Linking Measurement, Simulation and Prediction

Photographic Acquisition of Local HDRI and Use of IBL for Simulation

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In the last decade Computational Building Performance Simulation (CBPS) has acquired the reputation of a solid analytical method. However, this reputation relies mostly on the admittedly advanced and robust theoretical and algorithmic basis of performance simulation techniques. On the practical side, building simulation has yet to live up to expectation. The main reason is that simulation use is not as widespread as it should. Applications are mostly academic, mainly validation studies. This has led us to the assumption that the applicability and usability of performance simulations require additional components that link them more closely to design processes and facilitate their integration in everyday design activities. In this paper we present the results of research into a working method for location-specific daylight simulation. Our method is based on the satisfication of a number of requirements common to many types of CBPS: validated simulation algorithms, flexible, fast calibration by means of real-world measurement, multiyear, location-specific environmental data, and support of both measured and mathematical environmental data models.

Keywords*: Simulation; daylight; integration.*

CBPS for daylight

A major drawback of measurement and calibration methods for CPBS is that they usually involve time-consuming measurement procedures. Adequate measurement implies measuring under a variety of conditions to achieve overall averaging. Such limitations also influence the usability of the results, reinforcing normative approaches to design analysis which may be based on scientific fact but are however not tempered by the designed variation of the built environment and the diversity of contextual constraints-factors which make simplistic evaluation systems inexact and unsupportive of thorough analyses and innovative synthesis (Maver 1987; Serra 1998). As a result, a complex phenomenon as daylight factors is underrated, ignored or otherwise underrated, as any comparison between the attention received by artificial light fixtures and the form and performance of windows and related fixtures can reveal (Bean 2004).

We suggest a radically different approach: by taking measurements and a full snapshot of all relevant conditions, a single, fully documented session can be conducted in just a few hours. In terms of technology, new lightweight and flexible measuring and capture devices have made this possible. The framework of the proposed method for daylight simulation divides the simulation process in several key components common to CBPS:

- a (calibrated) digital building model
- a simulation calculation engine
- a (set of) environmental data

These base components are necessary for the performance of the system but the implementation is less critical. In our case 3dsMax is used for the construction of the 3D digital model and Radiance (Ward and Shakespeare 1998) for the simulation. These two constitute the 'static' part of the process. The dynamic part of the process consists of the representation of environmental phenomena. With daylight there are several methods of environmental description available. All descriptions make use of hemispherical sky dome models, often depicted as a circular image.

Sky dome models

Mathematical models

In 1965 the Comission Internationale de l" Eclairage (CIE) agreed on the standardization of several mathematical sky domes for uniform calculations. The CIE Overcast Sky is the best known among these, and still widely used for calculation of Daylight Factors. Its obvious drawbacks are orientation and time independence. Its application should be limited to worst-case calculations.

In 2005 a new range of 15 types of sky conditions has been implemented as the CIE Standard Sky definition (CIE 2003). This recent standard, based on the Perez all-weather sky model, covers a wide range of sky phenomena.

Observed models

Following the sky model introduced by Tregenza, which divides the sky dome in 145 patches with even luminances, a network of ground-based daylight observation stations measures occurring daylight at high accuracy. Since these stations are elaborate, they are few and far apart. There is only one such IDMP station in The Netherlands, located in the very south (Eindhoven), and its measured data are not freely available.

A more recent development in daylight data is based on satellite observation. Based on hourly satellite photography of atmospheric conditions, daylight data is extrapolated. It is therefore a combination of observation and mathematical model. This method is not as precise as ground based measurement but data can be generated for any location. At distances longer than 34 km from an IDMP station the use of satellite data is preferable. Another major advantage of the satellite data at *www.Satel-Light.com* is its free availability. Combined with the prospect of increasing accuracy with advancing satellite technology, we believe this type of dataset is the best choice. Daylight data are available as:

- Zenith luminance
- GHI: Global Horizontal Illuminance
- FHI: Diffuse Horizontal Illuminance
- DHI: Direct Horizontal Illuminance
- Solar Brightness
- Sky dome patch model, divided in 13 patches

From these data it should also be possible to derive the closest matching mathematical sky-dome in the 2005 SSLD range. As a result, the data can be used for year-round Daylight Performance calculations, based on local daylight data. There are several possible calculation strategies, varying from mean DF-based illuminance estimations to hourly year-round illuminance datasets.

Photographic models

All sky dome models described above suffer from the same limitation: they all are a coarse abstraction of actual skies. This makes sky-dome photography an

Figure 1
Series of photographs with varying shutter speeds

interesting alternative. Even a medium-sized digital SLR can provide a resolution of several million pixels, as opposed to the 145 or 13 in each patch of the sky models. Since normal photography cannot capture the full actual light range, special techniques have been developed to accomplish this, described in detail in the following paragraphs.

