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On the Use of Integrated Daylighting and Energy Simulations To Drive the Design of a Large Net-Zero Energy Office Building

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Rob Guglielmetti, Shanti Pless, and
Paul Torcellini

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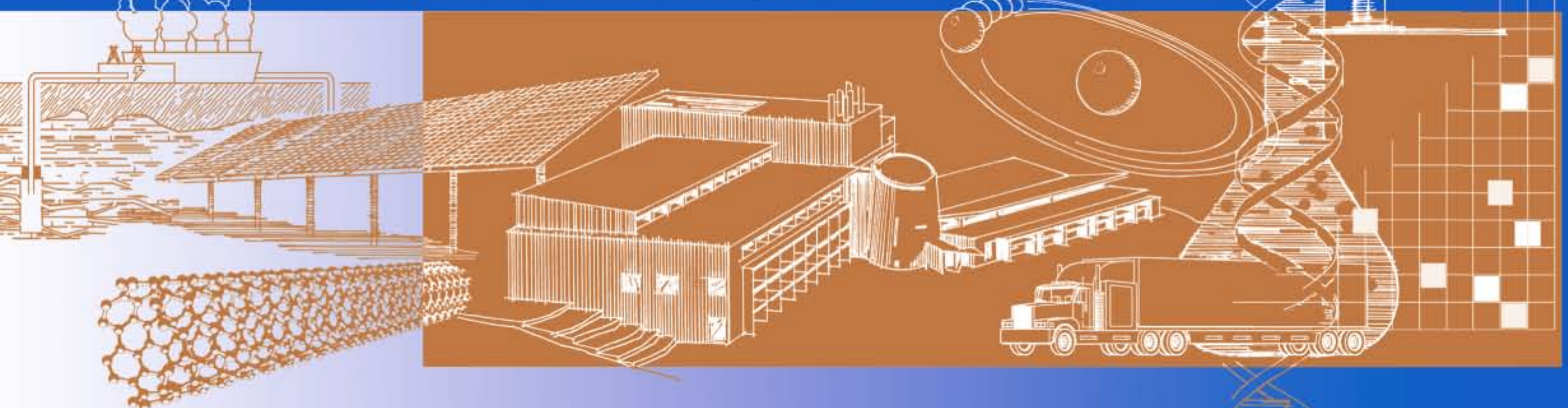

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ON THE USE OF INTEGRATED DAYLIGHTING AND ENERGY SIMULATIONS TO DRIVE THE DESIGN OF A LARGE NET-ZERO ENERGY OFFICE BUILDING

Rob Guglielmetti, Shanti Pless, and Paul A. Torcellini, Ph.D. P.E.
National Renewable Energy Laboratory, Golden, CO USA

ABSTRACT

This paper seeks to illustrate the challenges of integrating rigorous daylight and electric lighting simulation data with whole-building energy models, and defends the need for such integration in order to achieve aggressive energy savings in building designs. Through a case study example, we examine the ways daylighting – and daylighting simulation – drove the design of a large net-zero energy project.

In this paper, the author will give a detailed review of the daylighting and electric lighting design process for the National Renewable Energy Laboratory's Research Support Facility (RSF)[1], a 220,000 ft^2 net-zero energy project the author worked on as a daylighting consultant. A review of the issues involved in simulating and validating the daylighting performance of the RSF will be detailed, including daylighting simulation, electric lighting control response, and integration of Radiance simulation data into the building energy model. Daylighting was a key strategy in reaching the contractual energy use goals for the RSF project; the building's program, layout, orientation and interior/furniture design were all influenced by the daylighting design, and simulation was critical in ensuring these many design components worked together in an integrated fashion, and would perform as required to meet a very aggressive energy performance goal, as expressed in a target *energy use intensity* (EUI).

INTRODUCTION

The urgency of increasing energy efficiency in new building design and retrofits (and the need to demonstrate the effectiveness of lighting efficiency measures for code compliance and sustainable building ratings) has moved lighting simulation into a central role in sustainable lighting design. At the same time, energy modeling – long an established paradigm for evaluating the whole-building energy use of a given design – has also become an essential component of any code-compliant or sustainably rated building design process.

