462: Informing daylighting design with the Lightsolve approach: why and how

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Abstract

To efficiently and appropriately integrate daylighting strategies in their projects, building designers need reliable methods to address issues such as daily and seasonal variations or the balance between sufficient illumination with visual and thermal comfort aspects. This integration must also happen early in the design process to have a significant impact on energy savings and ultimate building performance.
This paper proposes to address this need by fulfilling three major objectives: support the design process using a goal-oriented approach based on iterative design improvement suggestions; provide climate-based annual metrics in a visual and synthesized form; and relate quantitative and qualitative performance criteria thanks to a novel interface for browsing daylighting analysis data in various forms. A methodology to achieve these objectives is described here as the Lightsolve approach.

Keywords: daylighting, design process, interactive optimization, energy, visualization

1. Introduction

For spaces in which the management of sunlight and daylight penetration is critical, special attention has to be given to fundamental design decisions such as orientation, massing, and openings position or size early on in the process because of their great impact on the ultimate performance of the space from a lighting and solar access standpoints. 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 analysis should affect the continuity and seamlessness of the design process as little as possible. Yet currently available daylighting simulation tools, whether intended for use in the early design stage or appropriate for more detailed analyses, 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 such as Daysim [1] and S.P.O.T.[2]) 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 visualization platform, that could display data on an annual basis and in connection with renderings, would become powerful in providing comprehensive information while minimizing disturbance of the design process.

To achieve these goals, the proposed 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. These aspects are combined with the setting-up of a system of pre-determined daylighting expert rules meant to get 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, similarly to feedback that a consultant would provide in a realistic design team scenario.

2. Integrated visualization of time-varied performance data

Because of the importance of orientation, latitude, sunlight penetration and climate on a building's daylighting performance, important efforts are being made to come up with ways to quantify daylight on an annual basis [3]. Building upon these efforts, and focusing on informing design early on in the process, it became clear that an emphasis on time-varied performance was also necessary so that the influence of sun position, weather and time of day can be considered. This information should 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 visualization of data has thus been chosen in the form of Temporal Maps [4] and a specific time-segmentation method applied to reduce the amount of data to produce and manage (section 2): as explained in section 3, this representation of numerical data in time-varying form is then connected to visual data in spatial varying form.

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 [5]: it 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 [6] and validated by Littlefair against the extensive BRE sky-luminance distribution dataset [7]. Each of the four standard CIE sky models (overcast, intermediate, clear, clear turbid) 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. This method of division results in 28 unique sun positions at 56 times of year, illustrated in Figure 1, combined with a set of additional one-bounce ray-tracing simulations performed for 1200 sun positions and overlayed on the map [5].

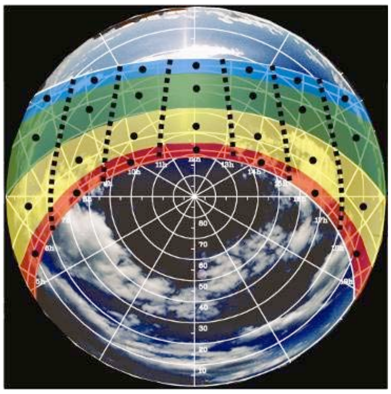

Figure 1. Time-segmentation method illustrated on a stereographic chart: each half year is split in four intervals, and each day (time between sunrise and sunset) is split in seven equal time intervals.

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. 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 space visualization. This means that each of these "representative" moments, standing for a whole period, will be directly connected to space visualization and renderings. The time-segmentation method can thus be considered as a solution between visualizing many instantaneous data point and combining them into comprehensive climate-based metrics such as Daylight Autonomy: 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 [4]. 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 (Figure 2a). This map was created with MATLAB using the 105,120 data points calculated by DAYSIM - one for every five minute interval during the year [8].

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 [5].

