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The effect of multichannel spectral simulation on the evaluation of lighting energy demand in an office room

Margarita Alwalidi, M.Sc.

Prof. Dr.-Ing. Sabine Hoffmann

Chair of Built Environment, RPTU Kaiserslautern, Germany

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TU NACHWUCHSRING

RPTU Rheinland-Pfälzische Technische Universität Kaiserslautern Landau

Agenda

1. Background: multichannel spectral simulations
2. Generation of spectral profile for the sky
3. Annual results for daylighting: spectral simulation with 3, 9, 27 and 81-channels
4. Electric lighting with continuous and discontinuous spectrum
5. Results: electrical lighting demand
6. Conclusion and outlook

Background

Consideration of the spectral composition of light

- Lighting enables visual tasks to be performed efficiently and accurately.
- Standards (e.g. DIN EN 12464-1): minimum illuminance levels, balanced luminance distribution, glare protection measures, etc.

The spectral composition has non-visual effects. It:

- is crucial for health and well-being.
- influences moods, emotions and also attention.

Source: https://thinklighting.blog/

Background
Consideration of the spectral composition of light

- Lighting enables visual tasks to be performed efficiently and accurately.
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The spectral composition has non-visual effects

- crucial for health and well-being.
- influences moods, emotions and also attention.

Non-visual metrics:

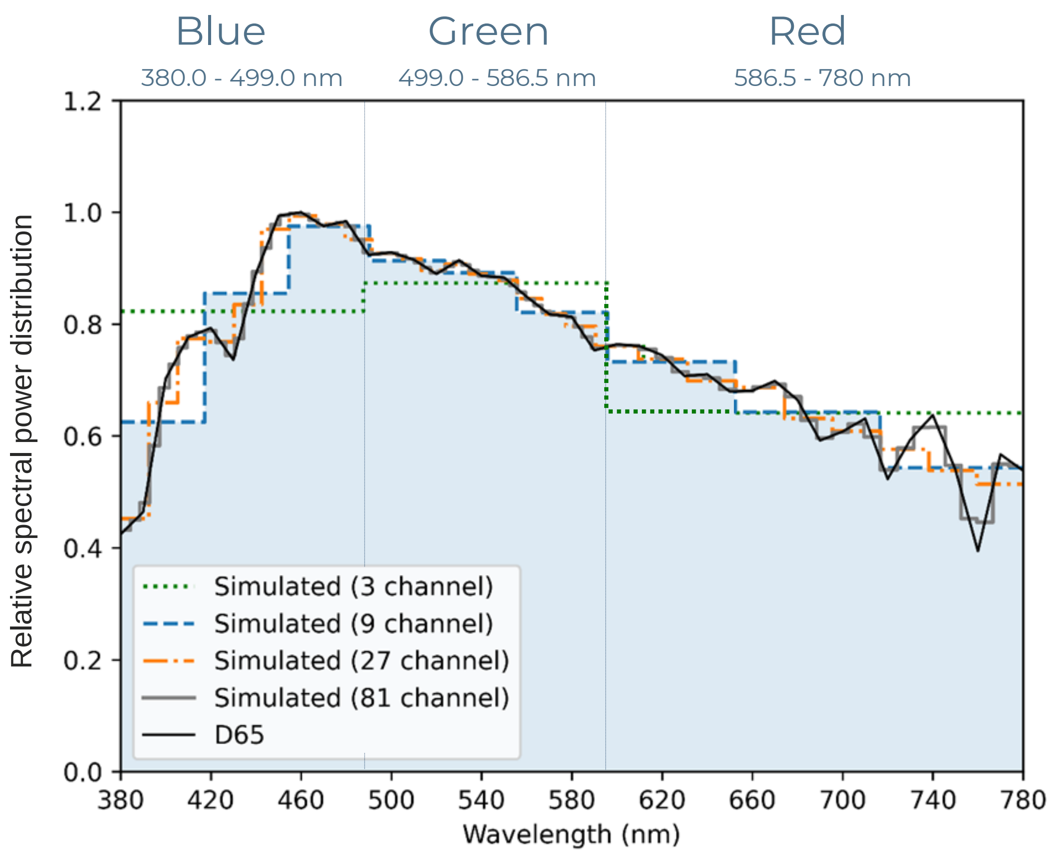
- thresholds for metrics such as Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) have been previously proposed.
- discoveries in this field will keep on coming.
- one thing is certain: light should be modelled spectrally, so that it can be converted into spectral metrics.

Source: https://thinklighting.blog/

Background

N-channel algorithm and spectral simulation tools

- The *N*-step algorithm was introduced in the field of psychophysics and color computation to achieve physical accuracy in lighting simulations and renderings in Radiance.
- The algorithm fragments the visible spectrum into *N* channels.
- If *N* is nine channels → three simulations will be performed, one in each of the discrete spectral wavelength bands.
- Two Radiance-derived tools implement the *N*-step algorithm by increasing the number of channels beyond three:
  - LARK (1.0 & 2.0): 3 and 9 channels
  - Adaptive Lighting For Alertness (ALFA): 81 channels



Spectral power distribution of D65 illuminant and discretization of the spectrum into three, nine, 27 and 81 channels.

Source: Ruppertsberg A. & Bloj M.; 2006, Yang J. & Maloney L.; 2001, Hall R.; 2012.

Background

Validation of a multichannel spectral simulation tool

Three lighting scenarios with 3, 9, 27 and 81 channels in a point-in-time simulation:

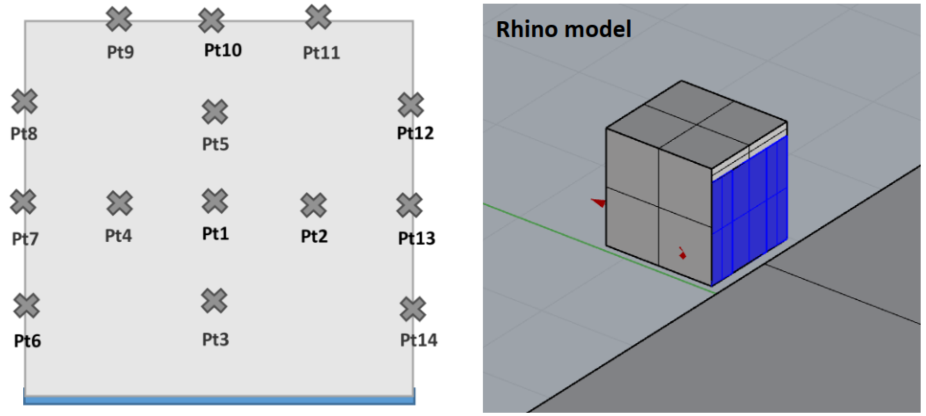
- Diffuse daylight
- Electric light
- Combination of daylight and electric light

Integral irradiance from 380 nm to 780 nm:

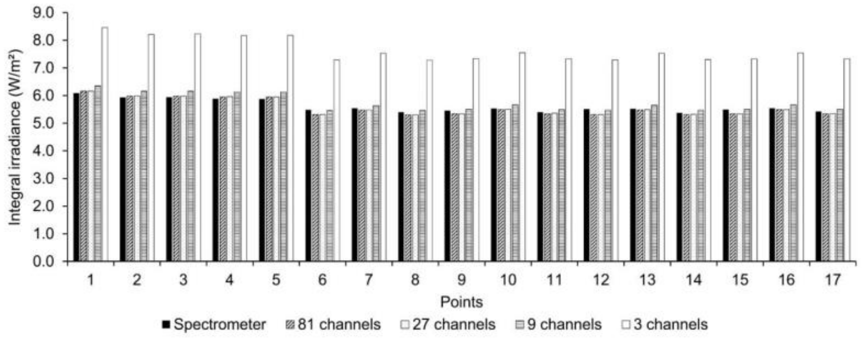
Improvement of the mean absolute percentage error (MAPE) by 13.9% to 33.9% for electric and combined light with 9 channel simulation.

