4.401/4.464 Environmental Technologies in Buildings

Christoph Reinhart
L09 Daylight Simulations
Lighting Module

- Light and Human Vision
- Daylighting Design Principles
- Daylight Simulations & Metrics
- Visual Comfort
- Electric Lighting
Daylight Simulations
Daylight Simulation

A computer-based calculation of the amount of daylight available inside or outside of a building under one or several sky conditions. Simulation outputs may be discrete numbers (illuminances and luminances) under selected sensor points within a scene or visualizations of a scene.
Architectural Rendering vs. Daylight Simulation

Fig 10.3 Photograph of the top floor of the Harvard Art Museum Extension by Renzo Piano, 2014

Fig 10.4 Design sketch of the Harvard Art Museum Extension (Artwork: Ammar Ahmed)

Fig 10.5 Architectural rendering of the Harvard Art Museum Extension (Model: Richard Aeck; Simulation: Ammar Ahmed)

Fig 10.6 Physically based daylight simulation of the Harvard Art Museum Extension (Simulation: Ammar Ahmed)

Sketch, rendering, and simulation courtesy of Ammar Ahmed. Used by permission.
Architectural vs. Daylight Models

- Generally both model types are very similar.

- To use an architectural model for daylighting analysis, different material types have to be organized by layers.

- You have to take care that material properties are assigned correctly and that all ‘relevant’ objects in your scene, such as trees, neighboring buildings, and wall thicknesses are included. Also pay attention to light leaks.
Why Daylighting Simulations?

- To demonstrate code compliance and to reduce risk. (Think of LEED green building certification.)

- To compare different design variants.
How often does that actually happen?

Question: If you are using thermal/energy simulations during design, how often have the results changed or influenced any design decisions?

Increase impact, improve communication

Is there interest in change?
Daylighting – Attitude towards Simulations

What is your general attitude towards daylight simulations?

Answered: 93   Skipped: 58

**Designers**

- 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

- I have not seen a case in which this type of analysis has helped us to design a better building.
- I appreciate insight gained from daylight simulations provided during design reviews by our sustainability consultants.
- I highly value insight gained from daylight simulations and believe that some of the simulations should be conducted by designers, if adequate training is provided.
- I highly value insight gained from daylight simulations and already use them during design.

**Experts**

- 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

- Positive attitude throughout. (Unclear why some experts fall into category 1.)
- Broad consensus regarding interest into training designers in the use of simulations.
Elements needed for a DL Simulation

- Building Model
- Area of Interest (analysis grid)
- Sky Model
- Simulation Algorithm
  - Global Illumination Algorithm
  - Luminous distribution
    - 0-500 cd/㎡
  - Illuminance distribution
    - 0-1000 Lux
Daylight Factor Calculation Methods

- 1920s Waldram Diagrams
- 1940s Daylight Factor Protractors + Original Split Flux Method
- 1980s Radiosity
- 1980s Raytracing
- 1990s Split Flux Method in Ecotect
Daylight Factor Definition

Target Levels:
- Standard daylit spaces (offices): 2%
- Brightly daylit spaces (classrooms): 3%
- Circulation Areas: 1%
Exercise – Determine the Daylight Factor at Point P
Daylight Factor Components

- **SC**: Percentage of weighted sky that a sensor can see compared to an unshaded sensor.

- **ERC**: Percentage of skylight reflected from neighboring buildings compared to an unshaded sensor.

- **IRC**: Light reflected within the building before being incident on a sensor.

\[ DF = SC + ERC + IRC \]
\[ SC_{\text{Waldarm}} = 86 \times 0.1\% \times 0.65 \times (1 - 0.16) = 4.7\% \]
Waldram Diagram

\[ \text{ERC}_{\text{Waldram}} = 16 \times 0.1\% \times 0.65 \times (1 - 0.16) \times 0.2 = 0.2\% \]

16 dark gray squares

Reflected Light

Frame Factor

\[ t_{\text{vis}} \]
Internally Reflected Component

\[
IRC_{\text{average}} = \frac{\tau \times W}{A \times (1-R)} (CR_{\text{upper}} + 5R_{\text{lower}})
\]

\(\tau\) = visual light transmittance

\(W\) = window area [m]

\(A\) = area of all internal surfaces

\(R\) = area weighted mean reflectance

\[
IRC_{\text{average}} = \frac{0.65 \times (1 - 0.16) \times 4.5m^2}{125.12m^2 \times (1-0.49)} (29.5 \times 0.38 + 5 \times 0.32) = 0.5
\]

Table:

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Daylight Factor Distribution

Fig 10.14 DF distribution in the obstructed reference office according to Waldram
Design Sky Values

Design Sky values represent a horizontal illuminance level that is exceeded 85% of the time between the hours of 9 am and 5 pm throughout the working year. Thus they also represent a worst-case scenario that you can design to and be sure your building will meet the desired light levels at least 85% of the time.
BRE Protractors

