice, on top of the difficulty of making such an immense domain of solutions converge at all. Instead, this paper proposes to create a system of expert rules that would analyze which design changes are likely to better achieve the designer’s goals.

In terms of user interaction, it seems most promising to try to replicate as closely as possible the dialogue a designer would have with a consultant. Hence, this system will be implemented as an iterative process in

which the designer is heavily involved and it is at the level of generating the “virtual consultant”’s suggestions that conventional optimization will be used. As is the case with a real consultant, there is a great educational potential in this approach: the designer will have the opportunity to get a better understanding of how daylighting performance relates to design decisions and environmental factors such as seasons, weather and time of day, and how some strategies affect certain parameters over others. In addition, it is likely that it will open up the range of design alternatives he would have considered, and thus be useful for design exploration, especially in the early stages.

The approach proposed in this paper, called Lightsolve, integrates these concepts and proposes a method to connect quantitative and qualitative annual performance analysis into an original form of goal-based design support.

## 2. Integrated visualisation of time-varied performance data

The default daylighting metric used today in design practice is the Daylight Factor (DF) or variants of it, i.e. the ratio of inside and outside illuminance under an overcast sky (Commission Internationale de l’Eclairage (CIE), 1970). Because this metric discards essential daylighting parameters such as orientation, latitude, sunlight penetration and climate, important efforts are being made to come up with alternative ways to quantify daylight on an annual basis (Reinhart, et al., 2006).

Two propositions of dynamic daylighting metrics have emerged so far. The first is called Daylight Autonomy (DA) and is calculated with the program Daysim (Reinhart, et al., 2001); it includes user behaviour for blind management (Reinhart, 2004), (Bourgeois, et al., 2006). The other is Useful Daylight Illuminance (UDI) (Nabil, et al., 2006), which adds an upper limit to acceptable illuminances for task performance.

These metrics are illuminance-based and incorporate climatic data over the whole year to produce a spatial map showing what percentage of occupied hours will not need additional artificial lighting to achieve a prescribed illuminance.

Whether measured in scale models or calculated with programs like Radiance, illuminance-based metrics are typically assessed over a grid of sensor positions for either given sky conditions (DF) or as a weighted sum over the whole year (DA).

It is important that an emphasis on annual variation be added so that the influence of sun position, weather and

time of day can be considered. This information should also be organized and presented in a way that is adapted to the designer’s needs and is appropriate for the type of models used and decisions made in the early stages of design. A highly graphical visualisation of data has thus been chosen in the form of Temporal Maps and a specific time-segmentation method applied to keep the amount of data reasonable. Indeed, the data transfer process needs to remain interactive and efficient to avoid hampering or delaying the design process. The chosen format in a way consists of the temporal counterparts to the location-specific metrics described above; they maintain time-dependency information by displaying numerical data in time-varying form (section 2) and are still connected to visual data in spatial varying form (section 3).

### 2.1 Time-segmentation method

The underlying concept of the so-called time-segmentation method is to split the year into a reasonably small number of periods and model the latter as averages of both the yearly and hourly intervals they each represent, accounting for the range of weather conditions that can statistically be expected.

This method is described and validated in detail in (Kleindienst, et al., 2008) and is briefly summarized here. Its overall concept is similar to an earlier proposal by (Herkel, 1997) but it greatly differs from the latter in terms of objectives and therefore in the adopted method: while Herkel’s main objective was to reduce calculation time (he thus grouped moments over the year that were not necessarily close in time), the objective here is to provide a designer with useful annual performance information, in a way it can become an immediate yet comprehensive support to take informed design decisions (see section 2.2).

The time-segmentation method starts by averaging Hourly Typical Meteorological Year (TMY2) data over a limited number of periods, during which sun positions and weather conditions are similar, using the ASRC-CIE sky model developed by Perez (Perez, et al., 1993). This model integrates simulations using the four standard CIE sky models (overcast, intermediate, clear, clear turbid) into one set of illuminance values (Commission Internationale de l’Eclairage (CIE), 1994).

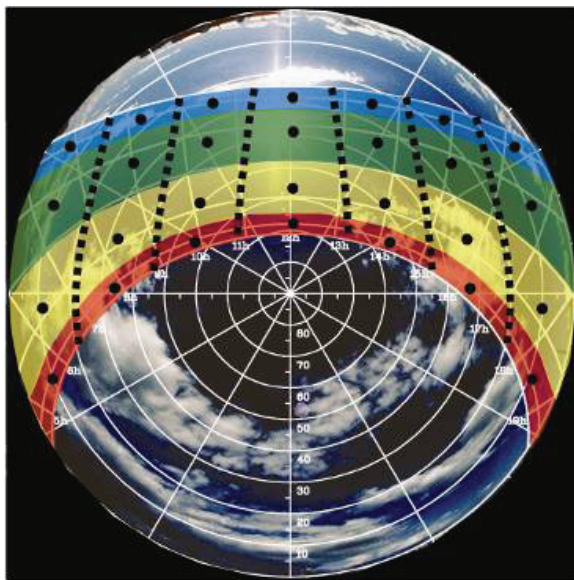
Each sky model is defined using brightness and clearness factors which are averaged over a certain period of time, then the resulting illuminance values are summed and weighted according to the sky type’s occurrence during that period: a higher weight is assigned to the statistically dominant sky conditions. The sun position associated with each period is that of

the “central moment” both by hour and day. This method of division results in 28 unique sun positions at 56 times of year, illustrated in Figure 1.

The ASRC/CIE model was chosen for the Lightsolve approach because it is both accurate and conducive to averaging many skies in a realistic way. It has been validated by Littlefair (Littlefair, 1994) against the extensive BRE sky-luminance distribution dataset, and it has exceeded most other sky models in accuracy, including the Perez All-Weather model (Perez, et al., 1993). It was also declared most likely to be adaptable to a wide range of climate zones (Perez, et al., 1992), (Littlefair, 1994).

Given typical meteorological data within time periods, we determine a unique representative illuminance value for that whole period. We also create four realistic, instantaneous sky maps, one per sky type, which each represent the entire period in question once categorized by sky type. These calculations are combined with a set of one-bounce ray-tracing simulations performed for 1200 sun positions and overlaid on the map. The overall method is described in (Kleindienst, et al., 2008).

This time-segmentation approach therefore contains a much richer information than what a sampling of “key” moments (even numerous) could provide (Geebelen, et al., 2005), (Glaser, et al., 2004) and can be used to calculate informative metrics such as interior illuminance over a workplane area, as explained in section 2.3.



**Figure 1** Time-segmentation method illustrated on a stereographic chart: each half year is split in four intervals, and each day (time between sunrise and sunset) is split in seven equal time intervals.

The calculation time saved by reducing the dataset from an hourly resolution (about 8000 data points) to 169 (56 x 3 sun-dependent sky models + 1 sun-independent overcast sky model) is not the major advantage of the time-segmentation approach, although it will clearly allow a much greater level of interactivity with the user. Even though this would be a precious advantage today, processors might improve reasonably quickly in performance and large sky conditions datasets can be produced quite rapidly by resorting to the Daylight Coefficients method (Reinhart, et al., 2001), (Bourgeois, et al., 2008), which calculates the individual contribution of a set of 145 sky patches to the illumination of a given point (Tregenza, 1987). One can therefore reproduce any sky luminance distribution without requiring a full simulation for every new sky condition, as long as the building model remains identical (an assumption that is unfortunately invalid in a design process and in Lightsolve, but valid in a performance analysis exercise).