Method for measurement, calibration and simulation

Measurement

Our method includes concurrent measurement of daylight levels (lux) and High Dynamic Range Imaging (HDRI) capture of the daylight source. Recent studies (Reinhard, Ward et al. 2006) have shown that HDRI assembly of sky luminances (with no visible sun) using exposure-varied series of low-dynamic range photographic images returns a reliable sky luminance source map. As a first step towards a reliable method, measurements and simulations are compared with daylight factors. Daylight levels are measured onsite, using a series of interconnected illuminance meters and a spot luminance meter.

High Dynamic Range sky luminance acquisition

The human eye is an adaptive system for capturing and experiencing luminances within a contrast ratio of 10000:1. In nature, however, contrast ratios of 100000000:1 are possible. To cope with this variance, the pupil contracts and expands, thus limiting the amount of light entering the eye. Standard photography captures a limited variance of luminances, thus representing only a fraction of occurring luminances. This limitation can be overcome by capturing a series of photographs with constant diaphragm and changing shutter speeds. The range width is determined by the occurring contrast ratio. Using a generally accepted 1-stop difference translates to a shutter speed range increase of 2 factors (i.e. 1/1000,1/250,1/64,1/16, ¼,). The outer limits of the series are determined by the following rule: the lightest photograph should not contain any black pixels, and the darkest photograph should not contain any white pixels.

Using software like HDRShop 2 a series of Low Dynamic Range (LDR) photographs can be combined into a High Dynamic Range Image (HDRI), containing the complete contrast ratio.

Figure 2
LDR images combined in HDR-file, containing complete sky contrast-ratio

The last step in the conversion of the photographic range is luminance calibration, in which the entire HDR image is multiplied by a factor derived from onsite spot-luminance measurement with a professional luminance meter.

Image Based Lighting (IBL)

After the photographic luminance is captured and calibrated, the resulting sky map can be used for lighting the 3D digital building model by using a method called Image Based Lighting (IBL) (Reinhard, Ward et al. 2006), which can simulate actual illuminances. By using IBL it is possible to digitally recreate the conditions under which the illuminance measurements were taken.

Calibration

The dataset consisting of a digital model of building and sky dome, including all measured values, can used for simulation and calculation of Daylight Factors. The calibration process starts with the comparison simulation results with the onsite measured Daylight Factors. It is in iterative process, in which re-measurement, simulation parameters and other aspects are continuously refined to achieve comparable DF data.

Simulation and analysis

A digital building model of which performance aspects have been calibrated with the method outlined above forms the basis for the analysis of future performance by means of computer simulation. It then becomes possible to perform simulations with all types of sky domes deemed appropriate, resulting in precise and detailed evaluation results which facilitate the identification of causal relations and alternatives. Depending on time and budget constraints we can use the following classification levels (in order of calculation and data magnitude):

- Daylight Factor calculations with CIE overcast sky
- Best / worst case situations with CIE SSLD skydomes
- Cumulative year calculations with cumulative Satel-Light data and Daylight Factor
- Daylight Autonomy and Useful Daylight Index calculations with hourly satellite data using Daylight Coefficients

At this moment we are able to perform the first three levels, with the fourth currently under development using the latest additions to Radiance (rtcontrib.exe).

Test case

The proposed method for integrating this system in CBPS has been tested in a temporarily vacant office space.

Digital building model

An accurate 3D model of the space was constructed, properly oriented and placed above the ground

Figure 3
Office building, selected office and digital model

plane. In order to be able to extract precise spatial and surface data, the model was constructed entirely as a single object (editable poly):

- Floor Area (SA): 22.86 m2
- Room Area (RA): 104.14 m2
- Daylight Area (DA): 14.40 m2
- Volume: 61.53 m3
- DA-FA Index: 63 %,
- DA-RA Index: 22 %
- RA-V Index: 1.69

Measured diffuse reflection coefficients materials:

- Walls: 0.90
- Floor: 0.37
- Ceiling: 0.83
- Door: 0.10
- Door-frame: 0.74
- Window sill: 0.08
- Window-frame: 0.54
- Heater: 0.69

  Measured transmission value:
- Window glass: 0.77

Model calibration

In this example the majority of measured and simulated daylight factors are within acceptable range (< 8% difference). Some points close to the windows suffer from larger errors. Our measurement of the glass transmissive data is the least exact of all measurements and needs refinement which should also take into account the state of the glass (scratches, dirt etc.).

In this case we found that it is possible to achieve comparable results with a mathematical sky model (conditions were close to a CIE cloudy sky) and with IBL based on the HDRI assembled map of the actually occurring sky conditions.

