Validation of F-matrix and six-phase method
Radiance Workshop, August 29-31, 2016

To quote Andy McNeil, Radiance Workshop 2013
more %@#$ @ phases?

Taoning Wang, Greg Ward, Eleanor Lee
Lawrence Berkeley National Laboratory, Anyhere Software
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11. 6-PHASE METHOD (F1H)
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Strategic Goals

Overall objectives

Support development of technological solutions that can help us meet aggressive carbon emission goals

Encourage market adoption to achieve significant widespread impacts within 2020-2030 timeframe

One approach

**Shading/daylighting window “attachments”** can be applied at a relatively low cost for the retrofit construction market → tools development for optically complex systems

Mitigate climate change
Motivation

Between 6 types of exterior shades:
- **78-94%** reduction in window heat gains
- **25% to 36%** reduction in lighting energy use
- **2-32%** of day with glare compared to low-e glazing with indoor shade

E.S. Lee et al., High Performance Building Façade Solutions, Final project report, California Energy Commission, CEC 500-06-041 (2009), Table 6.
Radiance → EnergyPlus workflow for operable indoor and outdoor coplanar shades

E.S. Lee et al., High Performance Building Façade Solutions – Phase II, Final project report, California Energy Commission, CEC 500-2015-033.
Coplanar exterior shading

Hilton Foundation, Agoura Hills
Stainless steel roller shade (shd 6)
(picture: ZGF architects)

Li Ka Shing, UC Berkeley campus
Aluminum louvers above window
Aluminum louvers in shutters (shd 8)
(picture: ZGF architects)

Federal Building, San Francisco
Metal mesh (similar to shd 10)
(picture: Morphosis architects)
Coplanar exterior shading

Number of hours indoor shades are lowered to control discomfort glare
Discomfort glare: DGP ≥ 0.38 or DGI ≥ 24

<table>
<thead>
<tr>
<th></th>
<th>Burbank, California</th>
<th></th>
<th>Oakland, California</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>East</td>
<td>South</td>
<td>West</td>
<td>East</td>
</tr>
<tr>
<td>no shade</td>
<td>3569</td>
<td>3575</td>
<td>3640</td>
<td>3338</td>
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<tr>
<td>shd 1</td>
<td>3623</td>
<td>3300</td>
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<td>1385</td>
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<td>121</td>
<td>127</td>
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<td>shd 4</td>
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<td>shd 5</td>
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</tr>
<tr>
<td>shd 6</td>
<td>257</td>
<td>0</td>
<td>190</td>
<td>177</td>
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<tr>
<td>shd 7a</td>
<td>862</td>
<td>660</td>
<td>970</td>
<td>706</td>
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<tr>
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<td>14</td>
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<td>shd 7c</td>
<td>469</td>
<td>9</td>
<td>409</td>
<td>385</td>
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<tr>
<td>shd 8(^1)</td>
<td>1145</td>
<td>1089</td>
<td>1199</td>
<td>954</td>
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<tr>
<td>shd 9(^5)</td>
<td>1036</td>
<td>922</td>
<td>1097</td>
<td>878</td>
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<td>shd 10(^5)</td>
<td>1387</td>
<td>1587</td>
<td>1490</td>
<td>1212</td>
</tr>
</tbody>
</table>

Rvis and cut-off angle of exterior shades affects number of hours

Sabine Hoffmann et al., Energy and Buildings 112 (2016): 279-298
Which in turn reduces annual energy use savings with no interior shades by 50% below code compared to the code with manually operated interior shades.
Strategic Goals revisited – why the matrices approach?