The main benefit is for the user. As mentioned earlier and detailed in section 3, one of the underlying concepts of the Lightsolve approach is to link quantifiable performance with qualitative criteria. This means that each of these “representative” moments, standing for a whole period, will be directly connected to space visualisation and renderings.

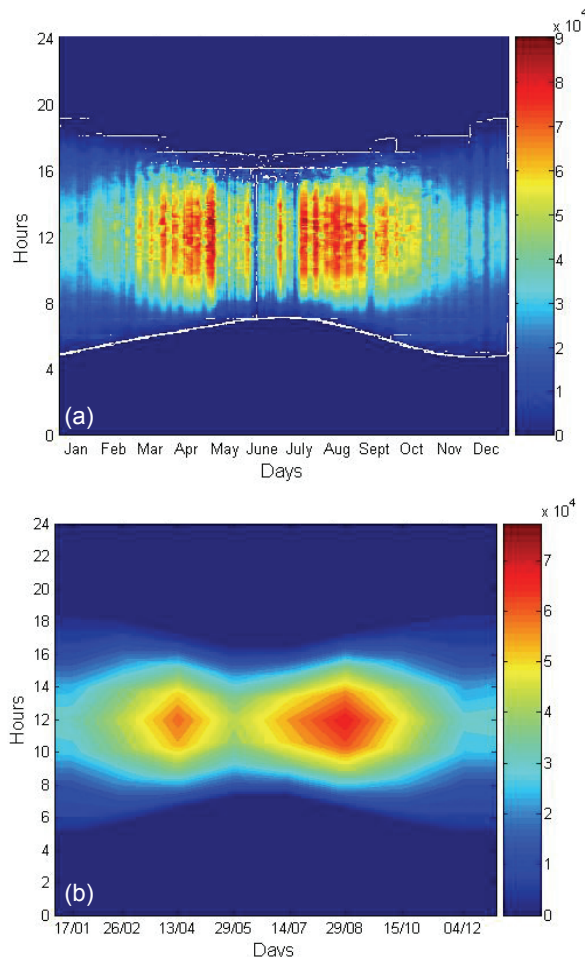
Any form of discrete sampling will lead to visualizing instantaneous conditions, determined by the sky conditions applying at that very moment. Not only would this process be overly time-consuming for reasonably short sampling time intervals, it would also leave it to the user to assimilate this information and process it mentally: he would have to observe and mentally absorb a huge amount of data before being able to understand how sky conditions vary over the year and how a given design responds to these outside conditions.

At the other end of the spectrum, there are climate-based metrics such as Daylight Autonomy that are very intuitive because they convey information about annual performance as one number: the percentage of occupied hours for which no additional lighting will be required to achieve a prescribed illuminance at a given point. But by using this cumulative approach in the data processing, critical design information related to weather variations, time of day and time of year gets hidden. The time-segmentation method can be considered as an in-between: it does not sample fewer moments but provides fewer data points that are denser in the information they contain.

## 2.2 Graphical representation

To be intuitive, immediate, and in line with the way architects and building designers typically work, information should be displayed graphically whenever possible. A very promising way to visually represent annual variation was found in the “Spatio-Temporal Irradiation Maps” (STIMAPs) format suggested by Mardaljevic (Mardaljevic, 2004). This format allows the user to see at a glance the way that hourly and seasonal changes affect the availability of daylight within or around a particular building design and is derived from data representing the full year.

An example of such a map is shown in Figure 2a, displaying the range of outside illuminances one can expect on a North facing façade in Sydney. This map was created with MATLAB using the 105,120 data points calculated by DAYSIM - one for every five minute interval during the year (Walkenhorst, et al., 2002), (Bourgeois, et al., 2006).



**Figure 2** Temporal Maps for a North-facing façade in Sydney displaying outside vertical illuminance in lux, based on (a) five minutes interval illuminance data calculated with DAYSIM and (b) a reduced set of 56 data points (interpolated) using the time-segmentation method for Lightsolve

The days of the year are plotted along the x-axis, the time of day (solar time) along the y-axis. As one can immediately see on this map, spring (March through early May) and late summer / early fall (end of July through end of September) are the periods of the year where the highest illuminances can be expected, especially from mid-morning to mid-afternoon, and might require careful solar shading strategies. The striations are due to overcast days, as these maps are climate-based. On the other hand, one can also observe that from October to March i.e. throughout the whole austral summer when the sun is highest, the strong dominance of overcast days combined with the cosine dependence of irradiation will make solar protection much less critical; a similar observation can be made for a two months period around the June solstice, when the sun is lowest. All these observations can be made by looking at this one graph; they are critical to a designer and will (or should) have a strong impact on the chosen daylighting and sunshading strategies to adopt.

Based on the time-segmentation method described above, a less detailed version of that map can be produced, shown on Figure 2b. The same critical observations can be made using this simpler map and hence will probably lead to similar design decisions. An extensive visual and numerical comparison between these two approaches is provided in (Kleindienst, et al., 2008).

## 2.3 Goal-based metrics

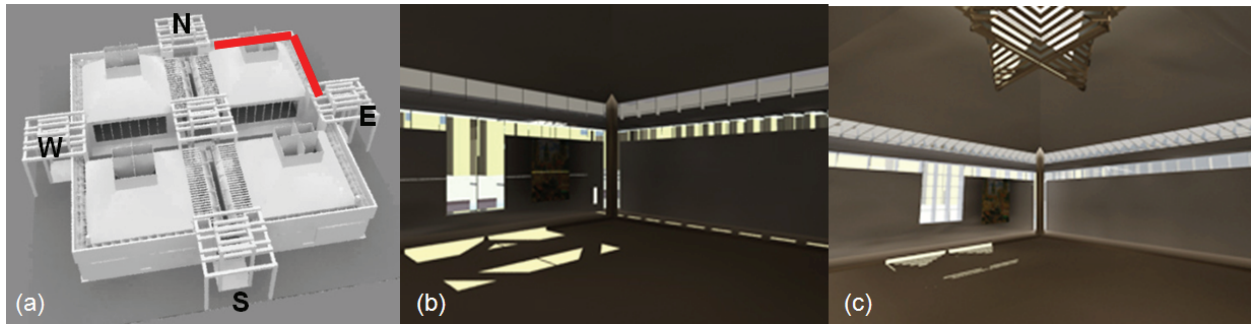
The previous sections have described why it is important and how it would be possible to also incorporate temporal information in a synthesized form. But displaying time-dependent information for every location in a space does not make any sense in the schematic phase of design, as we would again face the problem of overloading the user with data to process mentally.

Instead, because some degree of spatial averaging is acceptable at this stage as long as it still enables a gauging of two design scenarios against one another, a different approach was chosen, using goal-based rather than absolute metrics.

The objectives of the designer relating to daylight can be very diverse, ranging from maximizing energy savings to producing dramatic visual effects. A successful design will be one that fulfils his goals, or more specifically, best fulfils his highest priorities and at least acceptably fulfils his other objectives.

Four kinds of goal-based metrics are proposed, whose purpose is to answer four critical questions the designer is likely to try to address early on in the design process:





**Figure 3** Exterior and interior renderings of the museum case study in Boston: (a) Radiance model of the museum for design iteration 1 - the considered AOI are the indicated North and East walls of the NE exhibit space; (b) and (c) Interior renderings (3ds Max® by Autodesk®) for design iterations 1 and 2 respectively (both shown for May 29 at noon).