A = 11.0% at 48°
B = 3.8% at 30°
C = 0.8% at 15°
D = 0.1% at 6°
BRE Protractors

$A' = 0.3$
$B' = 0.3$
$C' = D' = 0.35$
$E' = 0$
BRE Protractors

\[ \text{ERC}_{\text{BRS}} = [(3.8\% - 0.1\%) + (0.8\% - 0.1\%)] \times 0.3 \times 0.2 \times \frac{0.65 \times (1 - 0.16)}{0.88} = 0.2\% \]

Frame Factor

Reflected Light

\[ t_{\text{vis}} \]

\[ t_{\text{vis}} \text{ (reference)} \]
BRE Protractors

\[ SC_{BRS} = \left( (11\% - 0.1\%) \times (0.3 + 0.3) - ((3.8\% - 0.1\% + 0.8\% - 0.1\%) \times 0.3) \right) \times \frac{0.65 \times (1 - 0.16)}{0.88} = 3.9\% \]

Equ 10-4
Split Flux Method in Ecotect

A geometric version of the Split Flux Method (BRE)

Raytracing: each ray represents an approximately equal solid angle of sky

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For a simple scene, all methods are comparable in the target range.

Fig 10.17 Daylight factor distribution in the obstructed reference office according to several calculation methods.
Comparison of a Best Practice Model using Ecotect-Split-Flux vs. Radiance

Dramatic difference between both engines due to wall thickness

Radiosity
Radiosity

- Originally developed in 1950s to describe radiation heat exchange between surfaces
- Adopted during 1980 at Cornell for computer rendering
- Goal to move beyond the constant “ambient”/ background illumination term
- Assumption that all surfaces are Lambertian

\[ \rho = \frac{\pi \times L}{E} \]
The reflectance of most surfaces can be approximated into a diffuse and specular reflectance term.
Radiosity Model

- Two concepts: enclosure & form factor
- Window at night is a diffuse reflector with $\rho = 8\%$
- $B_n = \text{Radiosity off surface } n$

\[ H_j = \sum_i B_{ij} F_{ij} \quad \text{or} \quad B_j = E_j + \rho_j \sum_i B_{ij} F_{ij} \quad \text{for } j = \text{all surfaces in a space} \]
Attractive for walkthrough animations since simulation does not have to be repeated.

Finite element approaches are used to subdivide surfaces where a large gradient exists.
Radiance
Survey on the Use of Daylight Simulations

Dear colleagues,

This is your opportunity to influence future developments of daylight simulation tools.

You are invited to participate in an online survey on the current use of daylight simulation tools during building design. The survey is carried out as part of an international research project of the International Energy Agency’s Task 31, Daylighting Buildings in the 21st Century. The survey is administered by the National Research Council Canada. The outcome of the survey will be used to:

- identify existing weaknesses of daylighting design software packages
- better understand design practitioners’ needs
- tailor the output of tools accordingly.

We would like you to fill out the following online questionnaire according to your daylighting design experience. Please respond to all of the items as openly and honestly as possible. There are no right or wrong answers; it is only your opinion that is important. All of the information that we obtain from you through this survey will be kept confidential. Your participation in this research is voluntary. Should you decide to participate in the survey, you still reserve the right to end your participation at any time and for any reason, without prejudice. To end your participation, just close your browser. There are no foreseeable risks or costs to you from participating in this research. There is no direct benefit to you, however we hope that the result from this research will help us to assist software developers to improve their tools.

Should you have any concerns, questions or suggestions, please contact Dr. Christoph Reinhart at christoph.reinhart@nrc-cnrc.gc.ca or +1 (613) 993 9703.

Completing the survey should take about 5 minutes of your time.

You can print a copy of this agreement for future reference. The results of this survey will be published on this website by April 2004.

Please note: The survey has been approved by the Ottawa Research Ethics Board of the National Research Council Canada as Protocol 2003-31. For any further going questions or concerns, please contact the secretary of the Ottawa Research Ethics Board, at Paula.Derjancic@nrc-cnrc.gc.ca or +1 (613) 993-4234.

- 185 participants from 27 countries (40% Canada & US)
- validation seems less of an issue
- out of 40 tools mentioned, >50% of votes for RADIANCE based tools

What is Radiance?

- Validated backwards raytracer (similar to mental ray).
What is Radiance?

- Validated backwards raytracer (similar to mental ray).
- Supports a wide variety of material properties and sky models.
- Has a longish learning curve. (“Magic” lies in simulation parameters.)

Note: If you really want to understand Radiance you will have to read the relevant sections from the Rendering with Radiance book!
Backward vs. Forward Raytracing

forward raytracer

backward raytracer (Radiance)
Accuracy of Daylight Simulations

The Radiance/Daysim daylight simulation program can efficiently and reliably model annual illuminance time series with a mean relative error of 20%.