For continuous daylight, minimal improvement that is not justified by increase of the simulation time.

→ *How significant is the improvement in the evaluation of lighting energy demand?*



Modeled box with 14 (daylight) and 17 (electric light) measurement points.



Irradiance predictions of N-channels alongside measured irradiance.

Source: Alwalidi M, Ganji Kheybari A, Subramaniam S, Hoffmann S. Development of a multichannel spectral simulation tool and experimental validation with different lighting scenarios. Lighting Research & Technology. 2023;0(0).

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Generation of the annual spectral profile of the sky

Determination of sky type based on sky clearness (ε):

- Clear sky: $\varepsilon > 4.5$
- Intermediate sky: $1.065 \leq \varepsilon \leq 4.5$
- Overcast sky: $\varepsilon < 1.065$

KL_8.0_30.0_12.5.sky

```
# C:\Radiance\bin\gendaylit 8.0 30.0 12.5 -g 0.180 -m -15 -a 49.43 -o 7.75 -W 317.0 354.0
# Local solar time: 10.97
# Solar altitude and azimuth: 47.0 -22.8
# epsilon, delta, atmospheric precipitable water content : 1.6225 0.3603 2.0000

void light solar
0
0
3 2.502e+06 2.502e+06 2.502e+06

solar source sun
0
0
4 0.264241 -0.628057 0.731930 0.533000

void brightfunc skyfunc
2 skybright perezlum.cal
0
10 3.930e+01 1.915e+01 -0.951257 -1.079485 11.257745 -3.056593 0.178367 0.264241 -0.628057 0.731930
```

Luminance and CCT correlation for clear sky:

Luminance range	Correlation
L < 3172 cd/m²	$\mathrm{CCT} = \dfrac{10^6}{-132.1 + 59.77 \times \log_{10}\mathrm{L}}$
3172 cd/m² < L < 5200 cd/m²	$\mathrm{CCT} = \dfrac{10^6}{10.2 \times \mathrm{L}^{0.26}}$
L > 5200 cd/m²	$\mathrm{CCT} = \dfrac{10^6}{181.35233 + \mathrm{LCF}\,(-4.22630 + \log_{10}\mathrm{L})}$ where: $\mathrm{LCF} = 21.56308 + (82.33165 - 0.77050 \times \gamma_s) \times (1.10439 + \log_{10}(\varepsilon - 0.9))$

Luminance and CCT correlation for overcast sky:

CCT = 6145 K

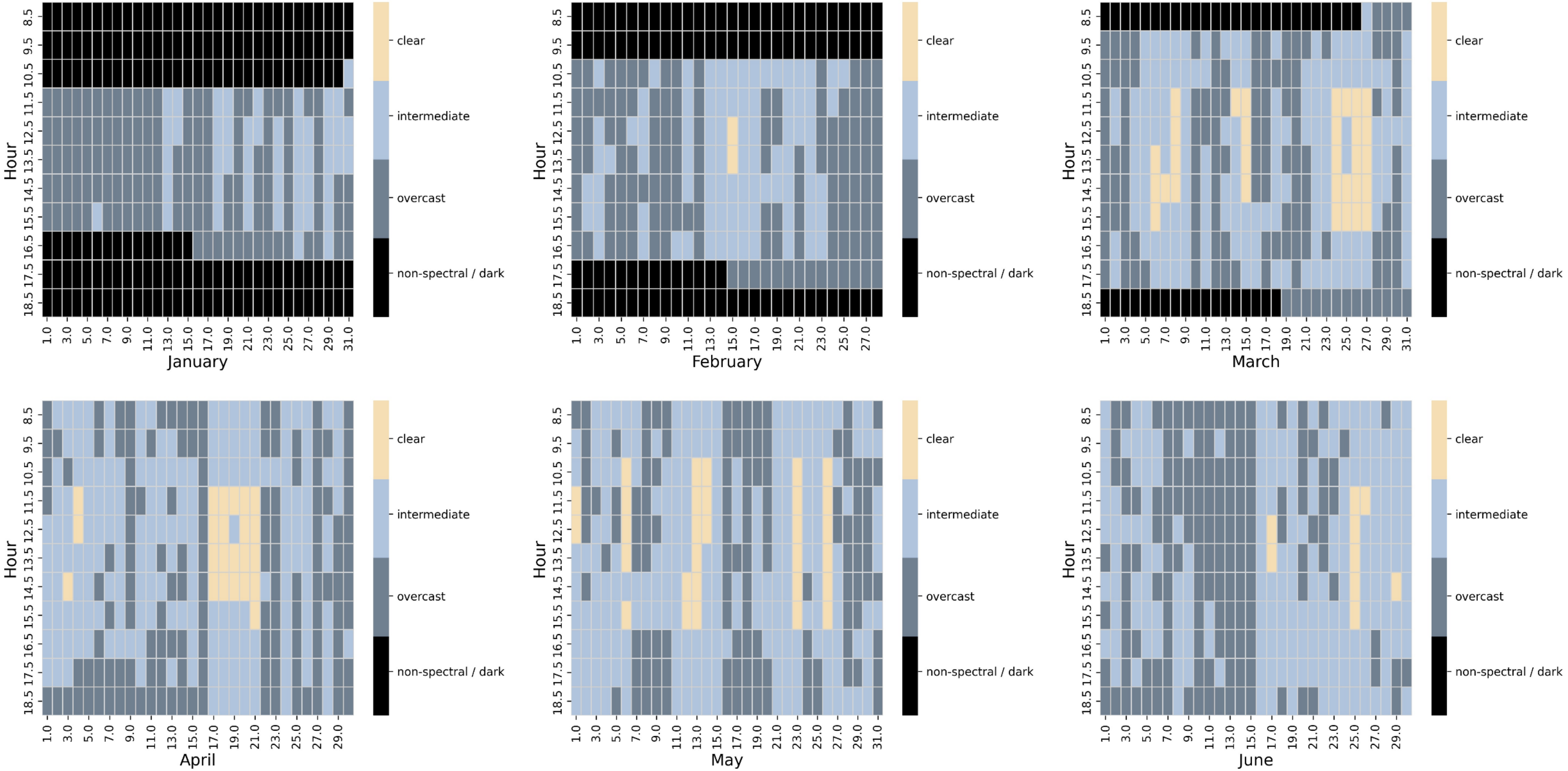
Intermediate sky?

Overcast if sky patch has only diffuse contribution.

Source: Diakite-Kortlever A, Knoop M. Forecast accuracy of existing luminance-related spectral sky models and their practical implications for the assessment of the non-image-forming effectiveness of daylight. Lighting Research & Technology. 2021.
Wienold J, Diakite A, Knoop M, Andersen M. Making simulations more colorful: Extension of gendaylit to create a colored sky. 17th International Radiance Workshop, Loughborough, UK. 2018.