#### a) Is there enough light?

This question usually pertains to one or more areas of interest to the designer, such as workplane area(s) and the way such areas are defined should be flexible in orientation (vertical, horizontal) and boundaries (user-defined). The answer can be based on a range of metrics (illuminance, luminance distribution, view of the sky etc) but is typically evaluated based the amount of light a given area of interest will receive per unit of surface, i.e. expressed in terms of illuminance. To efficiently inform the designer, he should ideally be asked to mentally process a minimal amount of data; yet these data should maintain enough information to answer the initial question reliably.

Simple averages over the entire area of interest (or a portion of it) were ruled out because conclusions about daylight may be similar for, typically, a very uniform and comfortable light distribution, and a highly heterogeneous one incurring discomfort glare risks. The performance indicator chosen instead is the proportion of the area of interest fulfilling user-defined illuminance requirements, similarly to DA calculations but accounting for an area over which many locations are first assessed then merged.

More specifically, all illuminance values calculated over the area of interest are given full credit if they are above a user-defined illuminance threshold (e.g. 500 lux) and partial credit if they are within a buffer illuminance interval below this target value (e.g. 300-500 lux), within which credit decreases linearly from 100% (at 500 lux) to 0% (at 300 lux) as values move away from the threshold. No credit is given if values are outside of the buffer interval. All credit and partial credit is then summed and turned into a percentage which indicates how much of the area of interest fulfils the chosen illuminance criteria. This time-dependent percentage dataset can then be displayed on a Temporal Map.

#### b) Is there too much light?

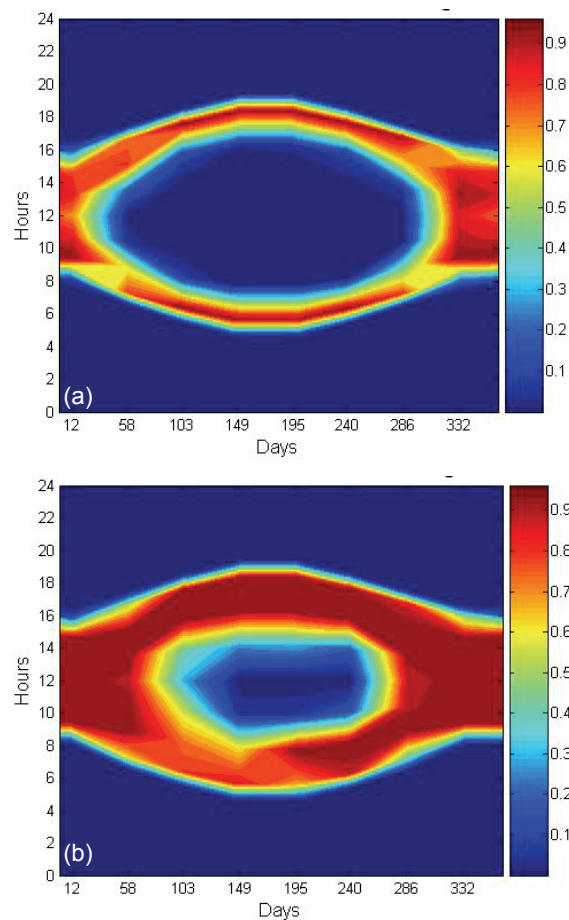
There are, again, several ways one could answer that question. If we use illuminance-based metrics, it comes down to defining an appropriate upper limit for illuminance to avoid (potential) discomfort glare and, then, to following the exact same procedure as described above: full credit given to any sensor points within the user-defined illuminance range (500 lux to 2000 lux e.g.), partial credit to points within a user-defined buffer illuminance zone on either side of the preferred range (300-500 lux and 2000-2500 lux e.g.), and no credit to points outside the buffer zone (< 300 lux or > 2500 lux e.g.).

This “double-bound” goal-based illuminance metric is illustrated for a moderately complex museum design example in Boston (Figure 3). Two design iterations are shown (Figs. 3b and 3c) and their associated time-varied performance maps given in Figure 4 for one area of interest (covering the N and E walls pointed out in Fig. 3a).

The colour scale on these maps is in percent and represents the proportion of AOI fulfilling prescribed illuminance requirements. These requirements (goals) were to achieve between 400 and 800 lux for art conservation purposes, with partial credit being given down to 200 lux and up to 1200 lux. Existing simulation tools (Radiance and 3ds® Max by Autodesk®) were used for this feasibility study, although Lightsolve will ultimately rely on a more adapted rendering engine, described in section 3.2.

Observing these goal-based temporal maps, it appears very clearly that although the design objectives were poorly fulfilled almost all the time in the first design iteration (Fig. 4a), the second one Fig. 4b) was able to restrict unacceptable periods to the summer only, from late morning until early afternoon. In this particular

case, the main issue was direct sun penetration at high angles through the skylight, and was solved by adding shading and diffusing elements.



**Figure 4** Comparison of time-varied performance between design iterations 1 and 2: (a) unacceptable performance most of the time, except in the middle of the winter; (b) greatly improved performance, except in the summer from late morning to early afternoon.

The second approach in addressing too high light levels is based on luminance distributions and glare estimation. Numerous efforts have been made in coming up with glare indices through surveys conducted either with luminaires (Commission Internationale de l'Eclairage (CIE), 1995), (Vos, 2003), (Ashdown, 2005) or, more recently, with daylight (Osterhaus, 2005), (Kim, et al., 2005), (Wienold, et al., 2006). A reliable prediction of occupant discomfort with a glare index still poses important challenges in design, mainly because of its strong dependency on the exact position of the observer (Ashdown, 2005), the large range of luminances involved, the human eye's adaptation to the predominant illumination conditions, and people's variable tolerance to glare (Tuaycharoen, et al., 2005).

A promising index called the Daylight Glare Probability (DGP) was proposed by Wienold (Wienold, et al., 2006), based on and validated with daylighting. It requires, however, that renderings be produced from the occupants' viewpoints, which usually involves a lot more computation time and user effort compared to the simple analytic calculations required by most of the other indices. However, as our goal-based performance metrics will be associated directly to renderings already (see section 3), this reliable and detailed metric, which is already expressed as a percentage, seems a good choice.

For this index, instead of choosing an area of interest, the designer must choose one or more viewpoints of interest, typically corresponding to key occupant positions in the space. A Temporal Map can then be created for each viewpoint, which, in the future, could be averaged or combined to offer a more general perspective of the glare risk within the space.

The other two metrics are currently at a conceptual development stage and will briefly be outlined here.

#### c) Is there excessive sun penetration?

Because any daylight penetration, especially sunlight, is inevitably accompanied by heat penetration, it is also important to at least acknowledge the risk of bringing in solar radiation because of its liabilities in terms of thermal discomfort and excessive cooling loads. Given the great complexity of accurate energy calculations and the many parameters involved, we adopted an approach closer to "raising a flag" i.e. intended to draw the designer's attention to the problem rather than trying to perform any kind of energy simulation (which would almost certainly produce poorer results than existing tools that have been developed over decades). The motivation behind this is to minimize the risk of having daylighting goals conflict with, rather than contribute to, an overall energy scheme.

The most straightforward calculation methodology in this case is, again, to use information that is already calculated for use in other metrics, which is in this case the illuminance on each window exterior, to estimate the solar input through each window area. Preliminary tests and further refinements will hopefully lead to a way of expressing how high the risk of overheating would be over the year, in a relative way.