A fundamental aspect to any optimized sustainable building design is the integration of many disparate building components so that they efficiently function as a single entity, but many of a building's systems are sized, designed and specified through individualized system-specific tools or code tables. Lighting designs are evaluated for how well they meet a target illumination level, chillers are sized to meet a certain cooling load, etc. But the potential exists for the lighting and the cooling systems to work in concert with one another through intelligent control of the lighting in response to available daylight, reducing both cooling and lighting loads, for example. Windows can allow natural daylight into a space, but they also can hasten heat losses in winter due to the decreased insulating capability of even advanced window glazing compared to traditional wall constructions. An optimal architectural design responds to all the variables that affect the various building systems, and the building itself. This optimization is most efficiently discovered through simulation.

Software tools exist today that can perform rigorous analysis of extremely complex physical interactions within buildings: lighting simulation, HVAC simulation, and computational fluid dynamics (CFD) tools are available to simulate many of these building elements, and they have each been developed to look at their respective pieces in great detail. But historically, the results of these simulations could not easily be shared from one modeling paradigm to another. Worse, modeling these different systems independently of one another flies in the face of integrated design. While the argument for integration is strong, some significant barriers remain:

[1] http://www.nrel.gov/sustainable_nrel/rsf.html

- Energy analysis tools such as EnergyPlus[2] and DOE-2[3] incorporate a daylighting function, however the algorithms employed to derive interior space daylight levels are crude compared to the more robust algorithms used in more specialized lighting simulation and analysis tools such as Radiance[4] (hybrid Monte Carlo and deterministic ray tracing approach) and AGi32[5] (radiosity).
- Even relatively simple daylighting-oriented building designs that result in a concave building section cannot be simulated in EnergyPlus or DOE-2 due to limitations in the software.
- Typical building models created for a building energy simulation will have infinitely thin wall constructions and other geometric simplifications in the model that mischaracterize the true relationship of the building form (and, critically, the electric lighting and photosensors) to the available daylight.
- A number of new daylighting strategies rely on advanced methods for delivering and redirecting daylight into spaces to improve the performance of a daylighting design. These so-called complex fenestration systems (CFS) offer the promise of delivering glare-free daylight to spaces for greater periods of the year, and to spaces that otherwise would never receive daylight, such as core spaces far from the building perimeter. The challenge of simulating the performance of CFS remains significant, however, particularly in an annual (hourly) simulation modality, even when advanced lighting simulation tools such as Radiance are used.

Perhaps as a result of these differences in modeling approaches and capabilities, energy- and daylight-modeling simulation tools have evolved on parallel but separate paths. There exist tools on both sides of the challenge to arrive at simulation-based performance evaluations of a given design, and the industry has used these tools very much in this parallel manner, largely relying on experience and intuition to integrate the results from these two separate analytical exercises. Certainly each simulation can inform the other, and if the daylighting design is simple enough – e.g. relies on windows and not CFS and occupant behavior modeling is not critical – then the methods within DOE-2 or EnergyPlus are adequate for determining the performance of a given design, and the more rigorous methods employed by Radiance or AGi32 can be used for demonstrating code and design guideline compliance (e.g. illuminance levels) and for visualizations and other analysis such as glare or photocontrol studies. It could be said that this is de rigueur in current sustainable building design. Indeed, the author has operated in this fashion for years, successfully. It took a unique project, with a very strict energy-use intensity goal, to take a different tack.

CURRENT LIGHTING SIMULATION TOOLS

A number of dedicated lighting simulation software tools exist such as Radiance [Ward 1994], AGi32, Autodesk 3ds Max Design, Dialux, Relux, et al. that give researchers and designers the ability to evaluate complex lighting designs, within complex architectural spaces. These programs are capable of simulating the performance of electric lighting fixtures (assuming a photometric information file based on a physical luminaire test report is provided), as well as the contributions from the sun and sky hemisphere, as well as ground reflections and the effects of local obstructions. These programs generally employ a radiosity or light-backwards raytracing algorithm to derive the photometric quantities of illuminance or luminance needed for the lighting design evaluation. Some of these programs have been independently validated [Mardaljevic 2000, Reinhart C F, Breton P-F 2009] and a trained user of these tools can expect accurate, physically-based simulation results. Depending on the program, a number of phenomena critical to the valid evaluation of the lighting performance can be simulated: transmittance and reflection (both diffuse and specular), absorption, chromatic effects, and of course the luminous flux distribution of both electric luminaires and daylight (sun and skylight as defined by a variety of sky models [ISO/CIE 2003, Perez 1993, Preetham 1999]). These tools all present the simulationist with more advanced lighting simulation capability over the daylighting tools found within popular building energy simulation tools such as EnergyPlus or DOE-2.