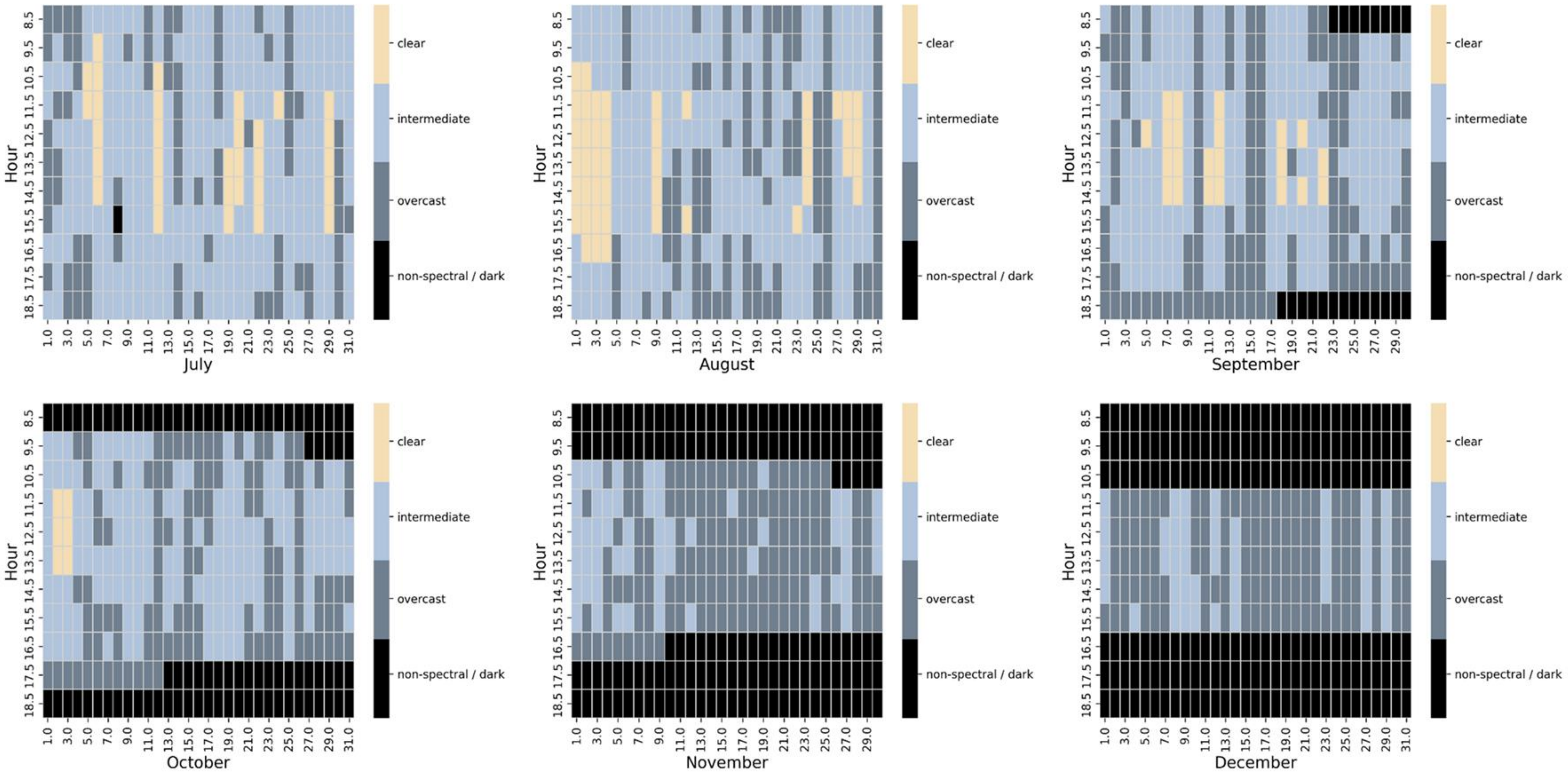
Generation of the annual spectral profile of the sky

Mannheim, Germany

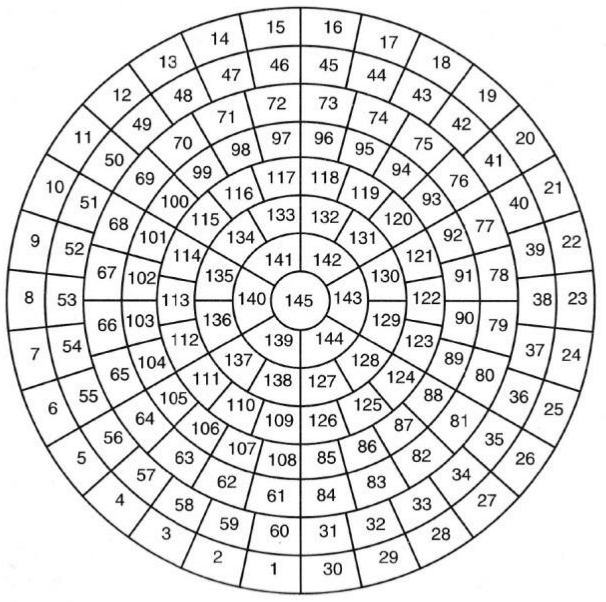


Generation of the annual spectral profile of the sky

Mannheim, Germany



Generation of the annual spectral profile of the sky



Total hours from 08:30 to 18:30: 4,015

Total hours if solar altitude is above 10°: 3,265

Matrix with 145 Reinhart patch subdivision via gendaymtx

↓

Patch RGB radiance

↓ $L = 179 \times (0.265R + 0.670G + 0.065B)$

Patch luminance

↓

Patch CCT

↓

Normalized patch SPD (CIE 015:2018)

↓

Absolute patch SPD → Mean normalized SPD of the dome

Source: Diakite-Kortlever A, Knoop M. Forecast accuracy of existing luminance-related spectral sky models and their practical implications for the assessment of the non-image-forming effectiveness of daylight. Lighting Research & Technology. 2021.

Reference office room

Geometry:

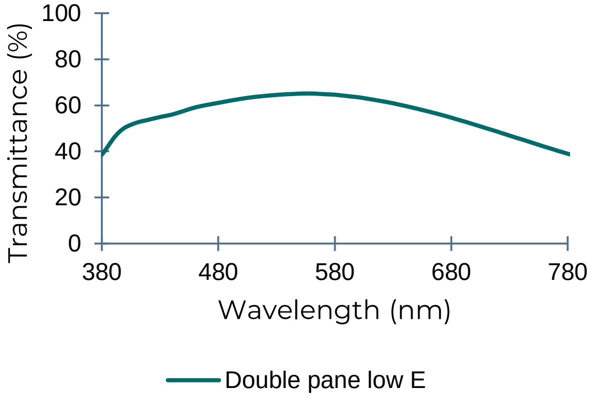
MIT reference office room

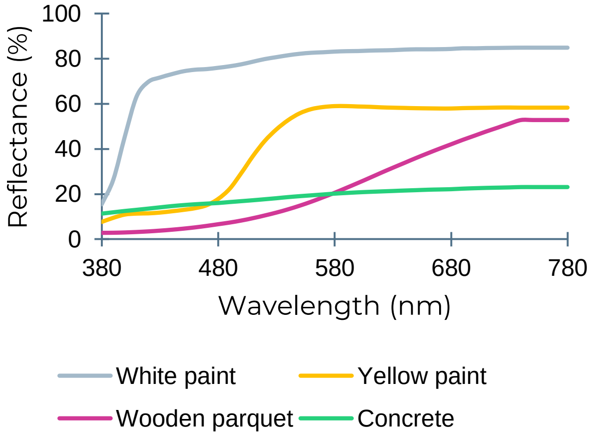
Location:

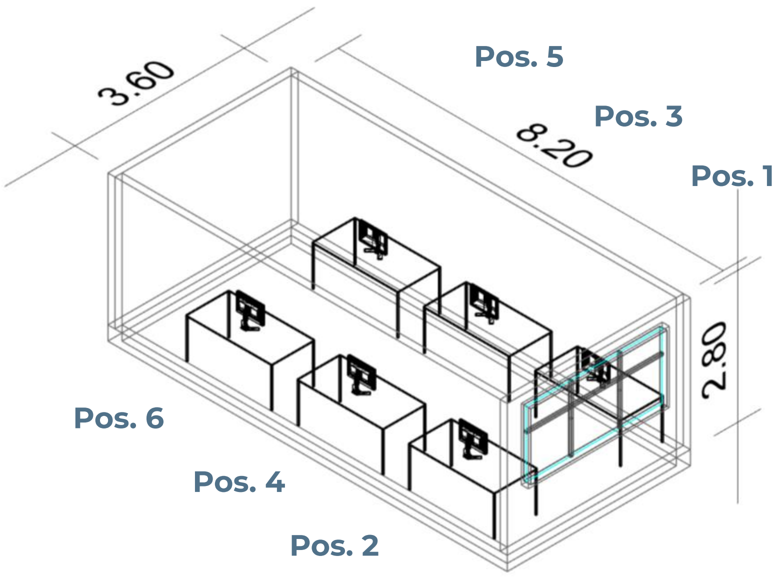
Mannheim, Germany

Surface	Material	Reflectance	Transmittance
Ceiling	White paint	80 %	
Walls	Yellow paint	50 %	
Floor	Wooden parquet	20 %	
Glazing	Double pane low E		65 %
Ground	Concrete	20 %	

Venetian blinds removed from the original model







- Floor area: 29.5 m²
- Total workplaces: 6
- Total workzones: 3

Source: *https://web.mit.edu/sustainabledesignlab/projects/ReferenceOffice/index.html*
J. Alstan Jakubiec (2022). Data-driven selection of typical opaque material reflectances for lighting simulation, LEUKOS, DOI: 10.1080/15502724.2022.2100788

Generation of the annual spectral profile of the sky

View-specific spectral profile

1. Generate hourly HDR images → Use of coloured sky as input for *N*-channels.

e.g. 28.04 at 15:30

view from position 1

9-channel simulation

380.0 - 499.0 nm

499.0 - 586.5 nm

586.5 - 780 nm

↓

2. Convert radiance of each pixel (except sun pixels) to luminance

↓

3. Mean average luminance of the visible part of the sky dome

↓

4. Derive CCT from luminance-CCT correlation

↓

5. Generate SPD according to CIE 015:2018

Source: Maskarenj M, Deroisy B, Altomonte S, A new tool and workflow for the simulation of the non-image forming effects of light, Energy and Buildings, 2022.

Example of the simulation with 9-channels

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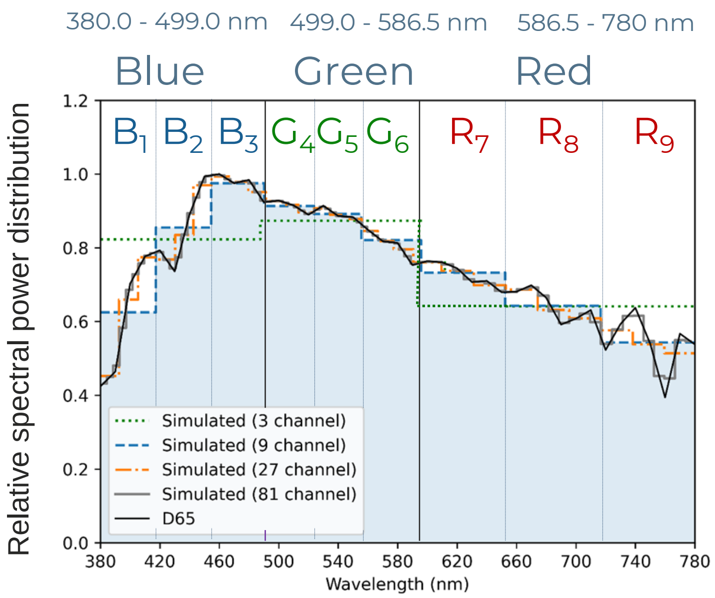
1. For each timestep, adjust the -c option of the *genskyvec* using the respective part of the SPD for each of the three simulation runs. (Input: dome or view-specific SPD scaled for energy balance).

2. Generate **three** octree files for the material definitions for each discrete wavelength band.

3. Generate **three matrices** for each octree file *using rfluxmtx*

4. Multiply the **three** DC matrices are against **three** lists of average patch radiances (from step 1) using *dctimestep*

Total simulated hours: 3,265



Spectral power distribution of D65 illuminant.

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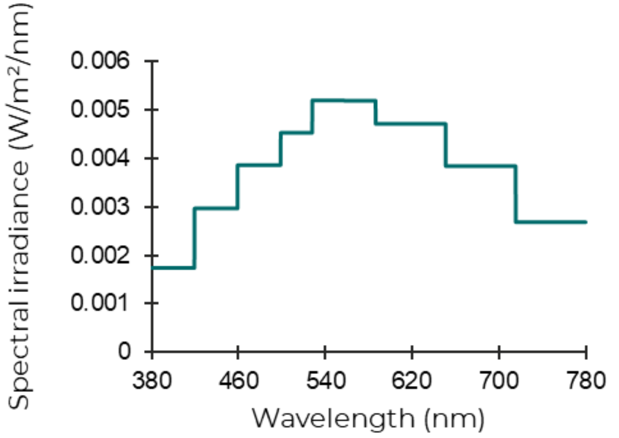
Annual results for daylighting
Postprocessing steps

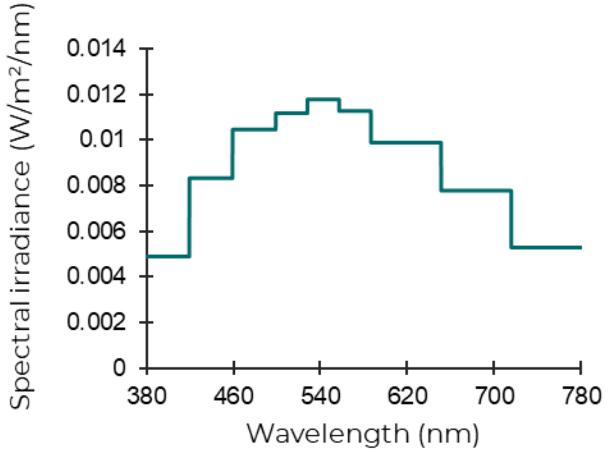
Example of the simulation with 9-channels