Develop technological solutions that can help us meet aggressive carbon emission goals

- Manufacturers: need for **parametric** tools for rapid prototyping and evaluation
- Architects: similar need for exploratory design and optimization (e.g., grasshopper/rhino + honeybee/ladybug)

Encourage market adoption to achieve significant widespread impacts within 2020-2030 timeframe

- Regulators: need **parametric** analysis for development of codes, standards, guidelines, rating and labeling systems that encourage informed decisionmaking by consumers

**Single design? Use DC approach...**
Non-coplanar exterior shading:
the final frontier…

Static systems: Parametric design for material selection, geometry

Operable, automated systems: potential to optimize solar control, daylight, & views?
Shading with non-Lambertian projections
(not accommodated in California Title-24 Standards or ASHRAE 90.1)

Genentech Building 35, South San Francisco. McNeil et al. 2014
http://eetd.lbl.gov/sites/all/files/lbnl-1005151_0.pdf
F-matrix for non-coplanar exterior shading

\[ i = VTFDs \]

where:

- \( i \) is the desired result vector (radiances, irradiances, etc.)
- \( V \) is the "View" matrix defining the lighting connection between results and exiting directions for a window group
- \( T \) is the "Transmission" matrix defining the BTDF of the window group
- \( F \) is the "Facade" matrix defining the flux transfer of exterior shading
- \( D \) is the "Daylight" matrix defining the coefficients between incoming directions for the window group and sky patches
- \( s \) is a vector of sky patch luminances for a particular time and date
Defining the F-matrix


UC San Diego Biomedical II building example
F-1 matrix

# Compute D matrix from exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 portF1.rad \skyglow.rad -i octs/model_3ph.oct > matrices/F1/facade.dmx
# Compute F matrix connecting clerestory glazing to exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass_clerestory.rad \portF1.rad -i octs/model_3ph.oct > matrices/F1/clerestory.fmx
# Compute F matrix connecting vision glazing to exterior aperture
rfluxmtx -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass_vision.rad \portF1.rad -i octs/model_3ph.oct > matrices/F1/vision.fmx
# Compute V matrix corresponding to illuminance points
rfluxmtx -faf -o matrices/%s.vmx -I+ -ab 7 -ad 50000 -lw 1e-7 \glazing.rad -i octs/model_3ph.oct < points.txt
# Followed by dctimestep or similar....
F wrapped matrix

# Compute D matrix from exterior aperture (4 surfaces)
\texttt{rfluxmtx} -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 portF1H.rad \skyglow.rad -i octs/model\_3ph.oct > matrices/F1H/facade.dmx

# Compute F matrix connecting clerestory glazing to exterior aperture
\texttt{rfluxmtx} -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass\_clerestory.rad \portF1H.rad -i octs/model\_3ph.oct > matrices/F1H/clerestory.fmx

# Compute F matrix connecting vision glazing to exterior aperture
\texttt{rfluxmtx} -ff -ab 4 -ad 10000 -lw 1e-5 -c 5000 glass\_vision.rad \portF1H.rad -i octs/model\_3ph.oct > matrices/F1H/vision.fmx

# Compute V matrix corresponding to illuminance points*
\texttt{rfluxmtx} -faf -o matrices/%s.vmx -I+ -ab 7 -ad 50000 -lw 1e-7 \glazing.rad -i octs/model\_3ph.oct < points.txt

# Followed by \texttt{dctimestep} or similar….
Comments

• For this example, we expect the F9-aperture calculation to be more accurate because it matches the original test condition more closely.
• In general, the F1 single aperture might be preferred if the model is a section of a larger façade.
• FH wrapped aperture is a compromise that can produce better results than a single face (F1) while still using only a single matrix.
Error analysis

**Compared F-matrix calculations to original 3-phase method** in west-facing structure
- 576 workplane illuminance test points
- No blinds and 5 venetian blind angles
- On 21st for each of 7 months, solstice-to-solstice
- One-hour intervals over daylight period

<table>
<thead>
<tr>
<th></th>
<th>Relative Error</th>
<th>Avg.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single F matrix</td>
<td></td>
<td>22%</td>
<td>33%</td>
</tr>
<tr>
<td>Wrapped F matrix</td>
<td></td>
<td>11%</td>
<td>21%</td>
</tr>
<tr>
<td>Nine F matrices</td>
<td></td>
<td>6%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Comparison between 3PH, F1, F1H, & F9 (all with no blinds)
Field Validation
Drop-arm awning

