Daylight dynamics to guide early stage design:

A user-driven goal-based approach to “good” lighting

MARILYNE ANDERSEN,
Interdisciplinary Laboratory of Performance-Integrated Design (LIPID),
Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland,
marilyne.andersen@epfl.ch

ANTOINE GUILLEMIN,
LIPID | EPFL, Lausanne, Switzerland, antoine.guillemin@epfl.ch

More and more refined methods are currently being developed that aim to inform designers about daylighting management in a comprehensive way, many of which try to investigate annual daylighting potential through climate-based modeling. In this paper, we propose to address the issue of dealing with very different quantities all relevant to ‘good’ daylighting performance (illumination potential, glare risks, aesthetics, physiological effects of light) by resorting to a goal-based approach, so that such quantities or metrics can all be evaluated on a relative basis within a single simulation framework and a unique, intuitive and visual format. Specifically, the paper proposes to build upon the goal-based approach adopted by the Lightsolve simulation framework to bring together physical, physiological and perceptual aspects of light around the temporal variability of their effects. A prototype interface is presented that proposes an interactive, highly visual simulation environment in which to integrate these goal-based concepts. The paper also describes the premices of an expert system aiming to guide the user towards improved design solutions. The objective is to support early stage design regarding both conventional aspects of daylight performance such as workplane illuminance, glare and associated solar gains, and unconventional ones such as perceptual or non-visual effects of daylight, all considered in combination within a unified framework of analysis.

Keywords: daylighting, non-visual lighting, goal-based performance metrics

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MARILYNE ANDERSEN[1], ANTOINE GUILLEMIN[1]

[1]Interdisciplinary Laboratory of Performance-Integrated Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

ABSTRACT: More and more refined methods are currently being developed that aim to inform designers about daylighting management in a comprehensive way, many of which try to investigate annual daylighting potential through climate-based modeling. In this paper, we propose to address the issue of dealing with very different quantities all relevant to 'good' daylighting performance (illumination potential, glare risks, aesthetics, physiological effects of light) by resorting to a goal-based approach, so that such quantities or metrics can all be evaluated on a relative basis within a single simulation framework and a unique, intuitive and visual format. Specifically, the paper proposes to build upon the goal-based approach adopted by the Lightsolve simulation framework to bring together physical, physiological and perceptual aspects of light around the temporal variability of their effects. A prototype interface is presented that proposes an interactive, highly visual simulation environment in which to integrate these goal-based concepts. The paper also describes the premices of an expert system aiming to guide the user towards improved design solutions. The objective is to support early stage design regarding both conventional aspects of daylight performance such as workplane illuminance, glare and associated solar gains, and unconventional ones such as perceptual or non-visual effects of daylight, all considered in combination within a unified framework of analysis.
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INTRODUCTION

The integration of building performance criteria into the design process has received a great level of attention in the last two decades, with a range of metrics [1] and of tools [2] available and still being developed to support our search for minimizing energy consumption or ecological footprint. One of its underlying principles is – typically – that the performance of a space will increase with user satisfaction and decrease with energy consumption [3] (towards discomfort compensation until occupant satisfaction is reached).

As far as daylight penetration is concerned, established metrics have been focusing on finding benchmarks for task illuminance and visual comfort (glare avoidance) [3,4], with varying degrees of applicability beyond the conditions in which they were measured, and with results that are often difficult to compare. Other studies have also looked at individual preferences [5], or at "light quality" indicators typically derived from luminance averages or ratios [6].

Daylight metrics concepts associated to entire space areas [7] or viewed scenes [8] rather than individual detection points have also been proposed. The latter tended to shift the focus back on daylight variability, not only its spatial distribution [8,9]. Overall, these multiple parallel efforts led to a strong interest in assessing the potential of optimization to support design, based on methods ranging from generative design [10] to human-guided search, knowledge-based or expert systems [11], including systems specifically aiming to demonstrate the under-explored potential of iterative processes [12] so as to increase control and educational value [13].

A major challenge in all these endeavors remains to define adequate target values that can guide design towards objectively "better" performance. Yet the question of "how good is good?" is actually far from trivial with the multifaceted, highly variable nature of daylighting performance, about which people – occupants as much as designers – have highly diverging opinions: optimization does not respond well to the non-deterministic, ill-defined and unpredictable nature of the design process, which is exactly where its creativity lies.