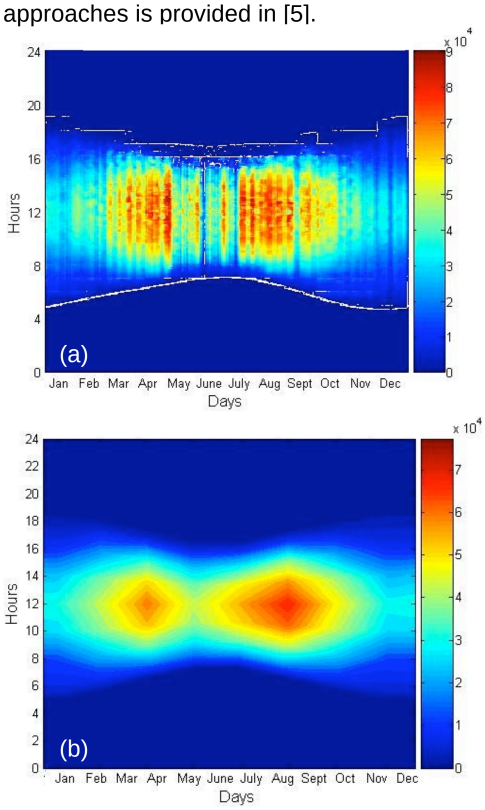

Figure 2. Temporal Maps for a North-facing façade in Sydney displaying outside vertical illuminance in lux, based on (a) five minutes intervals using DAYSIM and (b) a reduced set of 56 data points for Lightsolve

Figure 3. Renderings of a museum case study in Boston: (a) Radiance model - the considered areas are indicated for the NE exhibit space; (b) Interior rendering (3ds Max® by Autodesk®) on May 29 at noon; (c) time-varied performance.

2.3 Goal-based metrics

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.

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:

- *Is there enough light?* This question usually pertains to one or more areas of interest to the designer and the answer can be based on a range of metrics 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 reduce the amount of data the designer has to consider, 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 and given either full credit (fulfils goals), partial credit or no credit, then merged. All credit and partial credit is summed and turned into a percentage of area of interest that fulfills the chosen illuminance criteria. This time-dependent percentage dataset can then be displayed on a Temporal Map.

- *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. This "double-bound" goal-based illuminance metric is illustrated for a moderately complex museum design example in Boston (Figure 3). One design iteration is shown in Fig. 3b and its associated time-varied performance map in Figure 3c for one area of interest (covering the N and E walls pointed out in Fig. 3a). 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.

The second approach in addressing too high light levels is based on luminance distributions and glare estimation. A promising index called the Daylight Glare Probability (DGP) was proposed by Wienold & Christoffersen [9], based on and validated with daylighting. It requires 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. But, 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.

Two other metrics are currently at a conceptual development stage:

- *Are solar heat gains excessive?* 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 with its liabilities in thermal discomfort and excessive cooling loads. Given the 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 an actual energy simulation (which would certainly produce poorer results than 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.

- *Is the light distribution satisfying?* Although ambiances and enhancement effects are essential daylighting aspects from a designer's standpoint, it is unlikely that a general-purpose equation or formula can be developed to quantify these objectively and be agreed upon. Future work will include building upon existing light distribution indices in combination with more subjective categorizations of distribution patterns but will not be discussed at this early stage.

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, aesthetic and possible comfort issues produced for a range of sky and sun conditions to the extent renderings on screen can achieve this.

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. 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 visualizations 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 visualization options are proposed, such as animations (time-lapse movies), "image-based" Temporal Map displaying the renderings (or false color views of luminance or illuminance values) of each "representative" moment on a grid etc.

Initial testing of this interface by architecture students showed promise. Through a series of interviews and interface demonstrations [10], some main strengths and limitations were revealed. Overall, the reactions were particularly enthusiastic and students showed confidence that this type of visualization could help addressing design issues comprehensively and intuitively. 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 fulfill certain goals and how to improve the situation. This was in fact a rather positive point for the project, given that this is ultimate intent of Lightsolve, as explained in section 1.3 and further detailed in section 4).

