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Integrated Thermal and Light Simulations for Complex Daylight Systems Using TRNSYS and RADIANCE

Preliminary results from the project „Light From Façade“

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[1] Bartenbach LichtLabor, [2] University of Innsbruck

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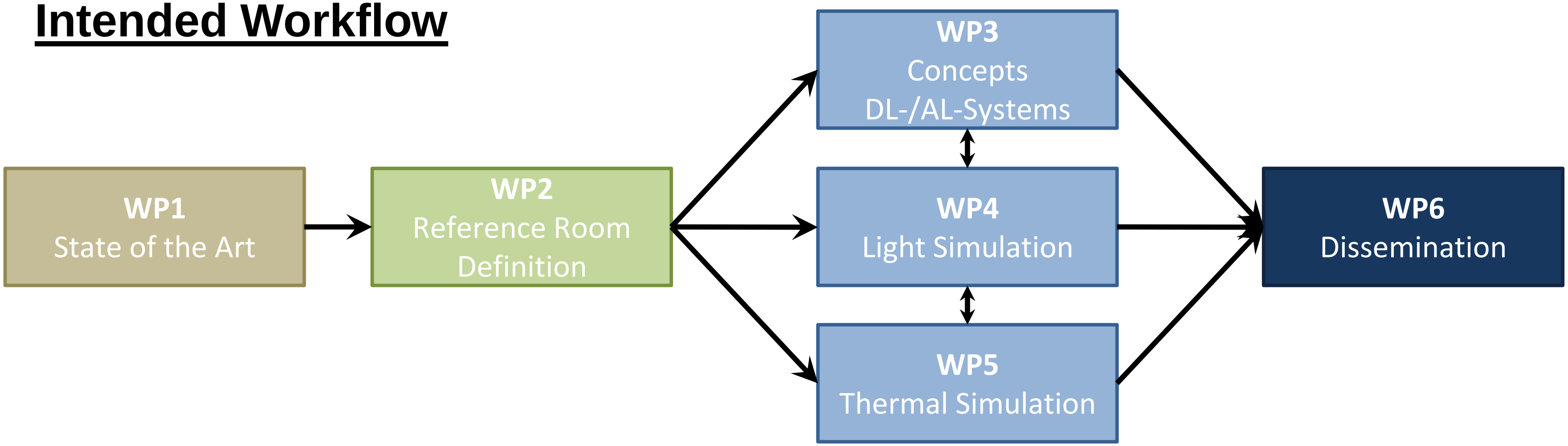
Intended Workflow