#### d) Is the light distribution satisfying?

Assessing the quality of a space involves even more factors than glare, many of which are difficult to quantify. Preliminary work in this area (Cuttle, 2004), (Protzman, et al., 2005), (Franz, et al., 2005), (Newsham, et al., 2005), (Manav, 2007) seems to indicate a good correlation between perceived quality

or interest on one hand, and average luminance and its square or a measure of its variability on the other (Newsham, et al., 2005). The adequacy of contrast and luminance-profile based metrics to represent light distribution patterns will be explored. It is unlikely that a general-purpose equation or formula can be developed to quantify ambiances and enhancement effects and be agreed upon by architects and daylighting analysts. Instead we will focus on developing visual associations for compelling light distribution patterns found in renowned works of architecture. This is an ambitious project, with an uncertain outcome. Its development is likely to require a major research effort and will probably be the last component in Lightsolve to take shape.

### 3. Connecting annual performance with visual effects

The representation of annual metrics as Temporal Maps provides a highly visual way to assess the quantitative daylight performance of a space. A platform through which these metrics can be studied in total synchronization with the space views they relate to is thus needed to connect them interactively and appreciate the visual effects, aesthetics and possible comfort issues produced for this range of sky and sun conditions.

#### 3.1 Analysis interface for interactive design exploration

We here present a prototype of a novel interface for browsing daylighting analysis data. The interface presents interactive temporal maps and renderings of the design from different camera viewpoints at different times of the year. Having now access to a comprehensive data visualisation platform from which he can interactively extract quantitative data and qualitative effects, the user is offered a form of design support that seamlessly informs him about how daylight varies over time - accounting for climate and thus predominant sky types -, how views relate to performance, and when (and to some extent why) some of his goals are (not) achieved.

To demonstrate the navigation capabilities of such an interface, a set of pre-computed renderings and urban surrounding views were produced in 3ds Max® by Autodesk® for the museum example described above, and embedded in an interactive analysis platform. This platform is shown on Figure 5. Temporal Maps were also created for three areas of interest in this museum (corridor, NE walls and workplane in South-West

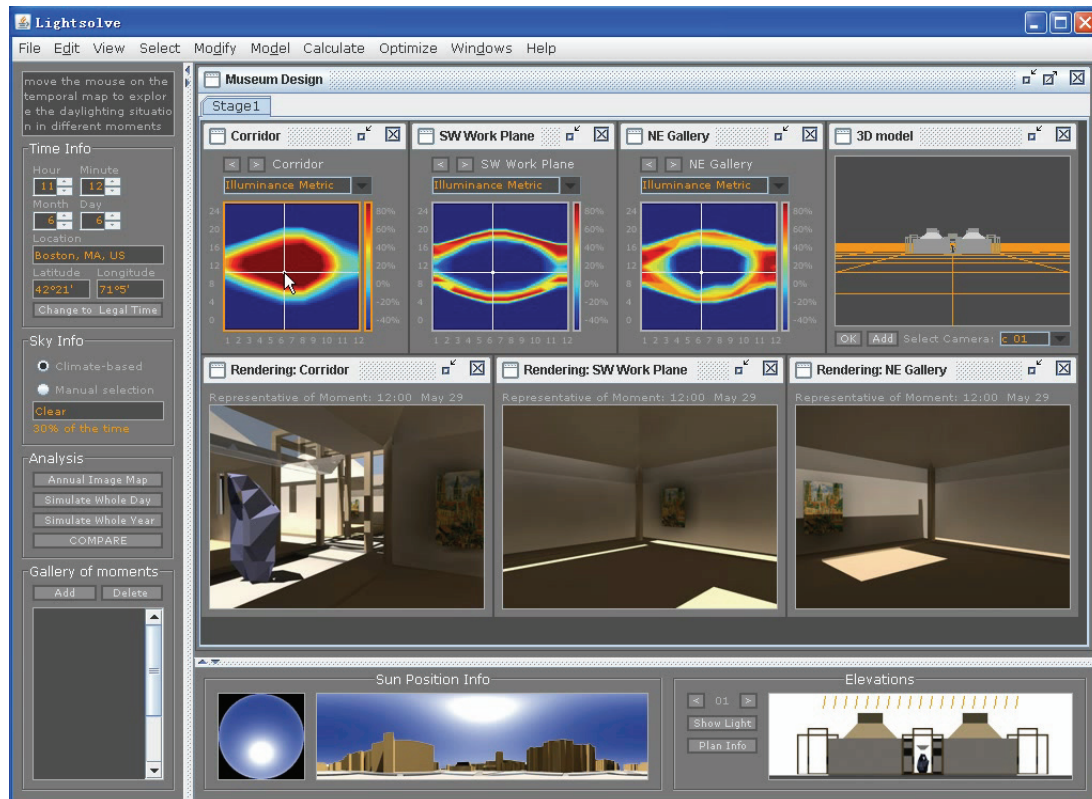
exhibit space), using Radiance simulations. The rendering engine described in section 3.2 will ultimately replace these pre-computed images and maps with visualisations produced interactively.

By moving the mouse over one of the Temporal Maps, the time and date displayed in the corresponding rendered image changes so as to consistently show the representative moment corresponding to the current cursor position. Using the four sky types of the ASRC-CIE sky model, the impact of weather and season are shown, with a percentage indicating the predominant sky type(s). By default, the interior rendering shows the predominant weather condition for the corresponding period of time so as to first convey information about the most likely conditions, although all four sky conditions can be viewed if desired.

Additional interactive visualisation options are proposed, such as animations (time-lapse movies) showing how conditions vary over the course of a day, or over the whole year at a given time, so that the range of daylighting conditions can be experienced as a sequence. Another possibility is to visualize the whole year as an “image-based” Temporal Map that displays the renderings (or false colour views of luminance or illuminance values) of each “representative” moment on a grid showing days of the year along the x-axis and time of day along the y-axis. A third feature worth mentioning is the comparison panel that can be opened to gauge interior views against one another in a very flexible way. The user can choose any design iteration stage, moment, sky type and viewpoint (previously defined through the 3D model navigation frame) and display the corresponding rendering next to others (up to four at a time) for comparison.

Initial testing of this interface by architecture students showed promise. Through a series of interviews and interface demonstrations (Yi, 2008), some main strengths and limitations were revealed. Overall, the reactions were particularly enthusiastic and students showed confidence that this type of visualisation could help addressing design issues comprehensively and intuitively. Having performance evaluation expressed through a consistent colour pattern (red is good, blue is bad) seemed extremely helpful to easily interpret the information provided to them and they found great value in connecting performance with weather and time, and data with images. The one reservation they had was about the lack of constructive feedback: the students showed an eager interest in getting design suggestions or explanations of why a design would fail to fulfil certain goals and how to improve the situation. This was in fact a rather positive point for the project,





**Figure 5** Design analysis interface for LightSolve. An immediate link between condensed annual performance data (Temporal Maps, top) and visual effects inside (interior renderings, middle), in connection to the current daylighting conditions (sky view, surroundings and sun angles on elevations, bottom) allow the user to interactively “navigate” through the daylight performance of his project both from a quantitative and a qualitative standpoints.