Example on 01.01 at 11:30

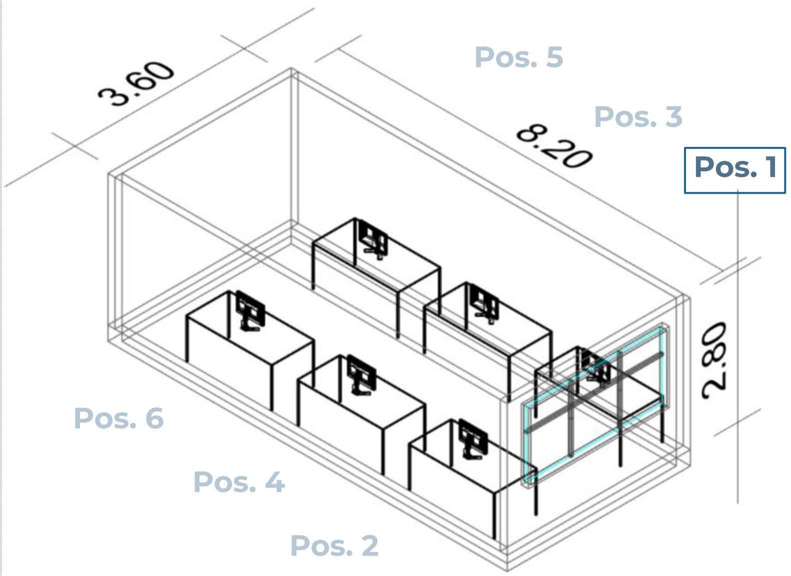
- Direct irradiance: 0 W/m²
- Diffuse irradiance: 68.0 W/m²
- Photopic illuminance at the desk level (0.80 m horizontal): 795.8 lx
- Melanopic equivalent daylight illuminance at the eye level (1.20 m vertical): 353.9 lx



Spectral irradiance at the eye level. Pos. 1.



Spectral irradiance at the desk level. Pos. 1.



Position 1 in reference office room.

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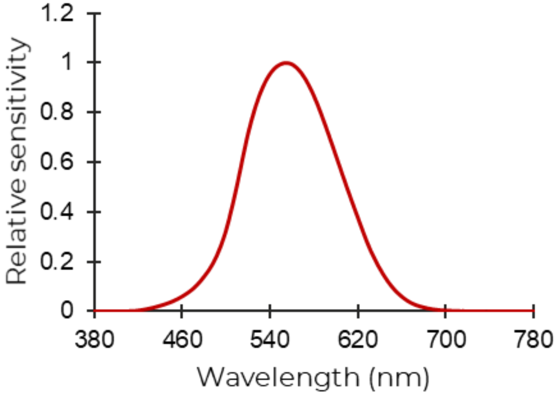
Annual results for daylighting

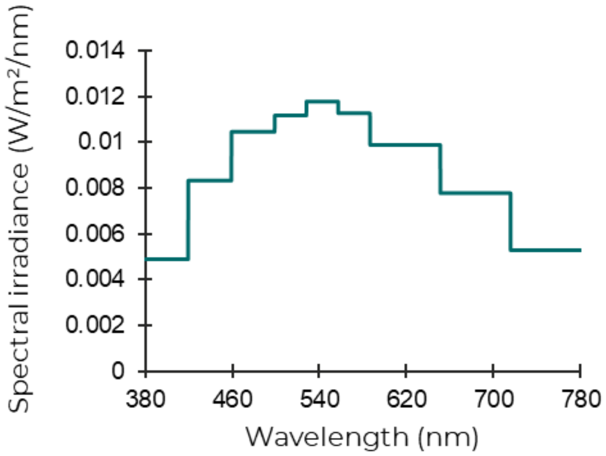
Melanopic equivalent daylight illuminance and photopic illuminance

photopic

683 lm/W **X** $\int_{380}^{780}$



X



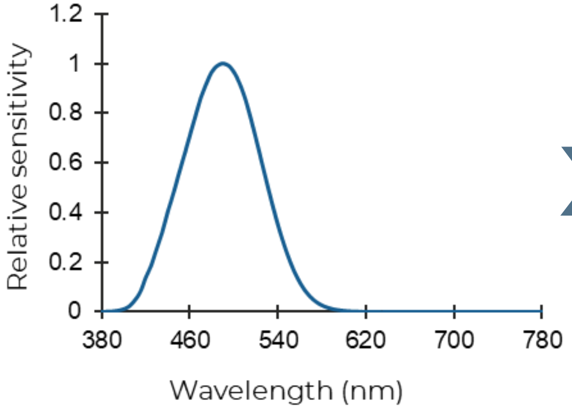
Luminous efficacy, *K*

Photopic sensitivity function

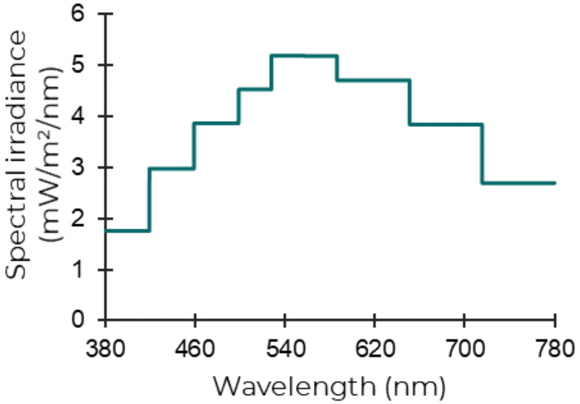
Spectral irradiance at the desk level. Pos. 1.

mEDI

($\int_{380}^{780}$



X



) / **1.326 mW/lm**

Melanopic sensitivity function

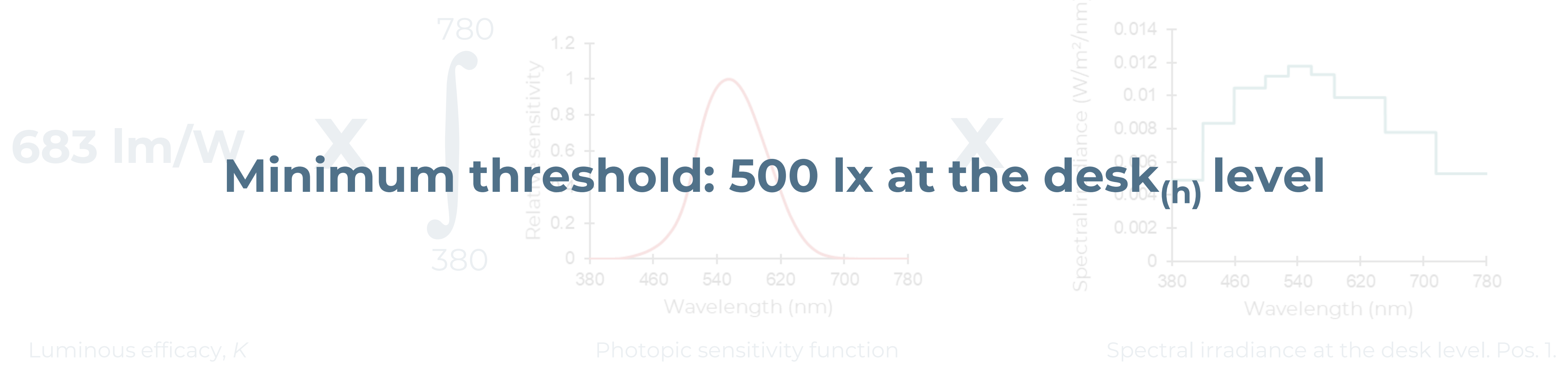
Spectral irradiance at the eye level. Pos. 1.