Arguably the most flexible of all the lighting simulation tools is Radiance. This open source software is built upon the unix toolbox model. Unconstrained by a graphical user interface (though

[2] http://apps1.eere.energy.gov/buildings/energyplus/

[3] http://doe2.com/DOE2/index.html

[4] http://radsite.lbl.gov/radiance/HOME.html

[5] http://www.agi32.com

some commercial and open source GUIs do exist), Radiance is a collection of programs that can be strung together via complex command line pipelines, shell scripts, or other glue programs such as Ruby, Python or Perl, to perform a variety of lighting simulation tasks. In addition to providing what is possibly the most rigorous lighting simulation capability currently available, Radiance has been extensively validated and is actively supported by its developer and the general Radiance user community[6]. Perhaps owing to all of these features, Radiance also serves as the background "engine" performing the actual lighting calculations for a number of other lighting software tools such as SPOT, Daysim, and indirectly, Ecotect.

At their most basic modality, these tools operate on a single point-in-time basis; that is, they are all designed to arrive at a solution for a given set of conditions, such as site latitude and longitude, building orientation, time of day, day of year, and sky condition. While the electric lighting can generally be simulated in a single calculation, a full understanding of the daylight contribution to a building's overall lighting design cannot be gleaned from a single simulation of a single point in time or sky condition. For an annual simulation, most of these programs employ some type of automated "daylight study" function, that automatically increments the time of day by some value to get a set of results that give an overview of the daylight and electric lighting performance over the course of the year. In these cases, the annual dataset is the end result of running a lengthy calculation, multiple times. Depending on the complexity of the simulation (number of light sources, building geometry detail), each point in time calculation can take several minutes to several hours; as a result, annual simulations rarely have the hourly resolution that is de rigueur in a typical energy modeling simulation in DOE-2 or EnergyPlus.

Common practice to keep these simulations tractable is to reduce the resolution of an annual simulation from monthly to seasonal. In this case, several "key days" are simulated, such as the equinox and the solstices, on an hourly – or more typically, semi-hourly – basis. This gives a range of illuminance levels resulting from extreme sun angles (low and high), and a midrange number as a result of the equinox simulation. From there, interpolation or intuition is used to understand the remainder of the annual distribution. In other words, experience and intuition tend to serve as data proxies, in order to expand a coarse dataset into a finer one due to simulation time constraints. The simulationist is left with a dataset that contains data from multiple estimations, of variable rigor.

Another approach involves the use of daylight coefficients [Tregenza and Waters 1983; Mardaljevic 2000, 2000; Reinhart 2001, Reinhart and Walkenhorst 2001]. With this approach, the contribution of light at a point is solved for many discrete sky segments and sun positions and then these coefficients are applied to a weather file through simple matrix multiplication. The initial calculation of the daylight coefficients is lengthy, but the hourly timestep illuminance calculations are very fast, allowing for annual illuminance estimations at the resolution typical for energy simulations (hourly) in a more reasonable timeframe. This approach has been used in research circles for several years, and is also the basis for the simulations in Daysim. Daysim is the only "packaged" software that offers the lighting simulationist the ability to analyze a daylighting design with daylight coefficients. To date, all daylight coefficient-based simulation approaches employ Radiance at the core.

One limitation that all of these tools exhibit is the inability to accurately solve for high flux light transport through so-called daylight redirection devices that employ specular optical redirecting surfaces. Light pipes, tubular daylight devices (TDDs), daylight redirecting devices and other CFS are generally best simulated with a forward raytracer (TracePro, Photopia. et al.), and the resulting performance mapped to a luminous descriptor. The standard format for this in lighting simulation software is the IESNA LM-63 Standard Format for the Transfer of Photometric Data – the same format used for tested luminaires. This method in essence concentrates the luminous flux from the sun and sky and all the optical redirections caused by the CFS onto a point (which is then usually spread over an area) just inside the CFS, allowing it to be treated as a direct light source in the lighting simulation. While this method works well, it requires a forward raytrace simulation for every timestep needed in the annual simulation or daylight study because the sun – the most significant contributor to the solution – is changing position at every timestep. Discrete simulations are also required for every site location (latitude & longitude), façade orientation, and for any significant obstruction conditions. As a result, the use of daylight redirecting technologies – potentially significant contributors to the viability of any daylighting design – is at this time very difficult to integrate into an annual simulation. The current research work in this area is discussed further in a following section (see "Future Trends").