With daylighting in particular, performance must be measured against goals that vary over time, by occupant profile and/or be driven by the designer's intent, which necessarily retains a part of subjectivity. In this paper, daylight as a desirable architectural component that satisfies both visual and psychological needs of occupants will be considered from a five perspectives formalized around a consistent goal-based concept:

- Worplane illuminance (visual task performance), based on the concept of Acceptable Illuminance Extent (AIE) introduced in [7];

- Discomfort glare (visual comfort), based on the concept of Glare Avoidance Extent introduced in (GAE) [7] but applied to full Daylight Glare Probability (DGP) [4] calculations;
- Solar gains management, based on the Solar Heat Scarcity / Surplus (SHS) concept introduced in [7];
- Perceptual daylight, based on the combined occurrences of contrast and variability within viewed scenes [8,14];
- Non-visual effects (direct and circadian), based on a dynamic model focusing on time-dependencies of spectral response and light exposure adaptation, including prior photic history [14,15].

The paper first provides an overview of how these different perspectives are described in terms of metrics. Then it describes the goal-based simulation and visualization framework that enables such a diversity of perspectives to be considered in a unified and interactive way, with a short introduction to ongoing work regarding the development of an iterative expert system.

OVERVIEW OF CONSIDERED DAYLIGHT PERFORMANCE 'PERSPECTIVES'

How well a given space is daylit is by essence a multifaceted question: it is a key factor in how well any visual task will be performed, a main driver of occupant satisfaction regarding visual and thermal comfort (and hence energy consumption resulting from trying to meet comfort requirements), has a strong impact on human health and well-being, a close association with (subjective) emotional delight and perceived quality of a space, and is highly dynamic and variable in nature resulting from a combination of predictable (sun course) and stochastic (weather) patterns.

Many approaches can be found that try to address each of these perspectives individually; the five perspectives considered here, illustrated in Figure 1 together with their associated "metrics" (introduced in previously published papers and briefly described below) offer the potential to move towards a more unified framework of decision support in the design process regarding daylighting performance.

Visual task lighting

Visual needs typically get translated into target illuminance levels or ratios [1,3], with the earliest "daylight factor" recommendations dating back to the end of the 19th century. More recently, climate-based modelling has become a widespread approach – at least in research but also to some extent in practice – so as to consider daylighting on an annual basis [1,3,7,14].

The illuminance-derived metric considered in the present framework (1st row in Fig. 1), called Acceptable Illuminance Extent (AIE), has been introduced in [7] and calculates how the percentage of a user-defined area of interest in which the illuminance stays within a chosen range varies over time. It therefore simply relies on surface illuminance (workplane, wall etc) and is typically double-bounded (lower and upper bounds) although upper bounds only make sense when too much light is an issue (such as for artwork exhibits e.g.).

This metric requires one or more light receiving surface(s) (or perimeter(s)) to be freely defined by the user in his/her 3D model, and the boundary conditions to be chosen. The latter should answer the following questions: below what illuminance threshold in [lux] shall we consider that there is basically no useful daylight penetration (acceptable low), above what threshold is illuminance perfectly satisfactory (desired-low), above what threshold (if any upper bound is necessary) are the conditions starting to be less ideal (desired-high) and above what threshold is there definitely too much light (acceptable-high)?

Comfortable lighting

There is a general consensus that discomfort glare is the main cause of occupant interactions with shading and thus a major source of potential dissatisfaction from occupants [5]. To quantify this effect, one index of note is the Daylight Glare Probability (DGP) [4], based on sidelit office conditions and considered the most reliable index for daylit workspaces, as it is the only one actually derived from daylighting conditions.

The metric called Glare Avoidance Extent (GAE), also introduced in [7] and used in the present context, relies on the DGP [4] (and its established boundary conditions) in combination with a principle similar to the AIE in the sense that it will convey an evaluation of how "glary" a whole zone within a space will be by evaluating the percentage of glare "sensors" (automatically generated so as to populate the perimeter of interest with a well-distributed set of view locations and directions) that show intolerable or disturbing visual conditions.