Melanopic efficacy of luminous radiation, $K^{D65}_{mel,V}$

Annual results for daylighting

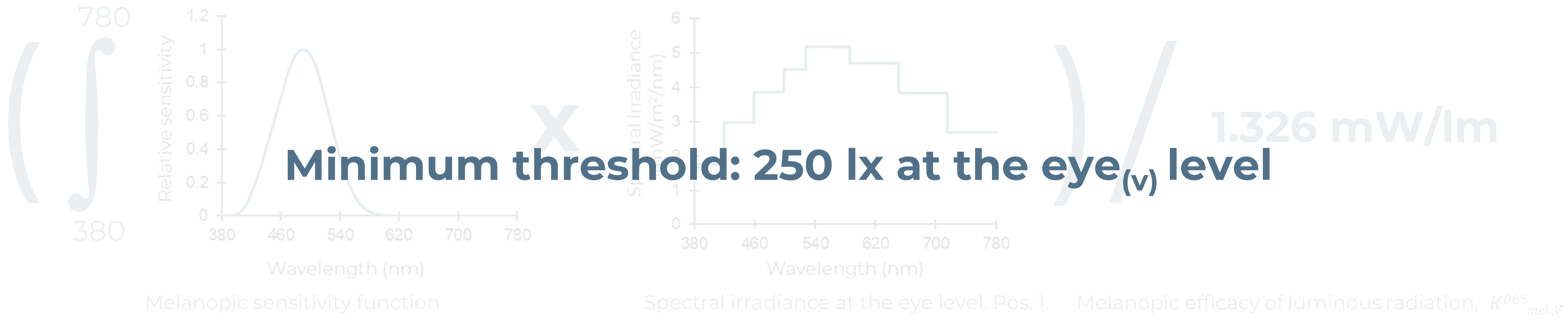
Melanopic equivalent daylight illuminance and photopic illuminance

photopic



Minimum threshold: 500 lx at the desk$_{(h)}$ level

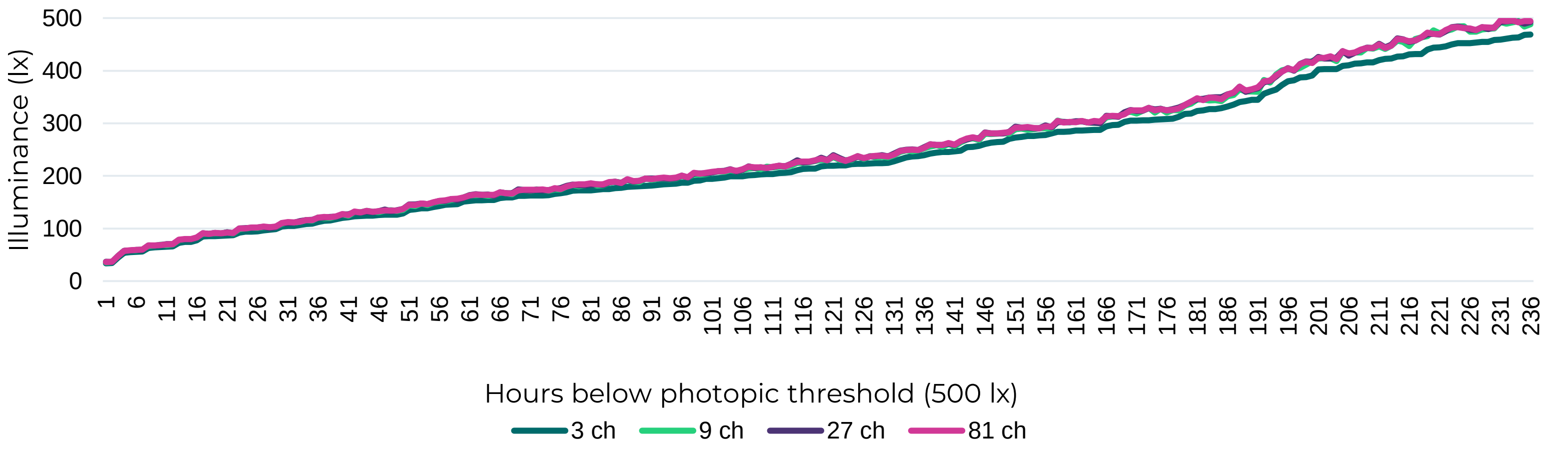
mEDI

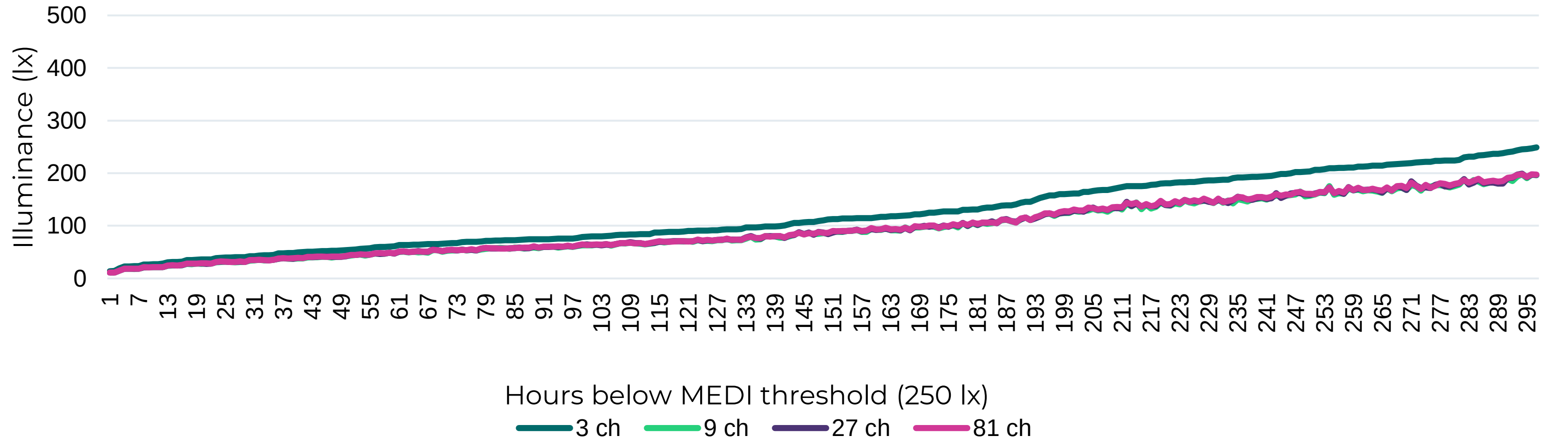


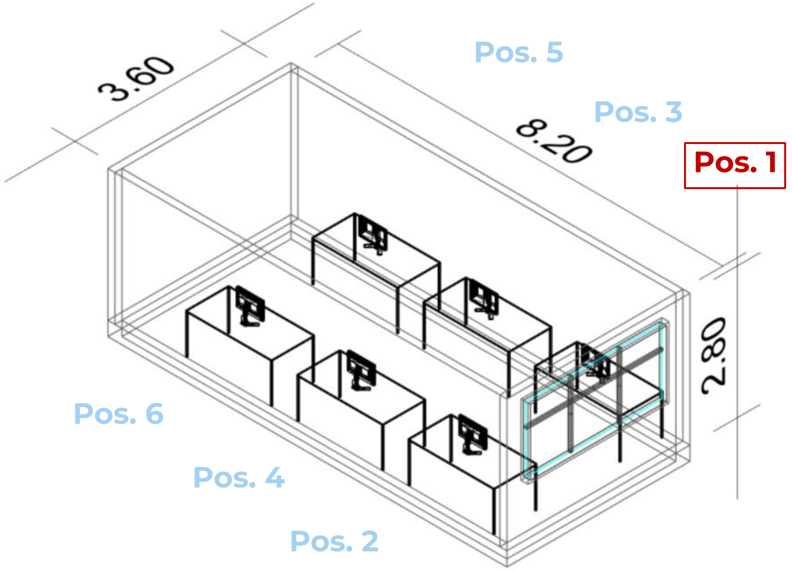
Minimum threshold: 250 lx at the eye$_{(v)}$ level