[6] http://www.radiance-online.org

CASE STUDY:

The National Renewable Energy Laboratory's Research Support Facility (RSF) is the newest building on NREL's campus, slated for completion in June of 2010, and was designed from the outset to be a net-zero energy building (NZEB). Indeed, the entire procurement process was designed to result in a building that produces as much energy as it consumes, on an annual basis.

With any NZEB, energy efficiency is a top priority. As such, the original RFP for the RSF included an annual energy use intensity (EUI) goal of 25 kBtu/ft2. This requirement was based on standard government building occupant density of 650 employees, 220,000 ft^2, and a data center to service the RSF occupants. Design efficiencies in space planning increased the number of potential occupants to 822 in the same floor area, and increased the number of people being served by the data center to approximately 1,200. With these increases in employee density, space efficiency, and data center loading, the RFP allowed for a per-person EUI goal normalization. The required EUI has thus been normalized to 32 kBtu/ft^2 with the prorated data center for 822 occupants, or 35 kBtu/ft^2 with the full data center loading. On-site renewable energy sources (PV and a wood chip furnace) will provide onsite power and supplemental heating, toward the ultimate goal of achieving a net-zero energy building (and an energy consumption rate at least 50% below ASHRAE Standard 90.1-2004). The RSF will also attain a NZEB:B-classification, meaning that all renewable energy sources needed to offset the building's energy use are located within the building site [Crawley, et al. 2009]. In addition to the EUI target, LEED Platinum certification by the United States Green Building Council (USGBC) was a project requirement, in particular the LEED Indoor Environmental Quality Part 8.1 (Daylight) credit.

Verification of the building's energy performance was needed, at an early stage in the design, in order for the design-build team to proceed in confidence.

Given the aggressive EUI goal, and the fact that the LEED daylight credit was an RFP mandate, daylighting was one energy efficiency strategy considered an essential component of the overall building design. Work to integrate and best take advantage of daylighting for this project took place during the design competition phase. It was in this conceptual phase that daylighting simulation with Radiance was already being used. After some basic best practices were employed (e.g. creating a long building plan form with the long axis aligned east-west for optimal daylight access and controllability, open space planning, and the creation of a high-mounted "daylight glazing" and a lower, shielded, "vision glazing" fenestration style), the team sought to extend the south daylight-illuminated zone as far north as possible, in plan. A daylight redirection device called the LightLouver Daylight System was selected to occupy the daylight glazing to provide glare control as well as to redirect the incoming solar radiation onto the ceiling and deeper into the space. In order to explore the capability of the LightLouver to maximize the floor depth, a 3D building model of the typical office wing was created in AutoCAD and simulated in Radiance. With an eye toward the LEED iEQ8.1 goal, point-in-time simulations were conducted using Radiance to determine how broadly an illuminance level of 25 footcandles could be achieved at 30" above the finished floor under clear skies, at noon, on the equinox – one of the compliance demonstration methods available under LEED iEQ 8.1[7]. A photometric file in the IESNA LM-63 format, representing the luminous output of a LightLouver unit located near the project site, under clear skies, at noon, was supplied by the manufacturer. This allowed for an efficient, accurate evaluation of the potentially significant contribution of the daylight-redirecting units for that timestep.

Extensive modeling by the design competition team revealed 60'-0" to be the maximum floor plan depth (north-south) that could be illuminated to the criteria set forth by the LEED compliance standards (i.e. 75% of normally occupied space achieving 25 footcandles under a clear sky at noon on the equinox). The Radiance model was modified to study different fenestration options such as window head heights, window to wall area ratios, glazing transmittance; different interior finishes were studied (mainly for the effect different surface reflectances had on illumination); furniture options such as partition height and interior wall and ceiling configurations were also investigated. With the preliminary selections on fenestration, glazing transmittance, and ceiling height, extending the floor depth north-south beyond 60'-0" created too large of a dark area approximately 2/3 north of the south perimeter that did not receive adequate daylight to allow for cost-effective dimming or switching of the electric lights (i.e., < 25 footcandles), and this essentially fixed the north-south dimension of the main office space wings of the building design at 60'-0". This was one of the first areas of the building design that was directly affected

[7] This project is being certified under LEED v2.2; the new LEED 3.0 simulation-based compliance path for the daylight credit is slightly different.

and shaped through daylight simulation. Interestingly, the integrated design of all these elements was being studied and simulated at a high degree of detail as far back as the design competition phase, even before the project was awarded to a design-build team.