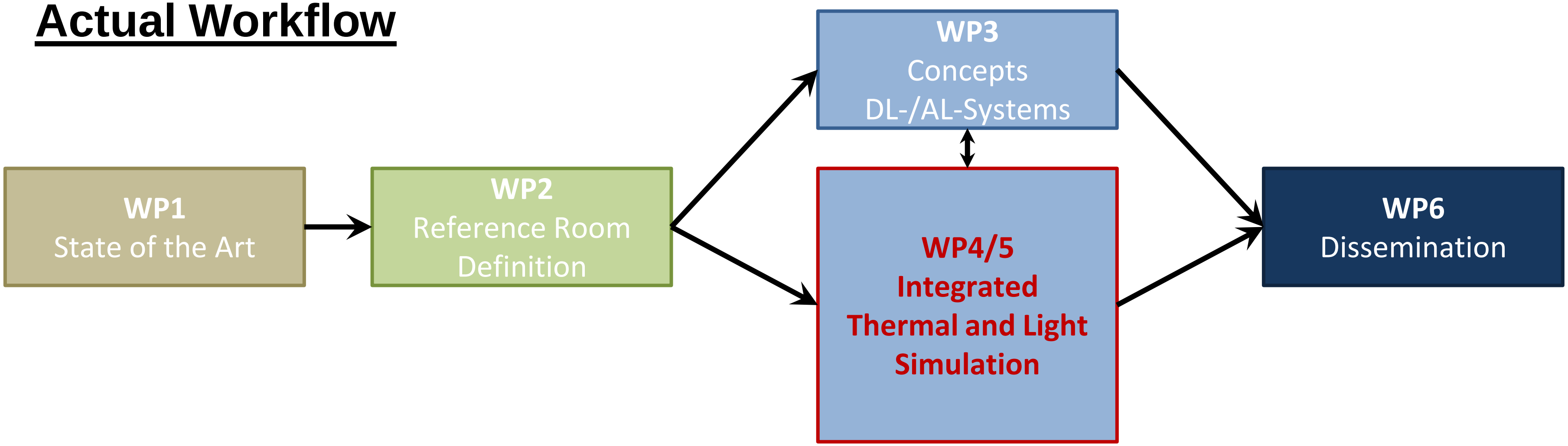


Goals

- **Artificial Lighting** out of the façade
- **Daylight System** to control light and solar input
- **Daylight Redirection** from the façade into the depth of the room
- **Integrated Control** of daylight system and artificial lighting
- **Optimization of complete system** with respect to
  - visual comfort (adequate illumination, view to outside, glare)
  - thermal comfort (SHGC, solar gains, surface temperatures)
  - energy (heating, cooling)

PROJECT „LIGHT FROM FAÇADE“

Actual Workflow



Goals

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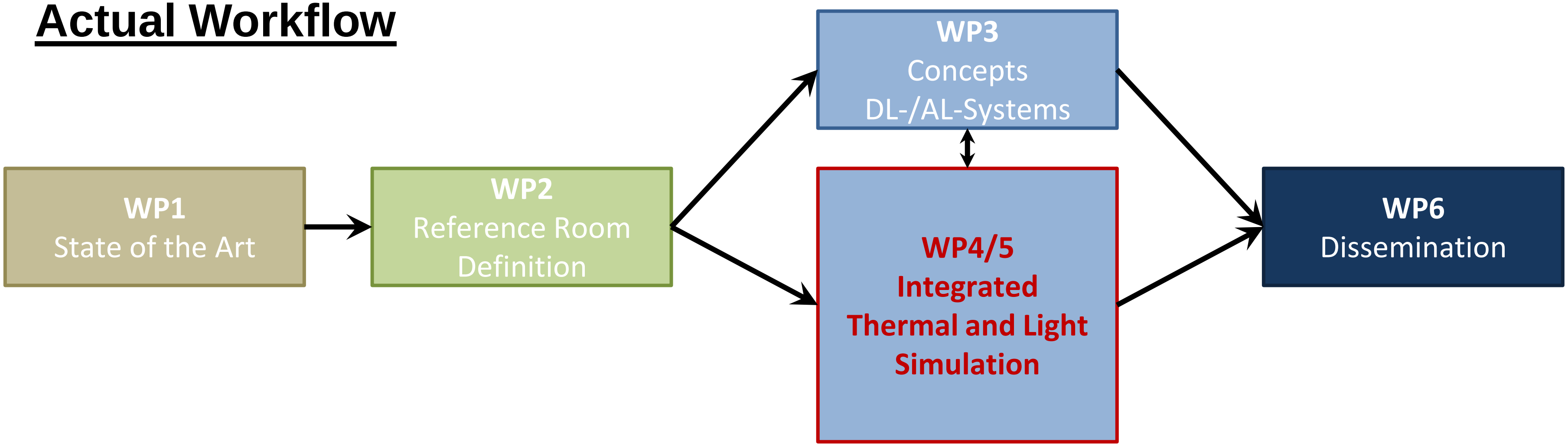
Actual Workflow



Aim of WP 4/5: Integrated Thermal and Light Simulation

- **Light simulations – RADIANCE**
  “Three Phase Daylight Coefficient Method”
- **Thermal simulations – TRNSYS**
  3 approaches (“g-value”, “fc-model”, “abs-approach”)
- **Integrated control – interaction between simulations**
  RADIANCE simulations called from especially defined “Type”