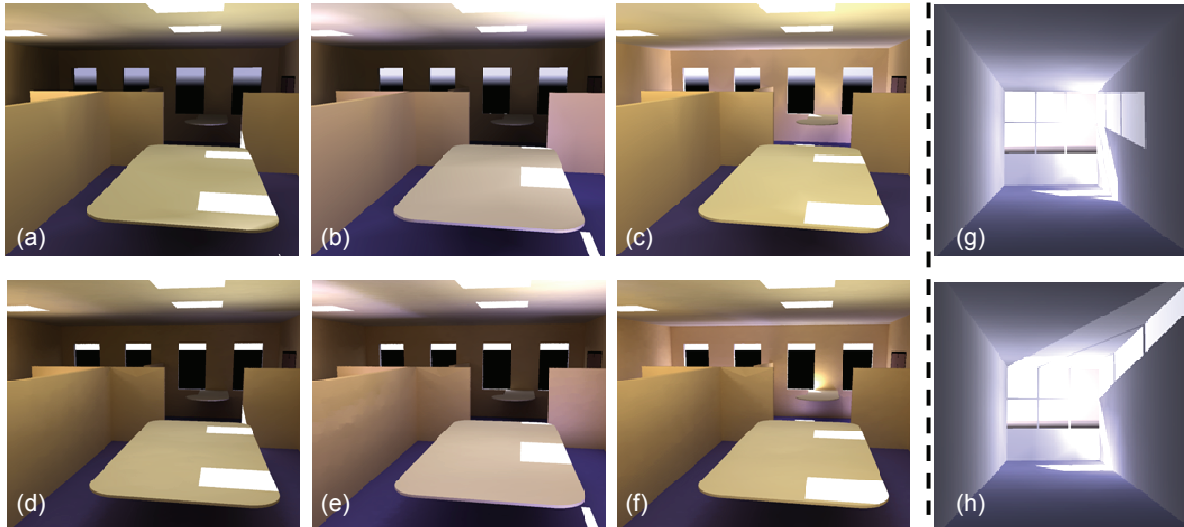
given that this is ultimate intent of Lightsolve, as explained in section 1.3 and further detailed in section 4). This preliminary survey (which was based on pre-computed data produced for the museum shown in Figure 3 and an office space on MIT’s campus) will be expanded to a more formal user study in the near future, once the modelling interface, the goals and constraints definition interface, and the expert support system will be connected to each other and work together as one system.

### 3.2 Interactive global illumination rendering method

To fully take advantage of the representation of annual metrics as Temporal Maps and of its connection with a database of images, fast rendering methods are required so that data and images can be produced interactively. And with the current emergence of more complex fenestration materials (Sullivan, et al., 1998), (Kischkoweit-Lopin, 2002), (Koester, 2004), (Andersen, et al., 2006), (Arasteh, et al., 2003), it also becomes critical that these methods can model conventional as well as advanced window technologies, as angularly and/or spectrally-selective window materials.

An interactive global illumination system for daylighting was created for this purpose, and is described in detail in (Cutler, et al., 2008). This hybrid system computes direct per-pixel illumination from the sun using shadow volumes (Crow, 1977), (Heidmann, 1991) and uses forward ray-tracing for the sky illumination. Indirect illumination (i.e. inter-reflections) is calculated using a radiosity-based method on a coarse grid (Goral, et al., 1984).

Figures 6a to 6c shows some rendering results, and how they compare with reference simulations produced with Radiance, shown in Figures 6d to 6f (parameters were set at high resolution to ensure accuracy; these renderings took about an hour each). Visually, the renderings are almost undistinguishable and numerical comparisons of pixel-by-pixel luminance values (either over the entire image or for an area of interest) consistently led to less than 10% errors for different scenes, sky and sun conditions and camera positions (Cutler, et al., 2008). A range of advanced fenestration systems was also tested, using measured BTDF data (Bidirectional Transmission Distribution Functions) from (Andersen, 2004) and including optical films,



**Figure 6** Comparison of hybrid radiosity/shadow volumes renderings (a-c) with accurate ground truth Radiance renderings (d-f) on June 21 at 10am (a,d), 12pm (b,e) and 2pm (c,f) for a medium sized office scene with low partition walls for latitude 43°N. The windows face west; direct sun penetration is through the skylights. Application to light-redirecting glazings: a holographic film (g) and the sun directing glass Lumitop™ (h) at 10am in a small test room.

blinds, prismatic panels and other systems. Two renderings are shown in Figures 6g and 6h, for a holographic film and the sun directing glass Lumitop™.

The hybrid radiosity/shadow volumes method is also very rapid; a model containing 1000 to 3000 triangular patches required an initialization time of 10 seconds to compute the form factors for radiosity and any subsequent change in viewpoint could be done in real-time (more than 30 frames per second). A change in time or day (which requires relighting) takes a little more than one second (Cutler, et al., 2008).

This rendering speed thus seems appropriate for interactive data and rendering production, given that the initialization process will only happen once for a full analysis (56 moments and all sky types). A display of the results will be continuously updated to maintain the interactive character of the analysis, as explained in section 4.

#### 4. Underlying concepts of the expert design support system

Although each of the developments described in the previous sections shows great potential in itself, it is their combination into a goal-driven approach that makes them become most powerful.

Despite the numerous previous studies in performance-based optimization, most have not considered a goal-driven or user-interactive approach. For example, only

a few studies (Caldas, et al., 2002), (Monks, et al., 2000) propose tools which allow the user to input specific performance goals for their designs. Likewise, few studies have addressed the issue of user-interactivity or design intent. One of the major roles for an architect in the design and construction process is the architectural design itself, and it is unlikely that an architect would choose a computer-generated design as a final solution, regardless of its optimized performance.

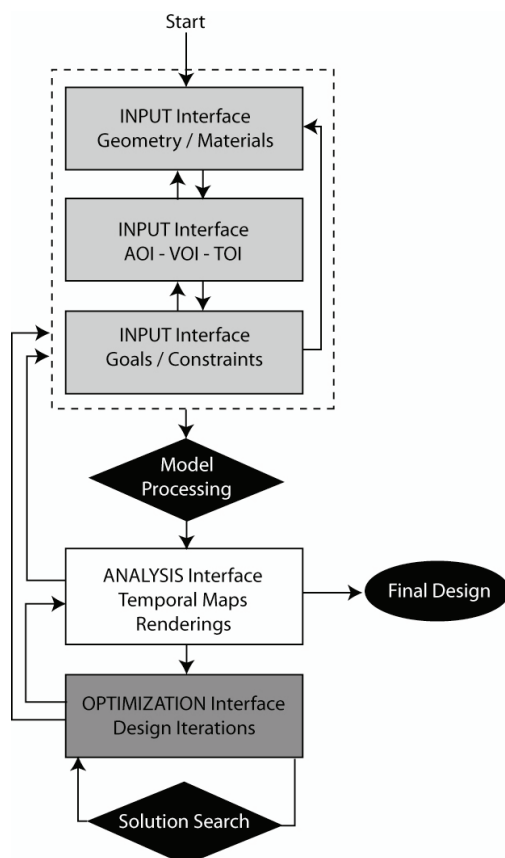
Some studies have attempted to address this issue by producing multiple final designs from which the user can choose (Marks, et al., 1997), (Coley, et al., 2002), (Yeh, 2006), (Znouda, et al., 2007). While this solution will provide the designer with several options instead of one, it does not allow him to truly interact with the system. Others have implemented interfaces which allow the user to interact with the tool while it is still processing (Anderson, et al., 1999), (Monks, et al., 2000), (Malkawi, et al., 2005).