Environmental data and cumulative year calculation

Yearly calculations were performed on the local dataset from the online meteorological sources of the Satel-Light project. The mean half hourly illuminance (MHI) in lux is calculated with the following formula on the basis of the cumulative FHI (Diffuse Horizontal Illuminance) data, the Daylight Factors and the total daylight half-hours (TDH):

$$MHI = FHI * DF / TDH \quad (1)$$

From the dataset generated for the city of Haarlem (data of year 1996) the mean illuminances at the measuring points are:

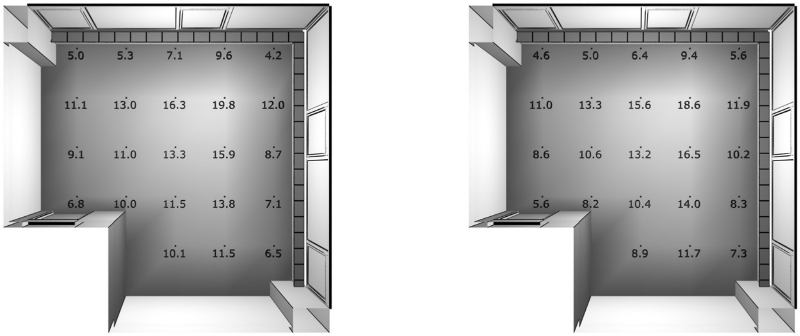

Figure 4
Measured (left) and HDRI–simulated (right) Daylight Factors

Conclusions

We realize that no simulation method will replace the different established national calculation standards. At the same time, building professionals should be aware of their limitations. None of these regulated calculation methods are designed to predict future building performance, nor is their accuracy tested against field measurements. Moreover, they provide little insight in the multiple requirements, from psychological and physiological to cost and energy use, or in the constraints for their satisfaction. The integrated solutions needed in daylighting problems refer to intricate networks of multi-scale objects and critical relationships between them are similarly complex, involving frequent reconsideration of common devices, even at the level of micro-structure (Köster 2004). While abstraction promotes integration, the solution of each component requires higher resolution and flexible evaluation methods. Such results can be achieved with the proposed method for daylight CPBS on the basis of:

- fast, onsite building measurement
- digital model calibration
- creation of applicable local sky dome dataset from satellite data
- simulation resulting in performance database of multi-year environment

Future work

Patched sky model

Our method will ultimately include an automatic abstraction of the Tregenza patched sky model (145 patches) (Tregenza 2004) into the coarser model (13 patches) used in the Satel-Light database. This will output desired user performance criteria, beginning with the Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic 2005) and working towards a general Daylight Performance Index (DPI).

Full spherical HDR environment

All sky domes suffer from the same restriction: they represent only half of reality. In order to capture the complete lighting environment on a point in space, we can construct a full spherical panorama in High Dynamic Range (a process involving some approximation).

Photographic measurement: luminance-illuminance

In order to extract illuminance data (lux) from a reliable HDRI capture of a scene containing accurate luminance (cd/m^2) measurements we need at least three additional elements:

- Measurement of reflection values of materials in scene.

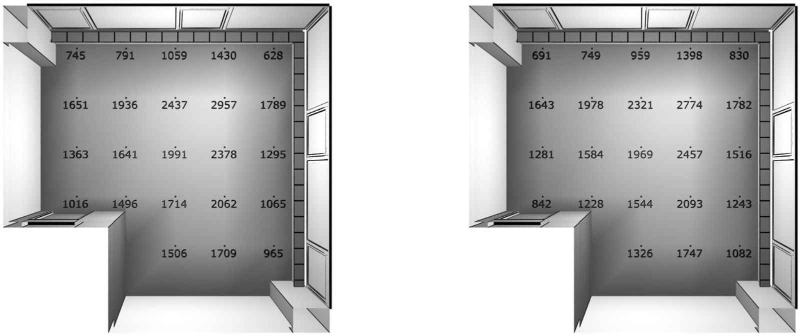

Figure 5
Mean yearly illuminances (lux) during daylight hours, from measured (left) and simulated (right) Daylight Factors

Figure 6
Full 360 degrees spherical map from four circular fisheye photographs

- Identification of material per pixel (or area of pixels), using a mask layer
- Data calibration using (il)luminance measuring equipment.

A depiction of illuminance can be generated with the equation:

$$E=\pi * L/r \quad (2)$$

Initial drawbacks involved in this extension include that materials are supposed to be perfectly diffuse and inaccuracies in the treatment of transparent objects.

Non-visible aspects of daylight

In addition to the analysis of the Daylight Performance of a building in regards to visible light, our simulation method should also be able to analyze other aspects of daylight that may not be visible. Recent research (Brainard, Hanifin et al. 2001) has shown that the stimulation spectra of hormones that determine our circadian rhythm are not the same as visible daylight. As a result, illuminance level calculations are not a good indicator of Biological Daylight Performance. Preliminary work on simulation of this type of performance using Radiance appears promising (Wandachowicz 2006).

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