Application of RADIANCE for Development of Future Solutions

Case Studies of Virtual Natural Lighting Solutions and Photocatalytic Oxidation Modelling

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The built environment…

• In the future, the built environment will need to deal not only with “energy saving”, but also “very high-quality indoor environment”
  • Healthy
  • Productive
  • Comfortable
  • Energy-producing
  • …..
• Solutions are needed!
The future is so uncertain and highly complex:
The need to predict the performance of future solutions
→ using computational simulation tools
→ e.g. RADIANCE!

Radiance-online.org (2012)
Some familiar terms

- Lighting
- Wavelength
- Uniformity
- Distribution
- Building
- Simulation

- Light source
- Daylight
- Irradiance
- Perception
- Performance

- Raytracing
- Visual comfort
- Sky model
- Preference
- Optimisation

- Sustainability
- Material
- Glare index
- Behaviour
- Contrasts

- Preference
- Luminous intensity
- Uncertainty
Case #1

Virtual Natural Lighting Solutions

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The future is so uncertain and highly complex: The need to predict the performance of future solutions → using computational simulation tools. Low availability of natural (day-)light!
The idea
Approach towards VNLS (model)

Approach towards VNLS (model)

View complexity

Light directionality

With view, diffuse
Without view, diffuse
With view, directional
Without view, directional
Model without view, diffuse

- Typically diffuse light distribution
- Applied for situations where view is not considered the most important thing, e.g. when comparing energy consumption.

Philips Lighting (2007)
De Vries et al. (2009)
Smolders & de Kort (2012)
• For example, real windows under CIE overcast sky:
  gensky -c -b 22.9
• ...compared to virtual windows:
  light 11.856
  11.856  11.856
• Combined with general lighting ETAP luminaire 2x28 W
Model without view, diffuse – (3)

Northwest

Southwest

West-1

West-2

Illuminance (lx)

Distance from window (m)

Real windows

Virtual windows

Real windows

Virtual windows
• Typically (also) diffuse light distribution, but with image projected or displayed.
• Applied for situations where view is considered influential, e.g. when comparing glare perception from various view types.
Model with view, diffuse – (2)

• *For example*, comparing 5 different images as viewing scene

IJsselsteijn et al. (2008)
Model with view, diffuse – (3)

- 2D image mapped on light material

Source brightness without and with occlusion

Maintain 40 lx on the desk

Ambience parameters: –ab 3 –aa 0.15 –ar 128 –ad 512 –as 256
Model with view, diffuse – (4)
• Still in conceptual model.
• View is simplified: green “ground” and blue “sky”.
• Focused on directional light from the “ground” to the ceiling.
• Applied for optimising space availability and uniformity.
Model with simple view, directional – (2)

- **Input variables:**
  - Interval of tilt angle (°): 1.0; 1.5; 2.0
  - Beam angle (°): 38; 76; 114
  - Total luminous flux of the “sky” (lm): 6200, 11100, 19900
  - Distance between windows (m): 0; 0.75

Ambience parameters: –ab 4 –aa 0.15 –ar 128 –ad 512 –as 256 –ds 0.2
Model with simple view, directional – (3)

- **Output variables:**
  - **Space availability:**
    \[
    \%A = \frac{n(E \geq 500 \text{ lx})}{N} \times 100\% \quad ; \quad N = 1944
    \]
  - **Uniformity:**
    \[
    U_0 = \frac{E_{\text{min}}}{E_{\text{av}}}
    \]
  - **Average ground contribution on the ceiling:**
    \[
    \%G_{av} = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{E_{\text{ground-i}}}{E_{\text{total-i}}} \right] \times 100\% \quad ; \quad N = 10
    \]
  - **Average probability of discomfort glare:**
    \[
    PDG_{av} = \frac{1}{4} \left( DGP + DGI_n + UGR_n + CGI_n \right)
    \]
    where
    \[
    DGI_n = 0.01452 \times DGI; \quad UGR_n = 0.01607 \times UGR;
    \]
    \[
    CGI_n = 0.01607 \times CGI; \quad (\text{Jakubiec} \& \text{Reinhart}, 2012)
    \]
Compared to a similar scene where VNLS is replaced with real windows under CIE overcast sky, with equal average surface luminance.