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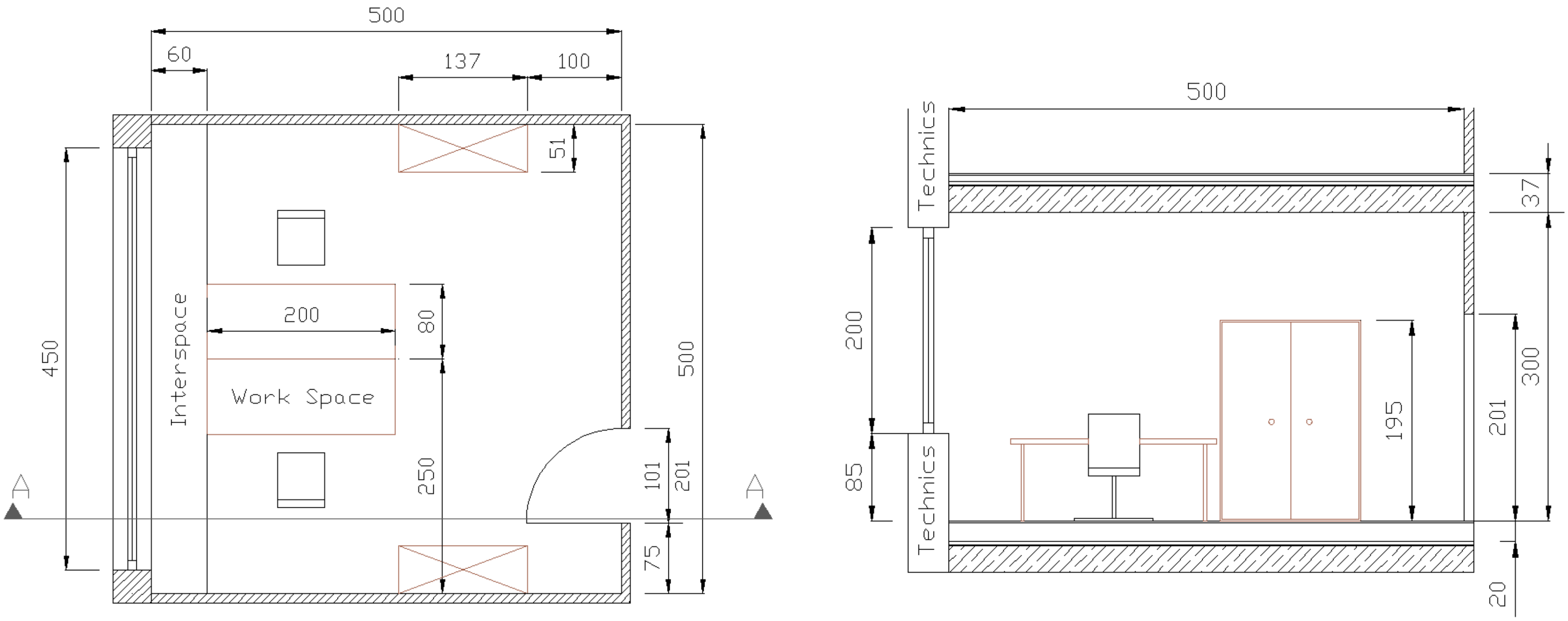
Reference room definition

- adopted from reference room as defined in project "MPPF - Multifunctional Plug & Play Façade"
- operating hours, loads, temperature ranges, … according to SIA 2024