Annual results for daylighting

Photopic illuminance and MEDI: underlit hours for position 1



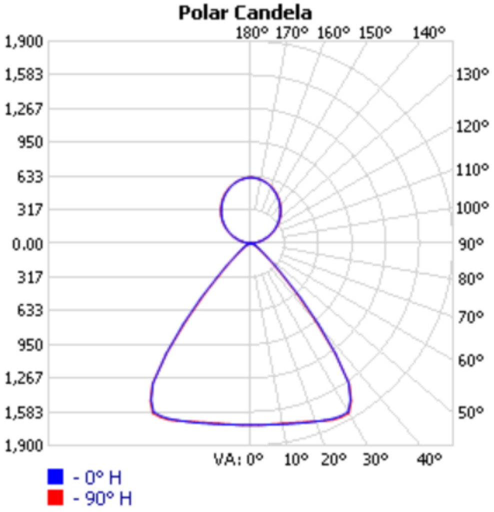


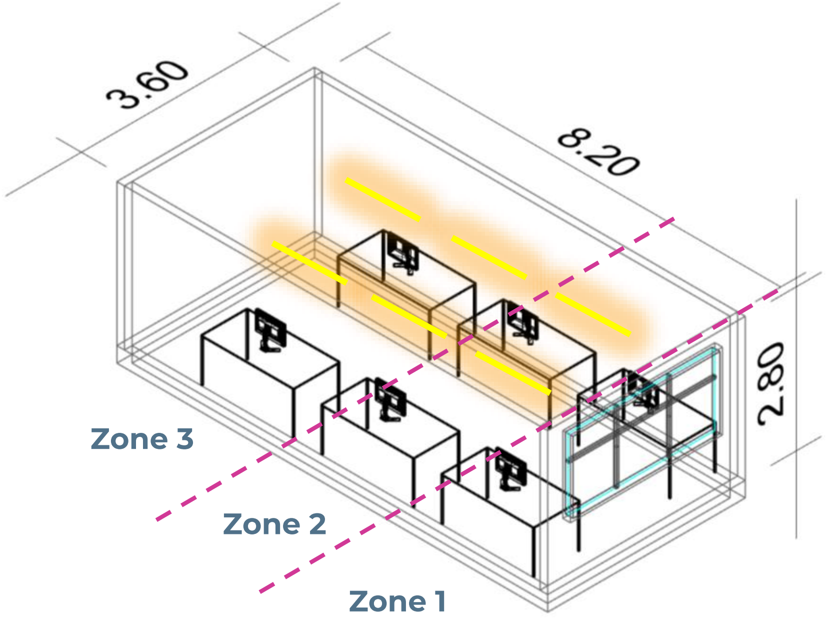


Reference office room.

Electric light
Selected luminaire

- Energy consumption: 34 W
- Tube dimensions: 0.052 m x 1.404 m
- Mounting height: 2.60 m
- Dimming dependent on the zone
- Supplements daylight (3 channels) to maintain appropriate level of illuminance in each zone
- Appropriate level of illuminance determined by the sensor with the lowest values in each zone





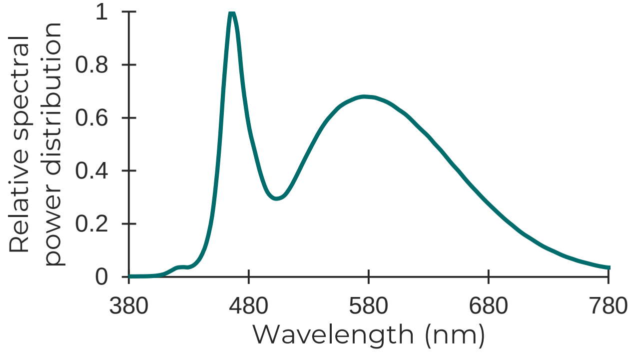
Electric light
Spectral power distribution

- Energy consumption: 34 W
- Tube dimensions: 0.052 m x 1.404 m
- Mounting height: 2.60 m

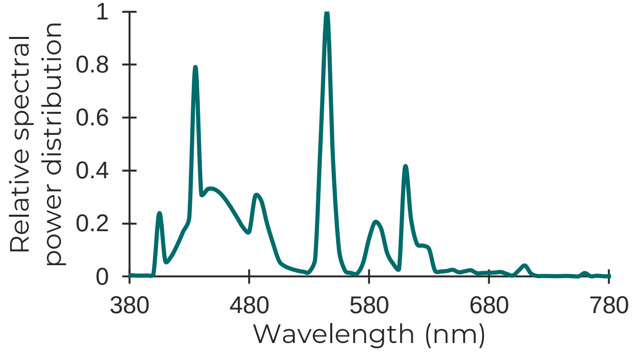
SPD defined in the ies2rad –c option

Relative SPD of the luminaires

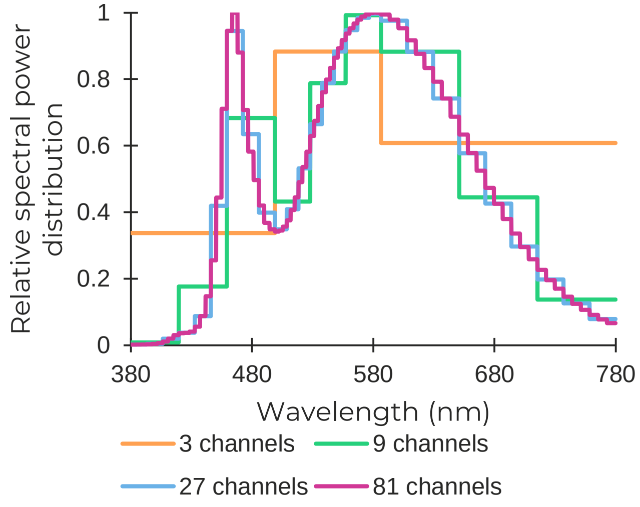
LED 4250 K

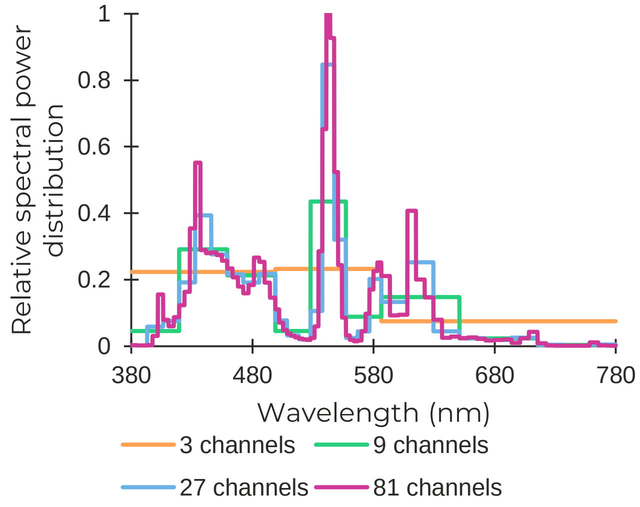


Fluorescent 13650 K



Relative SPD at the eye level





Results

Annual energy demand

LED 4250 K

Channels	Annual energy demand (kWh/m²a)	Deviation from 81 channels (%)
3	5.85	7.70
9	**6.25**	**1.34**
27	6.32	0.31
81	6.33	0.00