The proposed criteria:

- Space availability: $\%A_{\text{VNLS}} > \%A_{\text{RW}}$
- Uniformity: $U_{0_{\text{VNLS}}} \geq U_{0_{\text{RW}}}$
- Average ground contribution on the ceiling: $0.9(\%G_{av RW}) \leq \%G_{av VNLS} \leq 1.1(\%G_{av RW})$
- Average probability of discomfort glare: $PDG_{av VNLS} \leq PDG_{av RW}$
- Average surface luminance: $L_{av} \leq 3200 \text{ cd/m}^2$
Model with simple view, directional – (5)

- Probability of discomfort glare at position A, B, C:

<table>
<thead>
<tr>
<th>Type</th>
<th>Conf.</th>
<th>IA (°)</th>
<th>BA (°)</th>
<th>(\Phi) (lm)</th>
<th>Pos.</th>
<th>DGP</th>
<th>DGI(_n)</th>
<th>UGR(_n)</th>
<th>CGI(_n)</th>
<th>PDG(_{av})</th>
<th>Stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNLS</td>
<td>1a</td>
<td>2.0</td>
<td>76</td>
<td>11100</td>
<td>A</td>
<td>0.24</td>
<td>0.21</td>
<td>0.36</td>
<td>0.39</td>
<td>0.30</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.21</td>
<td>0.20</td>
<td>0.32</td>
<td>0.35</td>
<td>0.27</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>0.27</td>
<td>0.33</td>
<td>0.46</td>
<td>0.48</td>
<td>0.38</td>
<td>0.10</td>
</tr>
<tr>
<td>RW</td>
<td>1a</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>0.24</td>
<td>0.21</td>
<td>0.35</td>
<td>0.39</td>
<td>0.30</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.21</td>
<td>0.19</td>
<td>0.31</td>
<td>0.33</td>
<td>0.26</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>0.26</td>
<td>0.31</td>
<td>0.43</td>
<td>0.45</td>
<td>0.36</td>
<td>0.09</td>
</tr>
</tbody>
</table>

- Position C experiences the largest prob. of discomfort glare
- Standard dev. in VNLS scenes are comparable to those in RW scenes \(\rightarrow\) PDG\(_{av}\) can be used for comparing both VNLS and RW
• Results example of VNLS vs RW

<table>
<thead>
<tr>
<th>Type</th>
<th>Conf.</th>
<th>IA (°)</th>
<th>BA (°)</th>
<th>Φ (lm)</th>
<th>%A</th>
<th>U₀</th>
<th>%G_{av}</th>
<th>PDG_{av}</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNLS</td>
<td>1a</td>
<td>2.0</td>
<td>38</td>
<td>11100</td>
<td>28.0</td>
<td>0.37</td>
<td>48.8</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>1a</td>
<td>1.5</td>
<td>38</td>
<td>11100</td>
<td>29.3</td>
<td>0.37</td>
<td>46.8</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>1a</td>
<td>1.0</td>
<td>38</td>
<td>11100</td>
<td>29.9</td>
<td>0.37</td>
<td>44.6</td>
<td>0.35</td>
</tr>
<tr>
<td>RW</td>
<td>1a</td>
<td></td>
<td></td>
<td></td>
<td>14.3</td>
<td>0.18</td>
<td>14.3</td>
<td>0.39</td>
</tr>
<tr>
<td>VNLS</td>
<td>2a</td>
<td>2.0</td>
<td>76</td>
<td>6200</td>
<td>11.5</td>
<td>0.32</td>
<td>49.2</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>1.5</td>
<td>76</td>
<td>6200</td>
<td>9.4</td>
<td>0.33</td>
<td>46.5</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>1.0</td>
<td>114</td>
<td>6200</td>
<td>5.3</td>
<td>0.35</td>
<td>44.1</td>
<td>0.36</td>
</tr>
<tr>
<td>RW</td>
<td>2a</td>
<td></td>
<td></td>
<td></td>
<td>14.7</td>
<td>0.16</td>
<td>14.7</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The images show the luminescence distribution for different configurations.
Model with simple view, directional – (7)

- Most of the VNLS with BA = 114° (wide) satisfy all performance criteria.
- The total luminous flux is highly influential to the space availability.
- The beam angle is highly influential to the uniformity, average ground contribution, and average probability of discomfort glare.
Conclusions & outlook

• As a simulation tool, RADIANCE can be employed for predicting lighting performance of future solutions such as VNLS.

• The modeling approach is driven towards providing good directionality and complex view, while keeping the visual comfort comparable to the real window situation.

• The next steps will be improving all of the lighting aspects, as well as evaluating energy performance of the selected solutions with other simulation tools.
Case #2

Photocatalytic Oxidation Modelling

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Indoor Air Quality & Photocatalytic Oxidation

• Indoor Air Quality (IAQ) is important:
  • People in modern urban areas spend 85%-90% of their time indoor
  • Synthetic materials, combustion, human activities, industrial processes can release a range of pollutants, resulting in indoor air pollution
• Pollutants can be removed by source control, increasing ventilation rates or air purification.
• Photocatalytic Oxidation (PCO) is a potential technology for (passive) indoor air purification.
Photocatalytic Oxidation (PCO) modeling

• Previous research:
  1. Development of a kinetic model for NO$_x$ (inorganic compound)
  2. Implementation of the kinetic model in a Computation Fluid Dynamics (CFD) model
     H.A. Cubillos Sanabria, (2011)