Reference room: dimensions in cm

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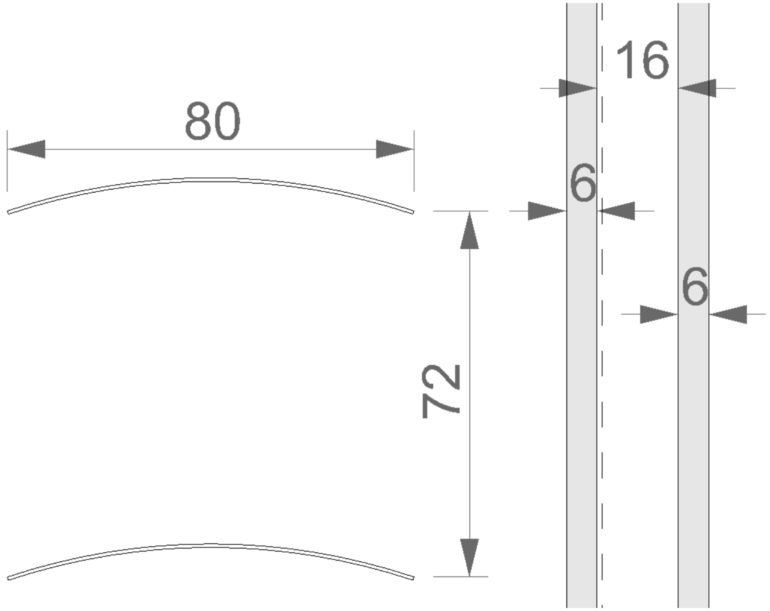
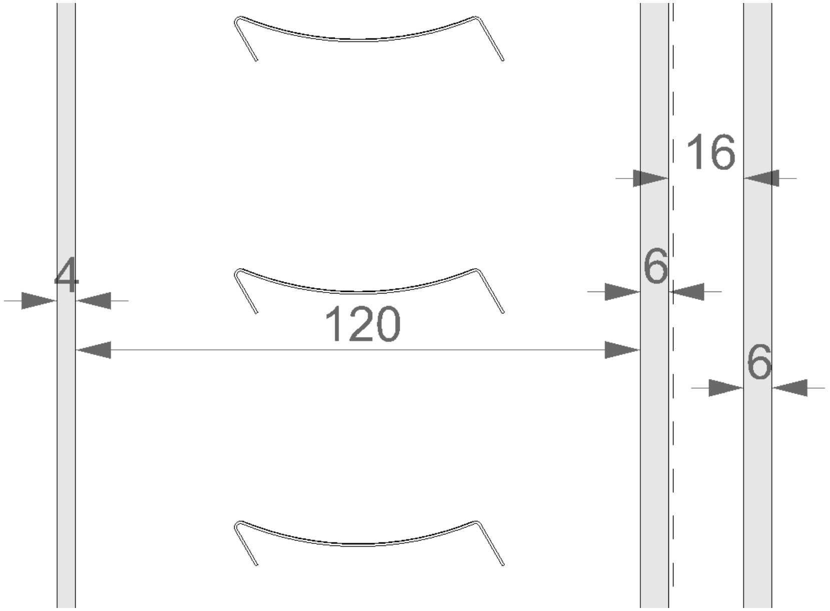
Reference System



- exterior venetian blinds
- diffuse, light gray, ρ = 48%
- double glazing
- 3 tilt angles (0°, 45°, 75°)

"Alar Lamella"



- blinds in casement window, 2 parts
- solid, specular foil, ρ = 91% (up)
- perforated, transmissive foil
  τ = 8.5% (down)
- double glazing + single pane
- 7 tilt angles for each part
  (0°, 15°, 30°, 45°, 60°, 75°, 90°)

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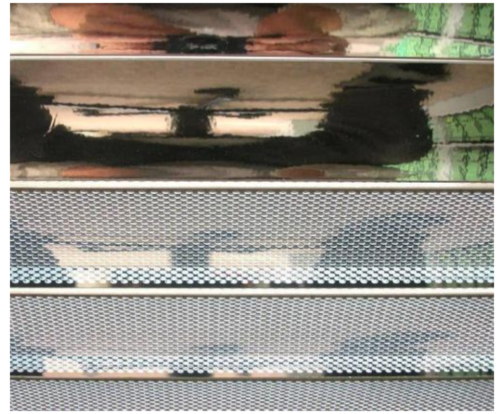
Reference System