Once the project was awarded and advanced to the design development phase, the author became involved in the project. As the project progressed through this phase, changes crept into the design, and previous estimates regarding room finishes and furniture dimensions had become more firmly established. As a result an entirely new building model was created, reflecting the known design to date for the main office wing area. The previous evaluation calculation (equinox design day) was re-done, and at that time it was discovered that the LEED criteria was no longer being met for the required 75% of the floor area. Initial results from Radiance simulation showed 69% of the floor area receiving at least 25 footcandles. Because the main office wings represent the majority of occupied space on the project, this model needed to show at a minimum that a 25 fc illuminance level was being maintained for LEED compliance.

While not pleasant news to break to the design team, the simulations allowed this news to be broken early, at a time when changes were cheaper and easier to integrate.

Once again, Radiance was used to evaluate various changes to the design to evaluate their impact on the daylighting, and a series of changes were recommended. Changes included increasing the size and lowering the mounting height of the LightLouver units, and a fortuitous discovery that the acoustical ceiling panels being installed to the metal decking had a surface reflectance higher than the white paint that was used in the initial simulation.

These changes were incorporated into the Radiance model, and by this time the model had been fairly well refined to represent the actual building design. The updated Radiance simulations showed that the main office wings were well-saturated with daylight, particularly the top floor, which has a sloped ceiling to optimize the orientation and hence the efficiency of the photovoltaic panels on the roof. Initially there was concern that the sloped roof would create a problem for the daylight redirection devices, by moving the reflecting surface up and away from the redirected sunlight. In fact, the Radiance simulations indicated that the roof slope actually improved the daylight uniformity on the top floor workplane, because the illuminance peak on the ceiling was moved farther back (farther north, in plan) on the ceiling, thus providing more redirected light to the northern half of the floor plate. At the same time, the roof slope decreased the incident angle of the sunlight on the ceiling, reducing the reflected daylight quantity at the perimeter where there was already an abundance of daylight. The overall effect was to increase the uniformity of the daylight illumination on the work plane on the top floor, essentially redistributing the wealth of daylight at the south perimeter more equitably to the entire floor plate. Figure 1 graphs the task illuminance profiles for the top and typical office wing floors on the equinox from north to south (left to right), while Figure 2 and Figure 3 show renderings of the top and typical floors, respectively. As Figure 1 illustrates, the top floor's sloped ceiling reduces the illuminance peak at the south perimeter, and the illuminance levels further north are increased, providing 50 to 60 footcandles across the entire top floor task plane.

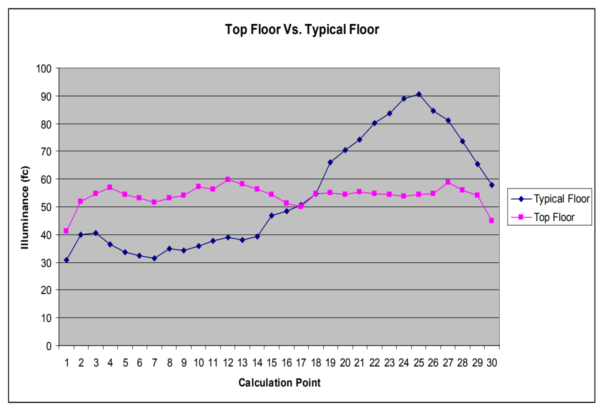

Figure 1: Task Illuminance Comparison, Top Versus Main Floors

Figure 2: Radiance Rendering of Top Floor

Figure 3: Radiance Rendering of Typical Floor

The next area of focus was the optimization of the electric lighting control zones such that they are best able to respond to available daylight while not being overly subdivided, which would have added cost and complexity to the design. For this, the Radmap[8] utility was used to generate annual illuminance plots of each floor of the RSF. Radmap is a Python script that parses a typical meterological year (TMY) weather file and generates a "cumulative sky" description for use in Radiance[9]. The cumulative sky is simply an amalgam of all the daytime skies for a given climate, as defined by the direct normal and diffuse horizontal irradiance in the TMY file, translated to Radiance "gensky" commands, and thus to CIE standard sky types. The cumulative sky therefore contains several thousand solar light source descriptions, as well as a summed luminous distribution for all of the hourly sky and ground hemispheres. This file can then be combined with a Radiance building model and from this a single Radiance simulation will yield a cumulative radiative quantity, and, more importantly for this exercise, interior distribution.