This metric requires the user to either define a perimeter of interest (portion of a space) in which he/she is interested to assess glare from arbitrary view locations and directions (to assess the overall "glaryness" of the area) or to define one (or a set of) specific view location(s) and direction(s) that are critical in this particular space, where a conventional DGP analysis will be conducted. The user-defined goals will thus pertain to how sensitive to glare the considered space (or space portion) is to glare, which will determine which DGP thresholds to apply [4].

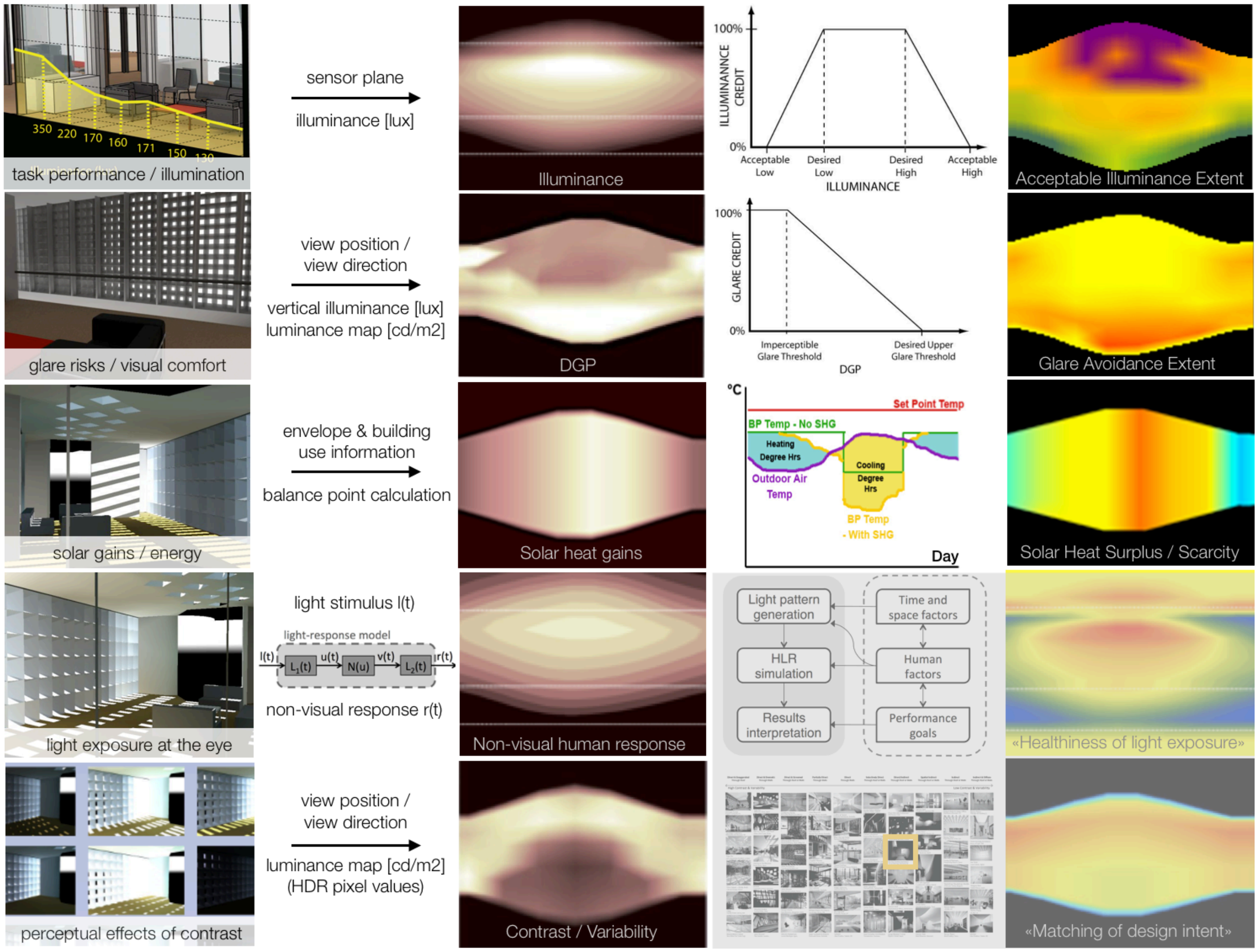


Figure 1: Overview of performance analysis framework: five different perspectives regarding daylighting performance (left column) lead to five quantitative approaches to extract "absolute" performance (middle column) i.e. evaluated on a linear scale from low to high. These quantities are used as inputs to threshold-based metrics leading to goal-based visualizations of performance according to a consistent color scale so as to compare "success" of highly dissimilar performance criteria (last 2 (greyed) are work in progress).