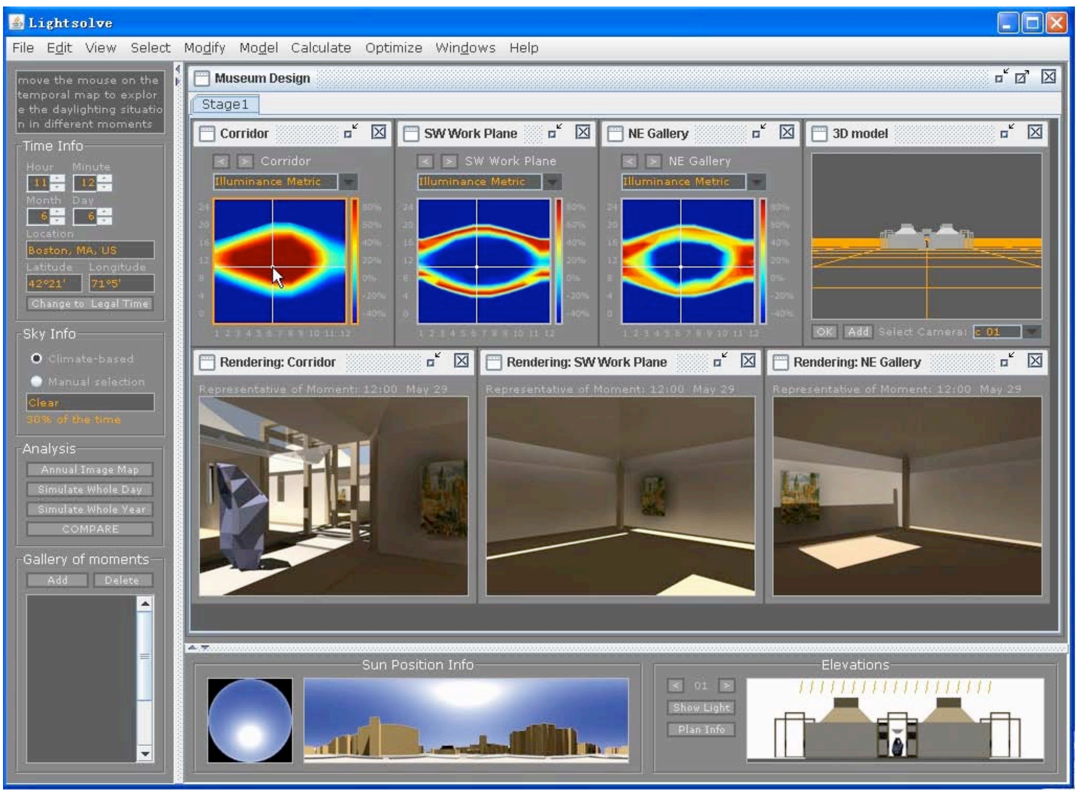

Figure 5. Design analysis interface for Lightsolve. Annual performance in the form of Temporal Maps (top) is linked to interior renderings (middle) and to the current daylight access conditions (bottom) so that the user can interactively "navigate" through the daylight performance of his project from a quantitative and a qualitative standpoints.

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 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 [11]. This hybrid system computes direct per-pixel illumination from the sun using shadow volumes [12] 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.

4. Underlying concepts of the expert design support system

Despite numerous previous studies in performance-based optimization, most have not considered a goal-driven or user-interactive approach. For example, only a few studies [13] 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. Some studies have attempted to address this by producing multiple final designs from which the user can choose [14]. 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 [15].

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.

Its overall concept and the key development phases are presented below.

4.1 Starting the process

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.

After the user has finished inputting information about his design, the program processes the data.

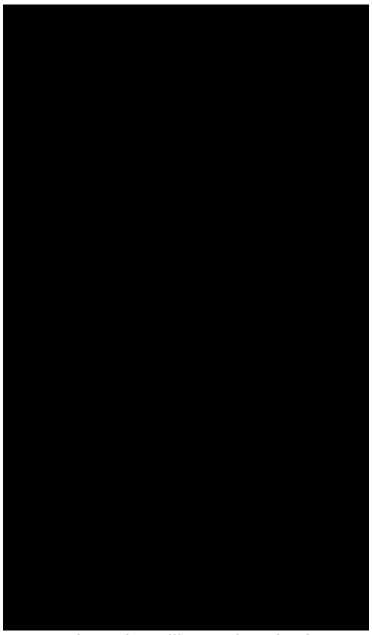

Figure 7. Flow chart illustrating the interactive optimization approach chosen for Lightsolve.

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 interface shown on Figure 5.

4.2 Goal-driven design support

The user-defined goals will 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 goals, constraints, areas, views and times of interest.

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.

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 fulfill the user’s objectives.

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 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 energy-based optimization [16] or the optimal control of a smart façade system [17]. To the best of the authors' knowledge, 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. 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 usually means maximizing its penetration and its potential to produce desired visual effects while addressing - or being aware of - 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.

6. Acknowledgements

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