As the main goal of this portion of analysis was to optimally group the electric light fixtures into zones that would be controlled during normal business hours, the TMY weather file was modified to include only the hours between 7:00 a.m. and 6:00 p.m. The resulting cumulative sky produced by radmap therefore described the daylight behavior we were most interested in.

The task of simulating the performance of the LightLouver units under such a sky model was the next consideration. As mentioned in the preceding section, CFS devices generally require a forward raytrace evaluation in order to accurately capture the contribution of the sun and sky through the CFS. The design team was unable to obtain a photometric file for a LightLouver unit under the hypothetical cumulative sky produced by radmap, so the model was updated to include the actual LightLouver geometry itself, and the light backwards ray tracing algorithm of Radiance was relied upon for locating all the direct sun and sky contributions. The LightLouver manufacturer was able to provide the design team with an actual 2D shop drawing of the LightLouver units in AutoCAD format, and the section was extruded into 3D geometry and placed in the Radiance model. Considering the odds of a ray making the journey from the camera plane, into the space, through the LightLouver slats and out into the sky dome to intersect a sun disc subtending one half of a degree, even with fairly aggressive simulation parameters, the expectation was that some solar flux would not be accounted for. This was an admittedly conservative approach to estimating the total illumination on the work plane, but one the team was comfortable with, and one that was tractable given the design schedule.

A parallel plan projection view of each floor was rendered with the Radiance rpict program; given the large number of solar light sources – and the aggressive settings required to ensure the light sources were accounted for as best as possible – the simulations took several hours to complete for each floor. But when visualized in falsecolor, the renderings afforded a clear view of the resulting daylight distribution in the space and allowed the design team to logically circuit the electric light fixtures so that they could best respond to the daylight while not adding too many zones. The distribution across the core was fairly uniform, leading to the decision to zone the two core rows of light fixtures together, rather than separately. The remaining rows were circuited into their own zones – a north perimeter zone and a south perimeter zone. It was also determined that the daylight saturation at the south perimeter was so high that the added resolution of continuous dimming ballasts was not needed, and lower-cost switching ballasts were used for this zone instead.

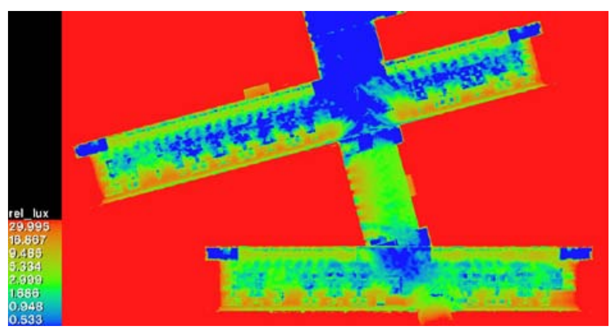

Figure 4: Cumulative Annual Sky Falsecolor Rendering

At this point in the design process, Radiance simulations helped to refine the building plan, fenestration, surface finishes, glazing transmittances, furniture dimensions and orientations, and lighting dimming zones. Radiance would now be called upon to provide a link to the energy model so the engineers doing the energy modeling – and ultimately responsible for determining the building's final EUI – had an estimate of the hourly lighting system response

[8] http://www.dream.unipa.it/dream/pub/dot/anselmo/radiance/05.php

[9] There are multiple sky generation options to radmap, but the cumulative sky option was the most useful for this exercise.

to the available daylight, one that incorporated the CFS. However conservatively this estimate was (given the process), this was better than not taking it into account at all (which was the only option available to the engineers modeling building energy use in DOE-2, since DOE-2's daylight simulation models cannot incorporate CFS).

For this phase of analysis, the Sensor Placement and Optimization Tool, or SPOT[10], was used. A feature of SPOT is the ability to generate a lighting schedule that can be merged with the DOE-2 energy simulation as a so-called "include file". This allows one to utilize Radiance for a rigorous evaluation of the direct and global illumination, using a validated light-backwards raytracing algorithm, and then to evaluate – using rsensor, a new tool added to the Radiance toolbox – a given photosensor's spatial response to the available daylight and resultant dimming or switching response over a number of control algorithms. This produces an 8,760-hour schedule of the lighting power fraction for a given design, in a given climate. While still divorced from the building energy use simulation, this represents a significant improvement in the depth and rigor of the lighting simulation portion of an annual energy simulation, and the ability to export the electric lighting system's control response to DOE-2 (and EnergyPlus with minor reformatting) poses a significant improvement in the integrated simulation and estimation of building energy savings through daylighting measures.