Radiance Material Modifiers

- Supports a wide variety of material properties and sky models.
“Magic” lies in simulation parameters.
Recommended simulation parameters for a simple scene.

<table>
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<tr>
<th>ambient bounces</th>
<th>ambient division</th>
<th>ambient sampling</th>
<th>ambient accuracy</th>
<th>ambient resolution</th>
<th>direct threshold</th>
<th>direct sampling</th>
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<td>20</td>
<td>0.1</td>
<td>300</td>
<td>0</td>
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</tbody>
</table>
# Radiance Simulation Parameters I

## Simulation Resolution

The simulation resolution can be calculated as follows:

\[
\text{simulation resolution} = \frac{\text{max scene dimensions} \times \text{ambient accuracy}}{\text{ambient resolution}}
\]

### Example:

- Ambient bounces: 5
- Ambient division: 1000
- Ambient sampling: 20
- Ambient accuracy: 0.1
- Ambient resolution: 300
- Direct threshold: 0
- Direct sampling: 0

\[
\frac{100 \text{ m} \times 0.1}{300} = \approx 3 \text{ cm (window mullion)}
\]
USDA Consolidation Laboratories
Ames, Iowa - AEC

Balance of daylight distribution in adjacent office and laboratory spaces. Rules of thumb do not apply any more.

Courtesy of Zack Rogers, PE, President, Daylighting Innovations. LLC. Used with permission.
Radiance Scene Complexity II

- ambient bounces: 7
- ambient division: 1500
- ambient sampling: 100
- ambient accuracy: 0.1
- ambient resolution: 300
- direct threshold: 0
- direct sampling: 0

higher raytraing parameters for blinds

raytracing detail

recommended Radiance simulation parameters
Limitations of Radiance

Radiance will not necessarily “find” the sun.
Photonmapping

Papers:

Image courtesy of Lars O. Grobe. Used by permission.
Common Simulation Mistakes
How close do ‘simulation novices’ get?

- error analysis of 69 student models of a sidelit space
- comparison of simulation results using Ecotect-Split-Flux and Radiance

Error Sources: Geometric Modeling

Highest result
Mean DF = 10%
• Window head height too high
• No wall thickness
Mean DF = 7.5%

- No wall thickness
- No real trees (just construction lines)
Error Sources: Material Properties

Mean DF = 1.5%
• No wall thickness
• No glazings
69 Student Models

- Ecotect results lie over and under Radiance results
- A closer analysis shows that none of the students built a ‘correct’ model
- Better results in 2006 probably due to ‘simulation tips’
## Simulation Checklist

<table>
<thead>
<tr>
<th>Modeling aspect</th>
<th>Simulation tip</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General organization</strong></td>
<td>Organize scene elements with different surface properties on separate layers and assign meaningful material properties to all layers (see chapter 12). Make sure to only use elements that your daylight simulation program can handle. For example, some simulation programs do not recognize meshes. You should always visually inspect your model within the simulation environment before running any prolonged simulations. Make sure that your geometry is oriented properly. A common convention is for North and East to be along the positive Y and X axes, respectively. For quality assurance, run a clear sky simulation on December 21st at noon and check the location of the shadows.</td>
</tr>
<tr>
<td><strong>External obstructions</strong></td>
<td>Model all significant neighboring obstructions, such as adjacent buildings and trees, to the extent that they provide shading for the target space or building. Heights and floorplans of neighboring buildings may be extracted from Google maps as well as local GIS files and LIDAR data (if available). Remember to include a ground plane in your model to adequately account for ground reflectances (Fig 1-5.28).</td>
</tr>
<tr>
<td><strong>Opaque building elements</strong></td>
<td>For interior spaces, model all wall thicknesses, interior partitions, hanging ceilings and larger pieces of furniture. Try to model all space dimensions at least within a 5cm tolerance. Façade details should be modeled within a 2cm tolerance. Make sure that there are no &quot;holes&quot; in your model. To test for the existence of holes, you can model all materials as black surfaces and ensure that a simulation detects no interior daylight. Consider window frames and mullions by either modeling them geometrically or by reducing visual transmittances for windows and skylights by an appropriate frame factor (typically 0.8). Depending on the daylighting metric that you want to calculate, remember to adequately model any movable shading devices such as venetian blinds (see chapter 15).</td>
</tr>
<tr>
<td><strong>Window and skylights</strong></td>
<td>Check that all window glazings only consist of one surface. Several CAD tools model double/triple glazings as two/three closely spaced parallel surfaces whereas daylight simulation programs tend to assign the optical properties of multiple glazings to a single surface. Check that all windows are &quot;inserted&quot; into the wall planes and not &quot;overlaid&quot; on the wall surfaces. Several CAD tools suggest that you can create and visualize a window in many different ways, one being the placement of a window surface on top of a wall surface which creates two coplanar surfaces. In such an instance some daylight simulation programs may either ignore the window or somehow &quot;guess&quot; which surface to consider.</td>
</tr>
<tr>
<td><strong>Sensor grid</strong></td>
<td>When defining sensor grids make sure that the reference surface is facing the correct way. For example, a downward facing floor surface with a negative sensor offset may lead to the sensors facing the floor.</td>
</tr>
</tbody>
</table>
- Simulation of 10.485.
- Practicing good simulation habits.
- Building trust in one’s own modeling skills.
Teaching daylight simulation in multiple steps leads to significantly better novices models.