• No radiance model was applied, causing to:
  - Neglect the glass cover in the reactor setup (1)
  - Assume a uniform irradiance distribution during modelling (2)
The concept

- A concept for PCO modelling is proposed, based on the previous research
  - Radiance model
  - Kinetics
  - Computation Fluid Dynamics

Radiance model → Kinetics → Computational Fluid Dynamics → Prediction air purification capability
The framework

**Preprocessing**
*(Input definitions)*
- Geometry
- Meshing
- Flow type
- Field equations
- Optical properties materials
- Emission model light sources
- Reaction mechanisms
- Reaction kinetics (Rate limiting steps)
- Fit empirical constants

**Processing**
*(Calculations)*
- Continuity Equation
- Turbulence model / Wall function
- Radiance equation
- Momentum Equations
- Kinetic model
- Species Transport Equations

**Post-processing**
*(processing of the results)*
- Verification
- Validation
- Report results
First modeling study of the reactor setup

(a) reactor setup

(b) reactor
Overview of the reactor setup model

(main dimensions in [m])

Casing

Luminaire

Mirror

Light sources

Catalyst sample

Reactor

Reactor
• An omnidirectional radiant intensity distribution over the longitudinal axis of the light source model is assumed, expressed in $L_i \text{[Wm}^{-2}\text{sr}^{-1}]$.  

![Diagram of light source model]

• The light source model is composed out of a:  
  (1) lamp base (no emission)  
  (2) border region ($L = L_i/2$)  
  (3) main light emitting area ($L = L_i$)
Sampling grid

(a) Reactor setup

(b) Reactor

(c) Sampling grid

\[ E_{\text{calibrate}} \left[ \frac{W}{m^2} \right] \]
\[ h = 185 \text{ mm} \]

\[ E_{\text{glass}} \left[ \frac{W}{m^2} \right] \]
\[ h = 150 \text{ mm} \]

\[ E_{\text{catalyst}} \left[ \frac{W}{m^2} \right] \]
\[ h = 139 \text{ mm} \]

Catalyst sample

Glass

E_{\text{glass}} \left[ \frac{W}{m^2} \right]

E_{\text{catalyst}} \left[ \frac{W}{m^2} \right]

E_{\text{calibrate}} \left[ \frac{W}{m^2} \right]
Transmission coefficient of the glass < 0.9273

Reflection coefficient catalyst surface = 0.88

L₁ = 34.8 W/(m²sr)

(rtrace) -I -ab 5 -dj 1.0 -ds 0.05 -aa 0.1 -ar 256 -st 0.07 -ad 1024 -as 64
**Impression: vertical cross-section**

\[ (rvu) -ab 1 -aa 0.3 -dj 1 -ds 0.1 \]
Impression: bottom-top & top-bottom view

(rv) -ab 1 -aa 0.3 -dj 1 -ds 0.1
Result of simulation & analytical calculation

\[
\frac{E_{\text{catalyst}}}{E_{\text{glass}}} = \tau_{\text{direct}} + \tau_{\text{indirect}}
\]

\[
\tau_{\text{direct}} = \tau_{\text{glass}}
\]

\[
\tau_{\text{glass}} = \sum_{i=1}^{n} \left( 1 - \left( \frac{n_2 - n_1}{n_2 + n_1} \right)^2 \right) \cdot \left( 1 - \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \right) \cdot \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^{4(i-1)}
\]

\[
\tau_{\text{indirect}} = \sum_{i=1}^{n} \left( (1 - \tau_{\text{glass}})^i \sigma_{\text{catalyst}}^i \tau_{\text{glass}} \right)
\]

\[
E_{\text{glass}} = \frac{E_{\text{catalyst}}}{(\tau_{\text{direct}} + \tau_{\text{indirect}})}
\]

\[
y = 0.0975x + 0.9004 \quad R^2 = 0.9995
\]

\[
y = 0.0727x + 0.9265 \quad R^2 = 0.9995
\]
Conclusion and outlook

- Both the measurement and the simulations have inaccuracies; the inaccuracy of the stochastic calculation is obtained with statistics.
  - The maximum error of the average values is ~4%, but due to uncertainty the error is raised to ~6%

- The analytical calculation could not provide a correct estimation of the $E_{\text{catalyst}}/E_{\text{glass}}$ ratio. Therefore, an equation from simulated data was derived:
  $$E_{\text{glass}} = (0.0975 \cdot \sigma_{\text{catalyst}} + 0.904) E_{\text{catalyst}}$$
  - The equation can be used to improve the kinetic model of NO$_x$

- Secondary modeling study in which:
  - The improved kinetic model is employed
  - Radiance model is integrated into a CFD model
  - Several cases are simulated in which the PCO is studied, using a benchmark office model for CFD
Questions?