Seasonal lighting

The energy impacts of satisfying thermal comfort benchmarks with active heating or cooling can become significant if excessive or insufficient daylight and its associated tradeoff – solar gains – must be compensated for to a too large extent. To account for both overheating risks and potentially reduced heating loads as a function of season (and building type, function, occupation etc), a new solar gains metric called Solar Heat Scarcity / Surplus (SHS), again introduced in [7], is used here to convey the urgency of either allowing more direct solar gain or avoiding it, based on revisited balance point calculations.

The calculation of SHS requires material information beyond the geometry and surface reflectivity inputs that are typically needed for the other metrics, in particular regarding heat transfer properties of the envelope components. In addition, ballpark numbers for heat gain, ventilation, occupancy, and operational information will be required, based on building type, as well as location (hence, climate type and weather statistics).

Healthy lighting

Based on the discovery of the novel photoreceptors in our eye's ganglion cell layer, responsible for synchronizing our internal circadian clock [16], light has become not only a therapeutic tool but also an essential element of healthy living. Currently, no model exists to predict the direct effects of light exposure on human health and well-being. Through the integration of knowledge from biology and mathematical modeling, we intend to address this challenge by building a block-structured model, introduced in [15], to simulate non-visual responses from discrete intensity and spectral inputs so as to integrate time- and spectral-dependencies of non-visual responses to light, and reconsider light intensity thresholds as a function of prior photic history.

Preliminary investigations as to how such a model could ultimately be used to inform design (especially for healthcare or high-vigilance environments e.g., see [17]) led to the need for a different simulation workflow for non-visual effects, where the absolute stimulus (here ocular light exposure, e.g. calculated as illuminance on a vertical plane) first has to be converted into a relative human response based on the model's outputs [14,15] then, in a second phase, gauged in terms of desirability in the considered context of specific building use and occupant profile (also influenced, e.g., by their sleep-wake cycle). Ultimately, the objective is to base the framework on performance goals that could indicate how appropriate (i.e. conducive to "health") the lighting pattern that the occupants are likely to be exposed to within that space will be over the day and year. This actually opens up considerations about occupational dynamics (how occupants move within and between spaces), a topic of investigation that has been introduced in a new way in [17].

Delightful lighting

Perception of daylight is the primary interpreter of the materiality and dynamism of any architectural space. However, the perceived qualitative aspects of daylight in a varying indoor space are underserved by the simplistic metrics currently available to designers. How then does a designer integrate changing light into design intentions? Existing studies on quantifying 'light quality' have tried to correlate perceived interest and satisfaction with luminance averages or some measure of their variability over static scenes [5]. The metrics considered in the present paper propose, instead, to integrate the dynamic aspects of perceived daylight as tangible guiding factors for design. Two metrics, introduced in [8], have been developed as a proof-of-concept: one expresses how "cumulative contrast" is distributed over space and time i.e. where (within s space) and when (over the day and/or year) we are likely to perceive the steepest gradients from dark to bright; the other one relates to the spatio-temporal variation of luminance as a "cumulative variability". Similarly, the latter evaluates where and when we will witness the most dramatic changes as time goes by in terms of bright versus dark areas.

To evaluate daylight contrast or variability as defined above, the current approach starts from user-defined viewpoints that are used to frame the spatial area where contrast is analysed over time. To identify an upper bound for contrast, only clear sky conditions are used [8] and pixel value gradient from one pixel to the next (for contrast analyses) or change from one moment to the next (for variability) is calculated and cumulated over space – resp. over time – to obtain an overall "amount" of contrast or variability at any given moment of the year – resp. any given point in space (within the defined viewing frame). Ultimately, the objective is to develop a goal-based approach from a taxonomy of reference spaces (Fig. 1 bottom, middle-right). The set of reference spaces should represent expressions of contrast and variability patterns architects can select as desirable luminous characters, regardless of their idiosyncratic interpretation of the quality of each space. The metric values associated with a selected reference space can then be extracted from the associated typological model and used as a target for a guided search, informing the design process without constraining it.