This type of user-interaction begins to approach the desired level of user-interactivity for the optimization method described here. In the approach we propose, the user will get access to a computer-based expert system to improve his original design; its uniqueness lies in its similarity to the interaction a designer would have with a consultant, making it conducive to a more natural design process than a pure optimization methods. The method has not yet been implemented, and will be the subject of a separate paper. Its overall concept and the key development phases are presented below.

#### 4.1 Starting the process

In order to incorporate a performance-based optimization scheme into the architectural design development, it is necessary to support both processes. However, these two processes are not naturally consonant: while the design process can be considered divergent, ill-defined, and unpredictable, the optimization process is usually convergent, well-defined, and algorithmic. It is therefore necessary to find a hybrid process that compromises certain characteristics of each approach.

The overall flow structure for the proposed method is shown on Figure 7 and includes three user interfaces. One allows the user to input and manipulate the geometry and materials used in the design; one allows the user to specify a set of areas of interest, views of interest, and times of interest (if not the whole year); and one allows the user to specify or change the goals and constraints associated to the current design problem.



**Figure 7** Flow chart illustrating the interactive optimization approach chosen for Lightsolve.

At present, it is anticipated that the geometry and materials interface will be similar to - or actually use -

simple and currently available commercial software with which designers may have previous experience, such as SketchUp (Google, 2007). The interface to define area(s), viewpoint(s) and time(s) of interest will allow the user to choose those critical areas, views and times for which goals need to be fulfilled. They will be associated with the specific goals (based a set of proposed metrics, described in section 2.3), and design constraints that are important to the designer.

After the user has finished inputting information about his design and its critical elements, the program will process the data. This processing will mainly consist of producing renderings and extracting data relevant to the calculation of the above described metrics. Although this calculation phase is expected to be short (see section 3.2), the user will watch as it unfolds so that he gets an immediate feedback as well as the opportunity to interrupt the process if parameters needed adjustment. When processing is complete, the user will be able to access the interactive analysis interface shown on Figure 5.

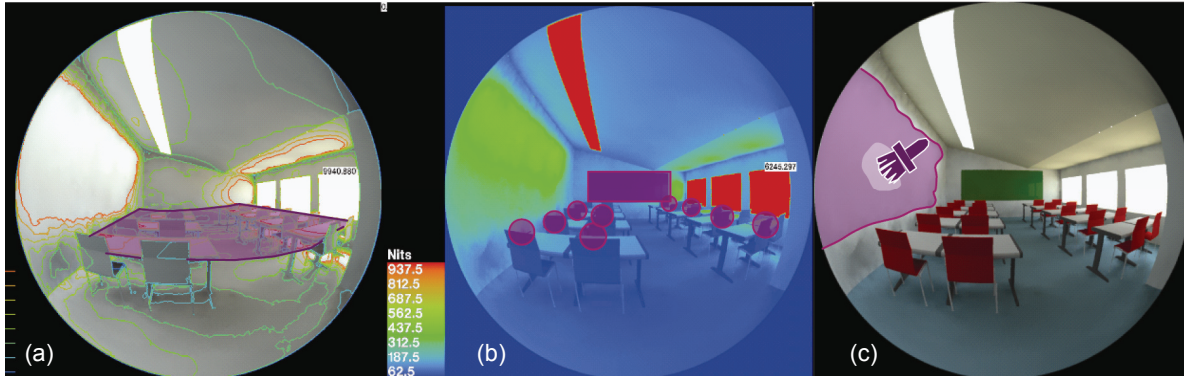
#### 4.2 Goal-driven design support

In the likely event that the initial design does not meet all of the user's goals, he will be given the option to use the expert system to improve his design.

Figure 8 illustrates the process with a classroom design example, for which possible goals could be: minimum illuminance over a given area of interest (Fig. 8a) but only during class hours and over the academic year e.g. (which would be the time of interest); avoidance of direct sunlight on the blackboard area and the pupils' viewpoint (Fig. 8b); a light-washing effect on a wall area at given times – note that visual effects could also be related to a viewpoint instead of an area –, as conceptually illustrated in Fig. 8c. In terms of constraints, geometrical and material parameters such as opening position and size, wall reflectances etc would only be allowed to vary within a certain range or be fixed.

Such user-defined goals can then be transcribed into a set of “ideal” Temporal Maps for each of the relevant metrics described in section 2.3. The objective function is an estimation of the weighted sum of the differences between “ideal” and “current” maps; this weighing depends on the priorities that the user establishes for his set of goals, constraints, areas, views and times of interest.

How to make this multi-variable optimization converge despite the overwhelming number of parameters to consider is explained in section 4.3.



**Figure 6** Comparison of hybrid radiosity/shadow volumes renderings (a-c) with accurate ground truth Radiance renderings (d-f) on June 21 at 10am (a,d), 12pm (b,e) and 2pm (c,f) for a medium sized office scene with low partition walls for latitude 43°N. The windows face west; direct sun penetration is through the skylights. Application to light-redirecting glazings: a holographic film (g) and the sun directing glass Lumitop™ (h) at 10am in a small test room.

As was the case during the initial model processing, the progressive creation of temporal maps and renderings during optimization will be shown to the user as the design evolves. This will allow him to understand what design changes are being made and how they impact performance in real time, hence greatly increasing the educational potential of the tool. He will also be made aware of which goals are currently satisfied at any moment and which goals are still unsatisfied. A set of “Expert Rules”, described in section 4.3, will be used to determine what the most appropriate sequence of design actions is to fulfil the user’s objectives.

To increase the chances of a seamless interaction, the user will be allowed to skip any steps in that sequence or choose to end the process at any time. He may also temporarily go back to an analytic mode (manual changes and re-evaluation), or choose to change goals or constraints if these were revealed inappropriate through this process.

After the process of input, analysis, and design “optimization” has been completed and a satisfactory solution has been found, the user can choose to exit the program, keeping the latest solution as his final design, or he can return to the input stage and choose to modify the proposed design (possibly based on previous iterations), adjust goals or constraints, or add views, areas, or times of interest. The user can repeat this cycle as many times as desired before finding a final solution.

#### 4.3 An expert system for design optimization

Because Lightsolve aims to provide an interactive tool which helps users satisfy their own goals and constraints, we cannot fully anticipate the design problem to be optimized, and this situation makes it difficult to select a traditional optimization strategy.

Instead, we will use a Design of Experiments (DoE) approach (Montgomery, 2004), (Wu, et al., 2000), (Diamond, 2001) to first establish a set of “Expert Rules”. Although the objectives and motivation were quite different, the DoE approach has been used in a building simulation context before such as for DIAL-Europe (where it proved inadequate in the end (Paule, 1999)), energy-based optimization (Mourshed, et al., 2003) and the optimal control of a smart façade system (Park, 2003). To the best of the authors’ knowledge, however, the creation of an “expert system” has not been attempted to inform a user-interactive optimization system.

For each individual design, Lightsolve will then utilize this expert rules set to narrow down a list of possible strategies to apply to the design in order to meet the user’s goals. This list may be quite general: for example, the first strategy may be to increase the south-facing window area, the second strategy may be to increase the height of the east-facing windows, and so on. We will use the Expert Rule set to indicate this general list of changes in the order of predicted effectiveness, and we will supplement with traditional optimization strategies to determine the exact values of each change.

Like the actual design process, the final result of this approach will be a design scheme which best satisfies the goals, within the given constraints. Because the designer remains involved during the entire process, no objective function need be fully or explicitly specified. In fact, we do not aim to find a global optimum or even a local optimum; instead, we rely on optimization in combination with a predefined set of expert rules to predict the effectiveness of certain design changes to improve the situation and inform on their adequacy to solve the issues.