Initiated field testing Summer 2016 at Position 3
BSDF of awning fabric

Flat weave fabric (Sunbrella 4633-0000, Linen)
Manufacturer’s data:
Tv,n-n = 0.08
Tv, n-h = 0.044
ρv, n-h = 0.40

LBNL BSDF measured data:
Lambda 950 spectrophotometer with 150 mm integrating sphere plus
angle tube accessory for Lambda 950

Measure diffuse and direct transmittance & reflectance at nine angles of incidence

Jonsson, J., Measurement procedure for optical and thermophysical properties of fenestration shading fabrics to be used in WINDOW, July 23, 205.
Solar instrumentation (at the Advanced Windows Testbed)

- Global horizontal irradiance
- Diffuse horizontal irradiance
- Direct normal irradiance
Skycam at FLEXLAB: skydome luminance distribution, global illuminance and irradiance

Plus separate sensors for direct and diffuse irradiance at FLEXLAB
Incident vertical illuminance
Set-up: workplane illuminance and HDR imaging

Canon 5D with Sigma 8 mm f3.5 fisheye lens
## MODEL PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>Tvis</th>
<th>Rvis (non specular)</th>
<th>Other</th>
</tr>
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<tbody>
<tr>
<td>Wall</td>
<td>65%</td>
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<tr>
<td>Ceiling</td>
<td>82%</td>
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<tr>
<td>Floor</td>
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<tr>
<td>Desk</td>
<td>63%</td>
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<tr>
<td>Door</td>
<td>55%</td>
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<tr>
<td>Monitor</td>
<td>9%</td>
<td>36%</td>
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<tr>
<td>Mullion</td>
<td>50%</td>
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<tr>
<td>Glass</td>
<td>64.9%</td>
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<tr>
<td>Awning</td>
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<td>Primitive BSDF</td>
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## SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>View Matrix</th>
<th>Transmission Matrix</th>
<th>Daylighting Matrix</th>
<th>Façade Matrix</th>
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<td>-ab</td>
<td>12</td>
<td>4</td>
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</tr>
<tr>
<td>-ad</td>
<td>60,000</td>
<td>2000</td>
<td>10,000</td>
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<td>-dc</td>
<td>1</td>
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<td></td>
</tr>
<tr>
<td>-c</td>
<td></td>
<td>500</td>
<td>5000</td>
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</table>

M & S PARAMS | INSTRUMENT | SKY SIMULATION | DC | 3-PH | 4-PH (F1) | 4-PH (F1H) | 4-PH (Fn) | 6-PH (F1) | 6-PH (F1H) | 6-PH (Fn)
# SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>DC</th>
<th>3-PHASE</th>
<th>4-PHASE METHOD</th>
<th>6-PHASE METHOD</th>
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<tr>
<td></td>
<td>F1</td>
<td>F1H</td>
<td>F4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equation:</th>
<th>1 = Ds</th>
<th>1 = VTDS</th>
<th>1 = VTFDS</th>
<th>1 = VTFDS – V_d T_d F_d D_d S_d + C_d S_sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>View Matrix</td>
<td>N X 2306</td>
<td>N X 145</td>
<td>N X 145</td>
<td>N X 145</td>
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<tr>
<td>Transmission Matrix (CFS BSDF)</td>
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<td>145 X 145</td>
<td>145 X 145</td>
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<td>Facade Matrix</td>
<td>N/A</td>
<td>N/A</td>
<td>145 X 145</td>
<td>145 X 145</td>
</tr>
<tr>
<td>Daylight Matrix</td>
<td>N/A</td>
<td>145 X 2306</td>
<td>145 X 2306</td>
<td>145 X 2306</td>
</tr>
</tbody>
</table>

| SKY     | 2306 X N | 2306 X N | 2306 X N | 2306 X N | 5612 X N |

**M & S PARAMS | INSTRUMENT | SKY SIMULATION | DC | 3-PH | 4-PH (F1) | 4-PH (F1H) | 4-PH (Fn) | 6-PH (F1) | 6-PH (F1H) | 6-PH (Fn)**
F1
F1H
F4