UNIFIED VISUALIZATION FRAMEWORK

As far as performance visualization is concerned, an original and intuitive concept was developed already in the original version of Lightsolve for goal-based performance representation [9], that emphasizes the temporal variation of performance by displaying it graphically alongside interactive renderings and with a highly original color scale.

Goal-based color scale

The triangular color scale introduced in [7] and reproduced in Figure 2 is ideally suited to visualize these five highly differing aspects within a consistent format, such that any outcome for any of these four metrics can be visualized as a single graph. Combined with the temporal map format [7,9] – with days of the year plotted along the x-axis and time of day along the y-axis such as in Fig. 1 middle and right columns) –, three outcomes are possible for a single point study: either the resulting data falls within the desired range, or it exceeds the maximum, or it does not reach the minimum. For a multiple point analysis allowing for buffer intervals [7], any color combination could emerge (e.g. purple as in Fig. 1 top right for a combination of too high (sunspots) and too low (overall too dim) illuminance levels within a given area of interest). By displaying goal compliance (Fig. 1 right) instead of absolute response (Fig. 1 middle), both the 'successfulness' of a design and the tradeoffs between dissimilar metrics become intuitive to understand, and harmful effects can easily be differentiated from beneficial ones.

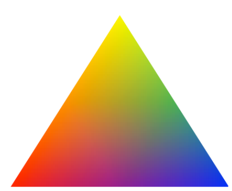


Figure 2: Triangular color scale: yellow is 100% achievement of goals, red is 100% too high, blue is 100% too low.

Visualization 'quartet'

The overall framework thus leads to a foursome or 'quartet' in terms of performance evaluation. There are two value scales: the so-called "absolute" scale based on a linear gradient from dark (low) to bright (high) (Fig. 1, middle column e.g.) vs. a goal-based scale based on the triangular scheme described above (Fig. 2, such as in Fig. 1, right column) and relating to how closely prescribed user goals are met. As a second duality, we consider 2 representations of performance distribution: over time such as illustrated in the temporal maps found in Fig. 1, versus over space such as illustrated in Figure 3: false-color renderings (based on either of the color scales) complement temporal information by showing how the considered quantities (middle column of Fig. 1 i.e. illuminance e.g.) is distributed over the perimeter of interest (workplane area e.g.) at any given moment, as further discussed in [14]. It is important to note that the "absolute" scale can sometimes represent a relative response such as in the "healthy lighting" model.

a  b 

Figure 3: Spatial representation of performance for a given moment of the year on an (a) absolute (here, illuminance [lux]) vs. (b) goal-based (here, AIE [%]) scale.

SIMULATION PLATFORM

Initially developed as a simulation platform allowing fast annual renderings displayed simultaneously with a time-mapped visualization of daylighting performance [7,9] and implemented as a SketchUp plugin, Lightsolve has recently been reprogrammed entirely to adopt a two-layered approach: for quantitative analyses, it now relies on the ubiquitous and extensively validated Radiance program for illuminance calculations (that the visual task, glare and healthy lighting modules all use as inputs) and for luminance distribution analyses (necessary for perceptual lighting analyses and also glare evaluation) [14]. For qualitative analyses (i.e. mainly the visualization of renderings), a hardware-driven, GPU-based renderer named OptiX has been implemented in the user interface to generate live renderings as the user explores the model and the lighting conditions. Thanks to an interactive, side-by-side display of temporal maps and spatial renderings [14], the user is offered a comprehensive overview of annual, seasonal and daily performance variations from 5 different perspectives simultaneously with an understanding of their associated spatial distribution.

Core structure

The structure of this new embodiment of the Lightsolve approach has been introduced in [14]: its main characteristics – as far as the present paper is concerned – are to be based on a modular structure (one module per performance perspective or metric, broadly speaking) so as to allow the implementation of future research outcomes regarding these metrics and offer a platform for demonstration and testing of new metrics.

Performance modules

Currently, the Lightsolve structure is organized such that the core engine calculates all the key lighting variables (especially illuminance and luminance distributions on/from selected surfaces/viewpoints) over the year, that are then used as inputs to the individual modules. Based on these input data, each module computes the performance criteria associated to its metric, as described above. Results are fed back to the core engine for data display. Since the outputs strongly differ from one module to the other, the core engine automatically adapts the visualization according to the considered performance perspective.