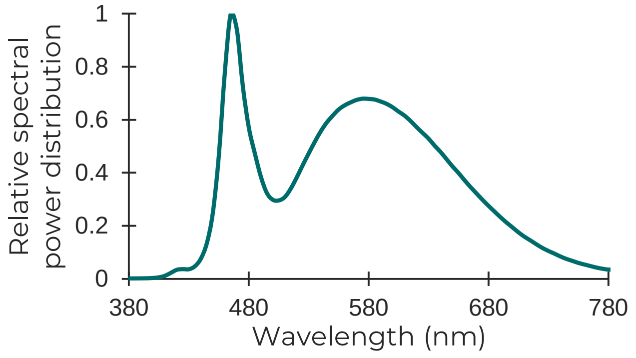
Fluorescent 13650 K

Channels	Annual energy demand (kWh/m²a)	Deviation from 81 channels (%)
3	3.75	14.47
9	**4.19**	**4.76**
27	4.30	2.09
81	4.39	0.00

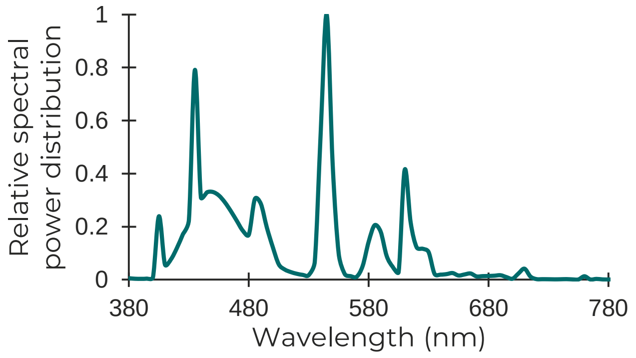
Relative SPD of the luminaires

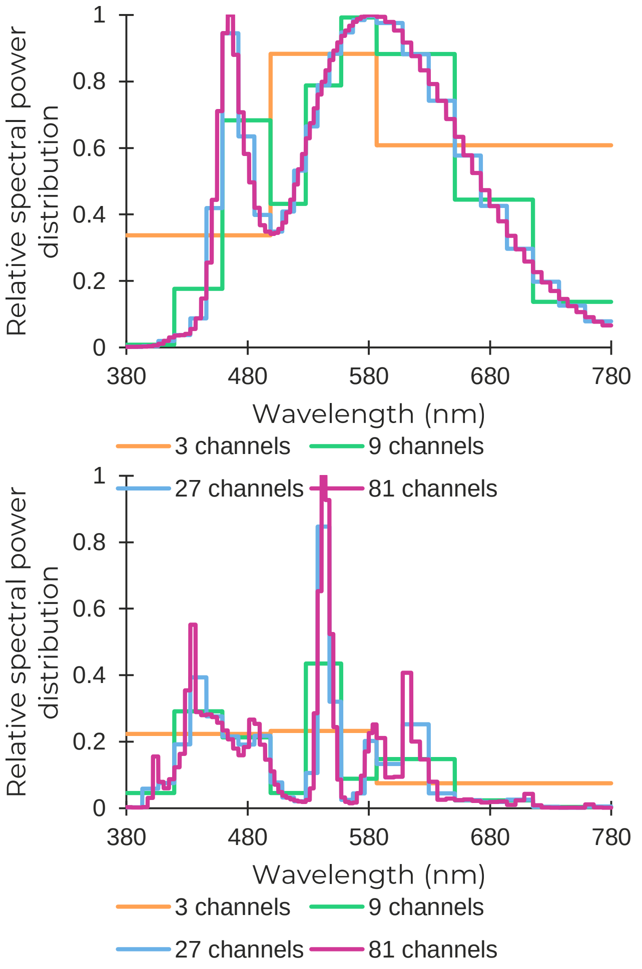
Relative SPD at the eye level

LED 4250 K



Fluorescent 13650 K





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Conclusion and outlook

- How significant is the improvement in the evaluation of lighting energy demand?
  - Approximately 15% more lighting energy is needed with 81 channels the investigated spectra in comparison to three channels
  - Nine-channel simulation maintained deviation below 5 % for both spectra in comparison to the 81 channels
- Multichannel spectral simulations are recommended for buildings with high lighting energy demand

Future steps:

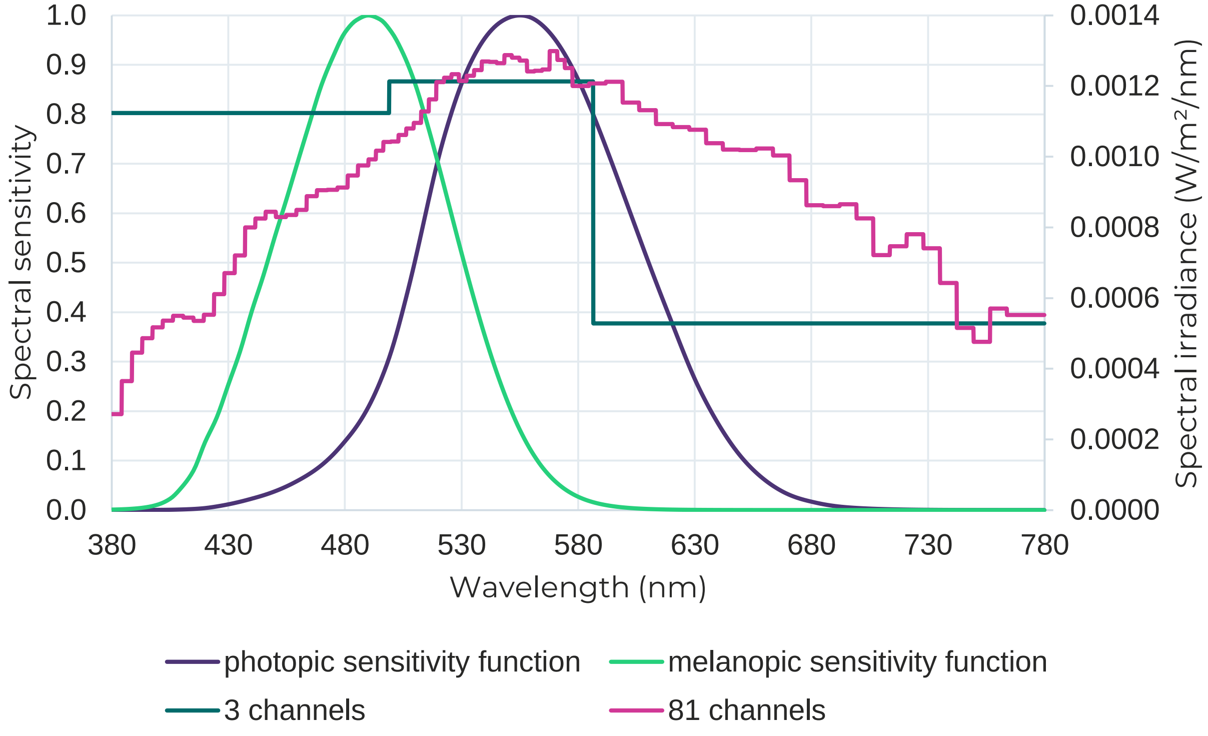
Trade off between accuracy and simulation time

- Simulation time: sequential or parallel simulation of the channels
- Simulation time could be significantly reduced if sky color could be defined only once for multiple timesteps (matrix simulation)

Thank you!

Margarita Alwalidi, M.Sc.

Mail: margarita.alwalidi@rptu.de
Internet: www.bauing.uni-kl.de/gst
www.livinglab-smartofficespace.de



Example on April 22 at 18:30