Irradiance caching on the GPU produces a twenty-fold speedup.

Smother gradients are produced by creating the irradiance cache prior to the final gather.


Code compliance versus optimization versus interactive design. Every fraction of a second counts.

Real Time Design Analysis

- Highly optimized daylight availability/glare analysis in DIVA4
- Same analysis in real time in AccereradRT
- 40 test subjects went through two shading design studies for 20 minutes each.

Real Time Design Analysis

- Real time users were in a state of flow with barely any state over 20 seconds.
- AcceleradRT results somewhat closer to the Pareto front.

Real Time Design Analysis

- More confident in glare assessment: 58% (AcceleradRT), 13% (DIVA-for-Rhino)
- More confident in final design performance: 58% (AcceleradRT), 23% (DIVA-for-Rhino)
- More familiar tool: 18% (AcceleradRT), 55% (DIVA-for-Rhino)
- Trust more to predict glare accurately: 35% (AcceleradRT), 28% (DIVA-for-Rhino)
- Found task more enjoyable: 63% (AcceleradRT), 15% (DIVA-for-Rhino)
- Found task more difficult: 18% (AcceleradRT), 53% (DIVA-for-Rhino)
- Found task more frustrating: 18% (AcceleradRT), 58% (DIVA-for-Rhino)
- Felt more hurried: 18% (AcceleradRT), 63% (DIVA-for-Rhino)
- Felt more relaxed: 63% (AcceleradRT), 18% (DIVA-for-Rhino)
- Felt more distracted: 25% (AcceleradRT), 53% (DIVA-for-Rhino)
- Time passed more quickly: 25% (AcceleradRT), 48% (DIVA-for-Rhino)
- Learned more: 58% (AcceleradRT), 10% (DIVA-for-Rhino)
- Preferred overall: 90% (AcceleradRT), 10% (DIVA-for-Rhino)

Intense/ exhilarating experience

Daylight Availability Metrics
Rights of Light

Fig 11.1 Ancient Lights’ sign below a window in Newman Passage, London.
Historical Background: “Right of Light”

“Before WWII, legal rights of light constituted practically the only profitable field for daylight experts.”

-P.J. Waldram, “A Measuring Diagram for Daylight Illumination” (1945)
Spite Fence

Photograph of San Francisco in 1877, taken by Eadweard Muybridge. This image is in the public domain.

Charles Crocker, a railroad baron, built an abnormally large wall around his neighbor’s house who had refused to sell his property to Crocker.
Daylight Factor Analysis - Example

Daylight Factor

DF > 2%
DF_{mean} = 4.6%
Daylight Factor – Design Implications

- Reference
- Window head height
- Glazing type
- Narrow floor plan
Daylight Factor – Design Implications

Note, there are LEED certified buildings that are fully glazed!
Daylight Factor – Design Implications III

Common argument:
• overcast sky as a worst case scenario
• venetian blinds (even if closed) still admit sufficient DL

Daylight factor does not take glare or solar gain control into account. The consequence of too large glazings:
Venetian blinds are closed most of the time.
Combine Daylight Factor Analysis with Shading Studies
LEED 2 and 3 criteria

- LEED v3: 10fc < E < 500fc on Sep 21 at 9am and 3pm
- Daylight factor > 2%
People can work under very bright sky conditions

Photo courtesy of Ammar Ahmed. Used with permission.
Limitations of Point-in-Time Daylight Availability Metrics

- Do not consider local climate data
- Ignore programmatic use (occupancy patterns, lighting requirements)
- Neglect the impact of movable shading devices (venetian blinds)
Climate-based Metrics
Solution? – Climate-Based Metrics

- As opposed to a static simulation that only considers one sky condition at a time, dynamic daylight simulations generate annual time series of interior illuminances and/or luminances.
Daylight Coefficients

\[ DC_\gamma(x) = \frac{E_\gamma(x)}{L_x \Delta_\gamma} \]

\[ E(x) = \sum_\gamma DC_\gamma(x) \Delta_\gamma L_\gamma \]
Spatial Daylight Autonomy Calculation

Image courtesy of Solemma. Used with permission.
Questions?