It was this capability of SPOT to predict the dimming response that led the author to use SPOT for the annual simulations of the RSF project. By default, SPOT is limited to the creation of simple box-type spaces by the user interface, but the author worked with a member of the SPOT development team who was able to use SPOT to analyze the daylighting controls on our detailed RSF model directly. Photometric files for the electric lights were obtained from the lighting designer; the exact luminaire layouts were added to the Radiance model, and were circuited and controlled as per the recommendations that came out of the preceding daylight simulations with the cumulative annual sky.

SPOT uses Radiance "behind the scenes" to generate a set of seasonal daylight illuminance data, based on CIE standard sky types (clear and overcast) to establish an idealized baseline of daylight saturation potential. From there the user can interactively investigate the effect of changing setpoints, bandwidth, and control algorithms to arrive at an optimal control scheme for the lighting design.

A TMY weather file is then provided to the program, and the file is parsed for sky conditions. The global horizontal daylight illuminance values computed in the first pass using CIE skies are then weighted by the values found in the TMY weather file, thus deriving a more climate-specific estimate of available daylight. This is accomplished in the following way: illuminance data in the TMY file, specifically, diffuse horizontal divided by global horizontal illuminance, is used to determine a sky cover ratio. The sky cover ratio along with solar declination are used to interpolate the daylight factors that were previously determined using a CIE sky and calculated global horizontal illuminance. Then, global horizontal illuminance data from the TMY file is used to scale the interpolated daylight factors into workplane illuminance. The resulting control response is computed using rsensor. As rsensor can accept spatial photosensor sensitivity data, which is available for a number of commercial photosensor models[11], this provides yet another level of depth to the daylighting simulation.

At this point SPOT can generate an 8,760-hour schedule of the lighting power fraction for up to three lighting control zones in a space. This schedule can then be exported and saved in the standard DOE-2 include file format.

This simulation was carried out for each floor of the RSF and the include files were then passed to the mechanical engineers on the project and used in the building energy simulations in lieu of the internal split flux daylighting calculation that DOE-2 utilizes. Several coordination exercises were undertaken between the author and the mechanical engineers to ensure that building envelope, lighting layouts, lighting power densities, control zones and occupancy schedules were in alignment between the two models.

Currently, the RSF project is under construction and is scheduled for completion in the summer of 2010. The current energy analysis – conducted with DOE-2 and incorporating the Radiance/SPOT-based daylighting simulation – predicts the RSF will use 3% less energy than the normalized 35 kBtu/ft^2/yr EUI goal, and projects energy use from lighting at 11%, approximately 7% below the national average. Should the building perform as expected, the RSF will be one

10 http://www.archenergy.com/SPOT

11 http://www.lrc.rpi.edu/nlpip/publicationDetails.asp?id=916&type=1

of the largest net-zero energy buildings in the world. The building will be extensively monitored post-occupancy and we expect the lighting energy use to be even lower than the simulation predictions, since the LightLouver contributions were very conservatively estimated in simulation. The realized building performance will certainly be the topic of a future paper(s).

For a project with such aggressive energy use goals, all disciplines needed to contribute to the overall reduction in energy use, and simulation of a fine resolution was required in order for every measure to be accounted for. Traditional pathways to energy efficiency in the lighting design were pushed to include new technologies that resisted simulation efforts, and in the end the Radiance toolset was applied in a variety of ways to satisfy the project's simulation and verification needs. The parallel path of Radiance- and DOE-2-based simulation required careful coordination between disciplines, as well as two building models. While not a perfect solution, this method did allow for a much more detailed analysis of the daylighting and electric lighting response to the available daylight. This also placed the responsibility of properly defining the electric lighting and control systems in the hands of the lighting and daylighting engineers, and allowed the mechanical engineers to focus on the specification of the remainder of the building systems. We believe this approach ensures the lighting simulations, as part of a whole building energy simulation, are as representative as possible and improves overall simulation quality.

VALIDATION

As this paper was being finalized, construction of the RSF was nearing completion, and the author had an opportunity to match a low dynamic range photograph of the main office space with a Radiance rendering. The initial results are shown in Figure 5 and Figure 6. We believe these images clearly illustrate the power of simulation in a qualitative context. Upon occupancy, high dynamic range (HDR) images will be taken of the RSF; these will likely match even better, visually, as Radiance renderings are high dynamic range images in their own right and therefore we can tonemap the two HDR images with the same global operator.