F4
Multiplying matrices

Port1: fm x dm
Port2: fm x dm
Port3: fm x dm
Port4: fm x dm

fdm x

dctimestep matrices/glazings.vmx (CFS BSDF) fdm x
texample.skv > output
SKY SIMULATION (no awning)
Outdoor incident vertical illuminance

Simulations with skycam data over predicts measured data (NMBE=-29%)

Simulations with pyroheliometer data under predicts measured data (NMBE=18%)
RESULTS | work-plane illuminance
overcast sky | near window sensor | skycam (July 4)

Workplane illuminance (lux)  Percentage error (%)

F1 is low due to “missing flux”
RESULTS | work-plane illuminance
sunny sky | near window sensor | skycam (July 16)

3- and 4-phase: Significant error due to spatial averaging over façade and/or direct-diffuse split by skycam
RESULTS | work-plane illuminance
overcast sky | back room sensor | skycam

3- and 4-phase: over-prediction at rear of room (3.8 m, 12.5 ft from window)
RESULTS | work-plane illuminance

sunny sky | back room sensor | skycam

3- and 4-phase: over-prediction at rear of room (3.8 m, 12.5 ft from window)
RESULTS | work-plane illuminance

near window sensor | skycam (July 4 &16)
RESULTS | work-plane illuminance

near window sensor | pyroheliometer
RESULTS | work-plane illuminance

near window sensor | skycam | 6ph

5ph

6ph_F1

6ph_F1H

6ph_F4
RESULTS | work-plane illuminance

back room sensor | skycam

DC

3ph

F1

F1H

F4
RESULTS | work-plane illuminance

back room sensor | pyroheliometer

DC

3ph

F1

F1H

F4
FISHEYE LENS DISTORTION CORRECTION

Sigma 8mm F3.5 lens does not take a perfect angular projection fisheye image, which is needed to more accurately evaluate glare (using Evalglare).

\[
\alpha = \arctan \left( \frac{\text{Grid Size (real)}}{d} \right)
\]

\[
\text{Grid Size (img)} \propto \frac{\alpha}{\pi}
\]
### RESULTS | luminance

<table>
<thead>
<tr>
<th>M &amp; S PARAMS</th>
<th>INSTRUMENT</th>
<th>SKY SIMULATION</th>
<th>DC</th>
<th>3-PH</th>
<th>4-PH (F1)</th>
<th>4-PH (F1H)</th>
<th>4-PH (F2)</th>
<th>6-PH (F1)</th>
<th>6-PH (F1H)</th>
<th>6-PH (F2)</th>
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<tr>
<td>sunny sky</td>
<td>Skycam</td>
<td>13:30 measured</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

- **measured**

- **DC**

- **3ph**

- **4ph_f1**

- **4ph_f1h**

- **4ph_f4**

---

Graph showing workplane luminance (lx) over time from 09:00 to 15:00.
RESULTS | luminance

sunny sky | skycam

3ph

F1

F1H

F4
Next steps and related work

- Sort out sources of error
- Measure and validate with more exterior shading configurations, including low angle winter solstice period
- In the works: F-matrix Tutorial (and more), Sarith Subramaniam, Penn State University (looking for potential review/testers!)
CREATING LOW-ENERGY FAÇADE SOLUTIONS FOR TODAY'S BUILDINGS

New fenestration technologies and systems that optimize the synergies between the façade, lighting, and mechanical systems can deliver high performance throughout a building's lifespan. These “integrated” solutions represent a key opportunity to significantly reduce energy and demand, helping to move us toward our goal of zero net energy buildings by 2030.
Acknowledgments

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GlenRaven
Sunbrella

Chris Humann and Andrew McNeil, Terrestrial Light

Anothai Thanachareonkit, Jacob Jonsson, Christoph Gehbauer, Darryl Dickerhoff, Daniel Fuller, Stephen Selkowitz, LBNL

https://facades.lbl.gov/