## 5. Conclusion

The overall aim of a successful daylighting design is to increase the amount of useful daylight in an architecturally satisfying way. This strategy aims to maximize its penetration and its potential in enhancing aesthetics while addressing – or pointing out to – its major liabilities such as glare, thermal discomfort, and overheating risks, seasonal and weather-based performance variability and, potentially, privacy concerns. The designer is thus faced with a range of parameters and variables to reconcile, which strongly fluctuate over time but need to harmoniously merge with his overall design scheme.

This paper shows how the Lightsolve approach can allow a designer to keep a comprehensive perspective throughout the design process and visualize how performance and aesthetics evolve throughout each iteration, without disturbing or interrupting the design process but rather facilitating a broad range of options. Unlike existing methods, Lightsolve allows an architect or building designer to evaluate the annual daylighting potential of a schematic building project *interactively*, and helps increase this potential by guiding him in making design decisions that bring the project closer to achieving his goals.

The key beneficiaries of this research are building engineers and architects, who will get to explore a large realm of design alternatives for their projects, including advanced technological solutions which are responsive both to performance criteria and to the more subjective issue of architectural quality. Lightsolve will provide them with a new form of project deliverable for their studio or to their clients and help them better envision how their space will perform and appear over time and under varying seasonal and weather conditions. In an indirect sense, Lightsolve will also teach the user which kinds of design changes are commonly needed for optimal daylight performance. Additionally, manufacturers and vendors of advanced daylighting materials or systems are other obvious recipients of this work. Lightsolve will provide their clients with intuitive ways of assessing, choosing, and optimizing the use of their products based on their performative and aesthetic effects in architectural spaces.

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## References

- Altmann, K., & Apian-Bennewitz, P. (2001). *Report on an Investigation of the Application and Limits of Currently Available Programme Types for Photorealistic Rendering of Light and Lighting in Architecture - The Kimbell Art Museum as a Case Study for Lightscape, Radiance and 3D-Studio MAX.*
- Andersen, M. (2004). *Innovative bi-directional video-goniophotometer for advanced fenestration systems.* Ph.D. Thesis, EPFL, LESO-PB, Lausanne.
- Andersen, M., & de Boer, J. (2006). Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems. *Energy and Buildings*, 38 (7), 836-848.
- Anderson, D., Anderson, E., Lesh, N., Marks, J., Perlin, K., Ratajczak, D., et al. (1999). Human-guided simple search: combining information visualization and heuristic search. *Workshop on New Paradigms in Information Visualization and Manipulation*, (pp. 21-25).
- Arasteh, D., Apte, J., & Huang, Y. (2003). Future Advanced Windows for Zero-Energy Homes. *ASHRAE Transactions*, 109, Part 2.
- Architectural Energy Corporation. (2006). *SPOT v. 3.1 – Sensor Placement + Optimization Tool, User's manual.*
- Ashdown, I. (2004). Modeling of Daylight for Interior Environments. *Proceedings of the IESNA 2004 conference.* Broadbeach, Australia.
- Ashdown, I. (2005). Sensitivity Analysis of Glare Rating Metrics. *LEUKOS - The Journal of the Illuminating Engineering Society of North America*, 2 (2), 115-122.
- Bourgeois, D., Reinhart, C., & Macdonald, I. (2006). Adding advanced behavioural models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control. *Energy and Buildings*, 38 (7), 814-823.
- Bourgeois, D., Reinhart, C., & Ward, G. (2008). A Standard daylight coefficient model for dynamic daylighting simulations. *Building Research and Information*, 36 (1), 68-82.
- Broadbent, G. (1988). *Design in Architecture: Architecture and the Human Sciences.* London: Fulton.
- Bund, S., & Yi-Luen Do, E. (2005). Spot! Fetch Light Interactive navigable 3D visualization of direct sunlight. *Automation in Construction*, 14 (2), 181-188.
- Caldas, L., & Norford, L. (2002). A design optimization tool based on a genetic algorithm. *Automation in Construction*, 11 (2), 173-184.
- Chutarat, A. (2001). *Experience of Light: The Use of an Inverse Method and a Genetic Algorithm in Daylighting*



- Design. Ph.D. Thesis, MIT, Building Technology, Dept of Architecture, Cambridge.
- Coley, D., & Schukat, S. (2002). Low-energy design: combining computer-based optimization and human judgement. *Building and Environment*, 37 (12), 1241-1247.
- Commission Internationale de l'Eclairage (CIE). (1970). Daylight. *CIE*, 16 (E-3.2).
- Commission Internationale de l'Eclairage (CIE). (1995). Discomfort glare in interior lighting. *CIE*, 117, 2-5.
- Commission Internationale de l'Eclairage (CIE). (1994). *Spatial distribution of daylight – Luminance distributions of various reference skies*. CIE Technical Report, Vienna.
- Crow, F. (1977). Shadow algorithms for computer graphics. *Proceedings of SIGGRAPH 77*, 11(2), pp. 242–248.
- Cutler, B., Sheng, Y., Martin, S., Glaser, D., & Andersen, M. (2008). Interactive Selection of Optimal Fenestration Materials for Schematic Architectural Daylighting Design. *Automation in Construction*, 17 (7), 809-823.
- Cuttle, C. (2004). Brightness, lightness, and providing 'a preconceived appearance to the interior. *Lighting Research and Technology*, 36 (3), 201–216.
- Cuttle, C. (2002). Identifying the human values associated with windows. *International Daylighting*, 5, 3-6.
- Diamond, W. (2001). *Practical experiment designs for engineers and scientists* (3rd Edition ed.). Wiley.
- Fernandes, L. (2006). *From Lighting Performance Goals to the Optical Characteristics of Fenestration*. Ph.D. Thesis, University of Colorado, Department of Civil, Environmental, and Architectural Engineering.
- Franz, G., von der Heyde, M., & Buelthoff, H. (2005). An empirical approach to the experience of architectural space in virtual reality—exploring relations between features and affective appraisals of rectangular indoor spaces. *Automation in Construction*, 14 (2), 165-172.
- Geebelen, B., van der Voorden, M., & Neuckermans, H. (2005). Fast and accurate simulation of long-term daylight, availability using the radiosity method. *Lighting Research and Technology*, 37 (4), 295-312.
- Glaser, D., Feng, O., Young, J., & Xiao, L. (2004). Towards an algebra for lighting simulation. *Building and Environment*, 39 (8), 895-903.
- Google. (2007). *Google SketchUp*. Retrieved July 13, 2007, from <http://www.sketchup.com/?sid=4>
- Goral, C., Torrance, K., Greenberg, D., & Battaile, B. (1984). Modelling the Interaction of Light Between Diffuse Surfaces. *Computer Graphics (Proceedings of SIGGRAPH 84)*, (pp. 213-222).
- Guzowski, M. (2000). *Daylighting for Sustainable Design*. McGraw-Hill.
- Heidmann, T. (1991). Real shadows, real time. *Iris Universe*, 18, pp. 28–31. Silicon Graphics, Inc.
- Herkel, S. (1997). Dynamic link of light- and thermal simulation: on the way to integrated planning tools. *Proceedings of Building Simulation 1997*. Prague, Czech Republic: IBPSA.
- Heschong-Mahone Group, Inc. (2003). *Windows and Classrooms: A Study of Student Performance and the Indoor Environment*. California Energy Commission.
- Hitchcock, R., & Carroll, W. (2003). DELight: A daylighting and electric lighting simulation engine. *Eighth International IBPSA Conference*, (pp. 483-490). Eindhoven, Netherlands, August 11-14.
- Kim, J.-J., & Wineman, J. (2005). *Are Windows and Views Really Better? A Quantitative Analysis of the Economic and Psychological Value of Views*. Rensselaer Polytechnic Institute, Lighting Research Center. Troy, NY: Daylight Dividend Program.
- Kim, W., & Koga, Y. (2005). Glare constant Gw for the evaluation of discomfort glare from windows. *Solar Energy*, 78 (1), 105–111.
- Kischkoweit-Lopin, M. (2002). An overview of daylighting systems. *Solar Energy*, 73 (2), 77-82.
- Kleindienst, S., Bodart, M., & Andersen, M. (2008). Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design. *LEUKOS - The Journal of the Illuminating Engineering Society of North America*, in press.
- Koester, H. (2004). *Dynamic Daylighting Architecture: Basics, Systems, Projects*. Birkhauser.
- Lam, W. (1986). *Sunlighting as Formgiver for Architecture*. Van Nostrand Reinhold.
- Lehar, M., & Glicksman, L. (2007). Rapid algorithm for modeling daylight distributions in office buildings. *Building and Environment*, 42 (8), 2908–2919.
- Littlefair, P. (1994). A Comparison of Sky Luminance Models with Measured Data from Garston. *Solar Energy*, 53 (4), 315-322.
- Malkawi, A., Srinivasan, R., Yi, Y., & Choudhary, R. (2005). Decision support and design evolution: integrating genetic algorithms, CFD, and visualization. *Automation in Construction*, 14 (1), 33-44.
- Manav, B. (2007). An experimental study on the appraisal of the visual environment at offices in relation to colour temperature and illuminance. *Building and Environment*, 42 (2), 979–983.
- Mardaljevic, J. (2004). Spatial-temporal dynamics of solar shading for a parametrically defined roof system. *Energy and Buildings*, 36 (8), 815-823.
- Marks, J., Andalman, B., Beardsley, P., Freeman, W., Gibson, S., Hodgins, J., et al. (1997). Design galleries: A general approach to setting parameters for computer graphics and animation. *Proceedings of SIGGRAPH 97 - Computer Graphics*, (pp. 389–400).
- Marsh, A. (2008). *ECOTECH: An Overview*. Retrieved 03 07, 2008, from Square One: <http://sql.com/products/ecotech>
- Monks, M., Oh, B., & Dorsey, J. (2000, May/June). Audiioptimization: Goal-Based Acoustic Design. *IEEE Computer Graphics and Applications*.
- Montgomery, D. (2004). *Design and analysis of experiments* (6th Edition ed.). Wiley.
- Mourshed, M., Kelliher, D., & Keane, M. (2003). ArDOT: A tool to optimize environmental design of buildings. *Proceedings of IBPSA 2003*.
- Nabil, A., & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38 (7), 905–913.