The typical outcome consists of a simultaneous visualization of temporal and spatial performance from either an "absolute" or a goal-based perspective (visualization 'quartet'): exploration over time (cursor over temporal map) gets translated into new renderings on the fly, and new view framings when exploring the rendered model (e.g. for a contrast or variability analysis such as in Fig. 4) will get translated into new contrast or variability temporal maps (cf. Fig. 3 bottom). As all five modules deliver their output data to the core engine, the switching from absolute to goal-based scale, from one moment to another and/or one performance perspective to the other can be highly interactive, providing the user with a dynamic framework to visualize and understand daylighting performance.

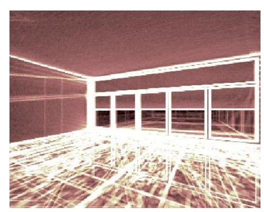
a  b 

Figure 4: View-based spatial representation: year-cumulative perceptual contrast (a) & variability (b) as 'absolute' values.

GUIDED SEARCH

Ultimately, Lightsolve is meant to offer pro-active guidance regarding design decisions to the user/designer, based on how closely the considered design matches the user-defined performance goals.

Foundations for an iterative expert system

The capability to act as a "virtual consultant" by offering a feedback loop had been implemented in the original version of Lightsolve [7,12]. The expert system developed for that purpose was highly innovative from many aspects, especially its iterative approach allowing for a high educational potential combined with the generation of a knowledge-base to rank design decisions based on their likelihood to result in an increased performance (with respect to user-defined goals).

More specifically, the user was asked to start with an original design (3D model), which would get iteratively modified and improved until performance goals were reached. Thanks to a step-by-step process, the user stays involved at every decision stage and can interactively visualize and decide about what design change option to consider. The method takes advantage of a knowledge-base populated using a set of previously completed simulations that quantify the effects of different design modifications (Fig. 5). The knowledge-base is used to guide a simple optimization algorithm and to improve its computational efficiency. It also provides feedback to the user, thus adding an educational potential.

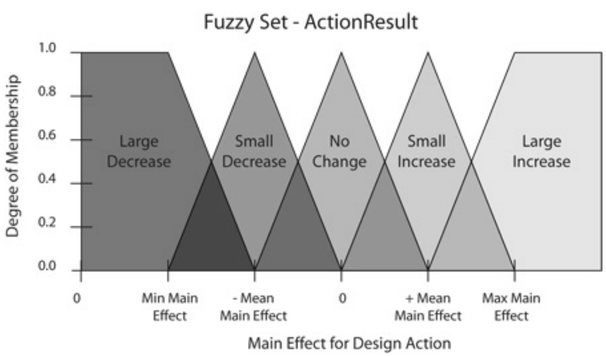


Figure 5: Fuzzy logic structure for design action values [12]

An original user survey was conducted to test the adequacy of this expert system to inform design effectively and intuitively, with very positive outcomes [13]. This initial expert system was, however, only applicable to illuminance and glare evaluation, and had important restrictions on orientation (façades facing cardinal directions) and geometry (square angles for all corners), which are amongst the limitations that the future expert system should be able to overcome.

Outlook to flexible user-driven optimization

A preliminary concept for this future expert system is to build a shareable knowledge-base of design effects, where performance impacts can be stored and where model similarities are evaluated to predict effects on performance. The idea is to integrate user inputs through an immersive interface that includes a case-based 'Machine Learning' structure to collect and later match user inputs, and a 'Clustering' engine for design changes classification into representative groups. This should lead to an iterative adoption of design changes, similarly to the original system but with a more efficient balancing of requests to the knowledge-base and to the calculation engine.

CONCLUSION

This paper presents a goal-based approach to address the multiplicity of perspectives from which daylighting performance can– and should – be evaluated in building design. Through five very different approaches ranging from task-driven illumination or comfort to human-driven health and perception – for which specific application examples are discussed in recent papers [13,14,17], it proposes a simulation & visualization framework (Lightsolve) in which to approach these from an integrated perspective ('visualization quartet') and in an interactive way. The Lightsolve platform, made available as a tool, opens new perspectives in climate-based, comprehensive daylighting design support at the schematic stages.

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