A potential future research project involves comparing simulation and HDR images of the RSF with user feedback solicited over the course of the coming year, to attempt to develop methods for using images to predict and identify "good" (and "bad") lighting. The RSF will also be closely monitored for energy use and illuminance levels for a period of one year following owner turnover in June of 2010, and during that time we expect to gain some additional insight about simulation's quantitative predictive capability.

Figure 5: RSF Construction Photo

Figure 6: RSF Radiance Rendering

FUTURE TRENDS:

As mentioned, Radiance employs a light-backwards ray tracing algorithm; one area where this algorithm comes to difficulty is when very small, very high flux light sources are obscured and/or redirected by geometry. The traditional methodology for resolving this is to use Radiance's mkillum utility to essentially move the initial light backwards ray origin from the view or calculation point to a point as close to the CFS as possible, conduct a standard Radiance raytracing exercise from there, and gather that data and use that as the basis for a direct light source in the subsequent Radiance simulation. The best method is to use a forward raytracer (TracePro et al.), or to physically test a sample of the CFS, and map the resulting performance to a luminous descriptor. While these methods work well, they require lengthy simulations or testing for every timestep, orientation and sky condition that would appear in the annual simulation or daylight study – an intractable problem.

A new proposal for solving a CFS distribution on an annual basis is the so-called "three-phase method" [Ward 2007]. New tools (rtcontrib, genklemsamp, genskyvec, dctimestep) have been added to Radiance in version 4.x that will potentially enable the lighting simulationist to create bidirectional scattering distribution functions (BSDFs) for CFS materials, and to apply them in a daylight coefficient-based annual daylight simulation.

This work is ongoing and is of great interest to those in the daylight simulation community, as it represents a pathway toward producing truly dynamic, climate-based daylight simulations that potentially can include contributions of CFS, occupant behavior models, granular control of electric lighting and photosensor control.

Bourgeois et al. (2008) also propose a refinement of the daylight coefficient / Daysim approach as well as a data format that could be used for sharing of daylight simulation data with building energy models. This proposed *DDS standard daylight coefficient model* increases the resolution of the daylight coefficient sky discretization scheme, is potentially rotationally invariant, includes dynamic shading elements in an annual daylight simulation, and defines a standard XML file format to structure the daylight coefficient data and calculated daylight performance metrics on a sensor point basis.

Emerging Radiance tools released in Radiance version 4.x that serve and work with data computed by rtcontrib, along with the DDS standard daylight coefficient model, form the foundation of a potentially large leap in the capability of the daylighting simulationist. The mathematical rigor of the calculations, the potential for hourly resolution of time series data (computable in reasonable timeframes), the ability to evaluate dynamic responses to daylight availability (via lighting controls, electrochromic glazing, occupant control of blinds & shades, etc.), and the standard format proposed for organizing the wealth of data these simulations can generate – and for sharing it all with energy models, design teams, utilities, building information models (BIMs) and building rating systems – represents a significant change in the way daylight simulation will factor into the design and construction process. Codes, standards and building rating systems will continue to evolve, in some cases adopting these tools and methods as their agents of formulation and refinement, and for determining compliance and ratings. Daylight simulation has reached a new plateau in sustainable, energy-efficient building design.

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14. ABSTRACT *(Maximum 200 Words)*

This paper illustrates the challenges of integrating rigorous daylight and electric lighting simulation data with whole-building energy models, and defends the need for such integration to achieve aggressive energy savings. Through a case study example, we examine the ways daylighting – and daylighting simulation – drove the design of a large net-zero energy project. We give a detailed review of the daylighting and electric lighting design process for the National Renewable Energy Laboratory's Research Support Facility (RSF), a 220,000 ft2 net-zero energy project the author worked on as a daylighting consultant. A review of the issues involved in simulating and validating the daylighting performance of the RSF will be detailed, including daylighting simulation, electric lighting control response, and integration of Radiance simulation data into the building energy model. Daylighting was a key strategy in reaching the contractual energy use goals for the RSF project; the building's program, layout, orientation and interior/furniture design were all influenced by the daylighting design, and simulation was critical in ensuring these many design components worked together in an integrated fashion, and would perform as required to meet a very aggressive energy performance goal, as expressed in a target energy use intensity.

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