- Newsham, G., Richardson, C., Blanchet, C., & Veitch, J. (2005). Lighting quality research using rendered images of offices. *Lighting Res. Technol.*, 37 (2), 93-115.
- Osterhaus, W. (2005). Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy*, 79 (2), 140–158.
- Park, C.-S. (2003). *Occupant responsive optimal control of smart facade system*. Ph.D. Thesis, Georgia Institute of Technology, College of Architecture.
- Paule, B. (1999). *Application de la logique floue a l'aide a la decision en eclaireage naturel*. Ph.D. Thesis, EPFL, Department of Architecture, Lausanne.
- Paule, B., & Scartezzini, J.-L. (1997). "Leso-DIAL", a new Computer-based Daylighting Design Tool. *Right Light 4. I. IAEEEL*.
- Perez, R., Michalsky, J., & Seals, R. (1992, Summer). Modelling Sky Luminance Angular distribution for Real sky conditions: experimental evaluation of existing algorithms. *Journal of the IES*, 84-92.
- Perez, R., Seals, R., & Michalsky, J. (1993). All-Weather Model for Sky Luminance Distribution - Preliminary configuration and Validation. *Solar Energy*, 50 (3), 235-245.
- Protzman, J., & Houser, K. (2005). On the Relationship between Object Modeling and the Subjective Response. *LEUKOS - The Journal of the Illuminating Engineering Society of North America*, 2 (1), 13-28.
- Reinhart, C. (2004). Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. *Solar Energy*, 77 (1), 15–28.
- Reinhart, C., & Fitz, A. (2006). Findings from a survey on the current use of daylight simulations in building design. *Energy and Buildings*, 38 (7), 824–835.
- Reinhart, C., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*, 33 (7), 683-697.
- Reinhart, C., Bourgeois, D., Dubrous, F., Laouadi, A., Lopez, P., & Stelescu, O. (2007). Daylight 1-2-3 - A state-of-the-art daylighting/energy analysis software for initial design investigations. *Proceedings of the Buildings Simulation 2007 (IBPSA)*. Beijing, China, September 3-6.
- Reinhart, C., Mardaljevic, J., & Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS - The Journal of the Illuminating Engineering Society of North America*, 3 (1), 7-31.
- Sullivan, R., Beltran, L., Lee, E., Rubin, M., & Selkowitz, S. (1998). *Energy and Daylight Performance of Angular Selective Glazings*. Lawrence Berkeley National Laboratory. U.S. Department of Energy.
- Tregenza, P. (1987). Subdivision of the Sky hemisphere for luminance measurements. *Light. Res. Technol.*, 19 (1), 13–14.
- Tuaycharoen, N., & Tregenza, P. (2005). Discomfort glare from interesting images. *Lighting Research and Technology*, 37 (4), 329-341.
- U.S Department of Energy. (2006). *2006 Building Energy Databook*. Retrieved 07 05, 2007, from <http://buildingsdatabook.eren.doe.gov>
- Veitch, J. (2005). Light, Lighting, and Health: Issues for Consideration. *LEUKOS*, 2 (2), 85–96.
- Vos, J. (2003). Reflections on glare. *Lighting Res. Technol.*, 33 (2), 163–176.
- Walkenhorst, O., Luther, J., Reinhart, C., & Timmer, J. (2002). Dynamic annual daylight simulations based on one-hour and one-minute means of irradiance data. *Solar Energy*, 72 (5), 385-395.
- Ward, G., & Shakespeare, R. (1998). *Rendering with Radiance – The Art and Science of Lighting Visualization*. Morgan Kaufmann Publishers, Inc.
- Webb, A. (2006). Considerations for Lighting in the Built Environment: Non-Visual Effects of Light. *Energy and Buildings*, 38, 721-727.
- Wienold, J., & Christoffersen, J. (2006). Evaluation Methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*, 38 (7), 743-757.
- Wu, C., & Hamada, M. (2000). *Experiments : planning, analysis, and parameter design optimization* (1st Edition ed.). Wiley.
- Yeh, I.-C. (2006). Architectural layout optimization using annealed neural network. *Automation in Construction*, 15 (4), 531-539.
- Yi, L. (2008). *A New Approach in Data Visualization to Integrate Time and Space Variability of Daylighting in the Design Process*. SMArchS Thesis, Massachusetts Institute of Technology, Department of Architecture.
- Znouda, E., Ghrab-Morcos, N., & Hadj-Alouane, A. (2007). Optimization of Mediterranean building design using genetic algorithms. *Energy and Buildings*, 39 (2), 148–153.