Alar Lamella



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RADIANCE Three Phase Daylight Coefficient Method

$$\begin{bmatrix} 1 \\ \vdots \\ n \end{bmatrix} = \begin{pmatrix} 1,1 & \dots & 1,145 \\ \vdots & \ddots & \vdots \\ n,1 & \dots & n,145 \end{pmatrix} \begin{pmatrix} 1,1 & \dots & 1,145 \\ \vdots & \ddots & \vdots \\ 145,1 & \dots & 145,145 \end{pmatrix} \begin{pmatrix} 1,1 & \dots & 1,2305 \\ \vdots & \ddots & \vdots \\ 145,1 & \dots & 145,2305 \end{pmatrix} \begin{bmatrix} 1 \\ \vdots \\ 2305 \end{bmatrix}$$

R	VMX	BSDF	DMX	S
(n x 1)	(n x 145)	(145 x 145)	(145 x 2305)	(2305 x 1)

R ……… Result: Illuminance and luminance values
VMX ….. View Matrix: Contribution of every Klems‘ patch from the interior side of the daylight system (145) to every measurement point
BSDF … Bidirectional Scattering Distribution Function: Function describing the properties of the daylight system (only transmission considered)
DMX …. Daylight Matrix: Contribution of every Reinhart sky patch (2305) to every Klems' patch at the exterior side of the daylight system
S ……… Sky Vector: Luminance of every single Reinhart sky patch

Simulation: pre-calculation: VMX, BSDF, DMX
every time step: S, R (= matrix multiplication)

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RADIANCE Three Phase Daylight Coefficient Method

$$\underbrace{\begin{bmatrix} 1 \\ . \\ . \\ . \\ n \end{bmatrix}}_{\substack{\textbf{R} \\ (n \times 1)}} = \underbrace{\begin{pmatrix} 1,1 & \dots & 1,145 \\ . & . & . \\ . & . & . \\ . & . & . \\ n,1 & \dots & n,145 \end{pmatrix}}_{\substack{\textbf{VMX} \\ (n \times 145)}} \underbrace{\begin{pmatrix} 1,1 & \dots & 1,145 \\ . & . & . \\ . & . & . \\ . & . & . \\ 145,1 & \dots & 145,145 \end{pmatrix}}_{\substack{\textbf{BSDF} \\ (145 \times 145)}} \underbrace{\begin{pmatrix} 1,1 & \dots & 1,2305 \\ . & . & . \\ . & . & . \\ . & . & . \\ 145,1 & \dots & 145,2305 \end{pmatrix}}_{\substack{\textbf{DMX} \\ (145 \times 2305)}} \underbrace{\begin{pmatrix} 1 \\ . \\ . \\ . \\ 2305 \end{pmatrix}}_{\substack{\textbf{S} \\ (2305 \times 1)}}$$

R .... Result: Illuminance and luminance values

VMX ..... View Matrix: Contribution of every Klems' patch from the interior side of the daylight system (145) to every measurement point

BSDF ... Bidirectional Scattering Distribution Function: Function describing the properties of the daylight system (only transmission considered)

DMX .... Daylight Matrix: Contribution of every Reinhart sky patch (2305) to every Klems' patch at the exterior side of the daylight system

S .... Sky Vector: luminance of every single Reinhart sky patch

Simulation: **Pre-Calculation: VMX, BSDF, DMX**
every time step: S, R (= matrix multiplication)

Detailed information on the work flow of the Three Phase DC Method can be found in Andy's excellent tutorial **"Radiance_CFS_Three_Phase_Tutorial.pdf"** on sites.google.com/a/lbl.gov/andy-radiance/cfs-tutorial/, in one of Greg's talks or in Greg's paper [in LEUKOS 7(4), 2011] **"Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance"**.

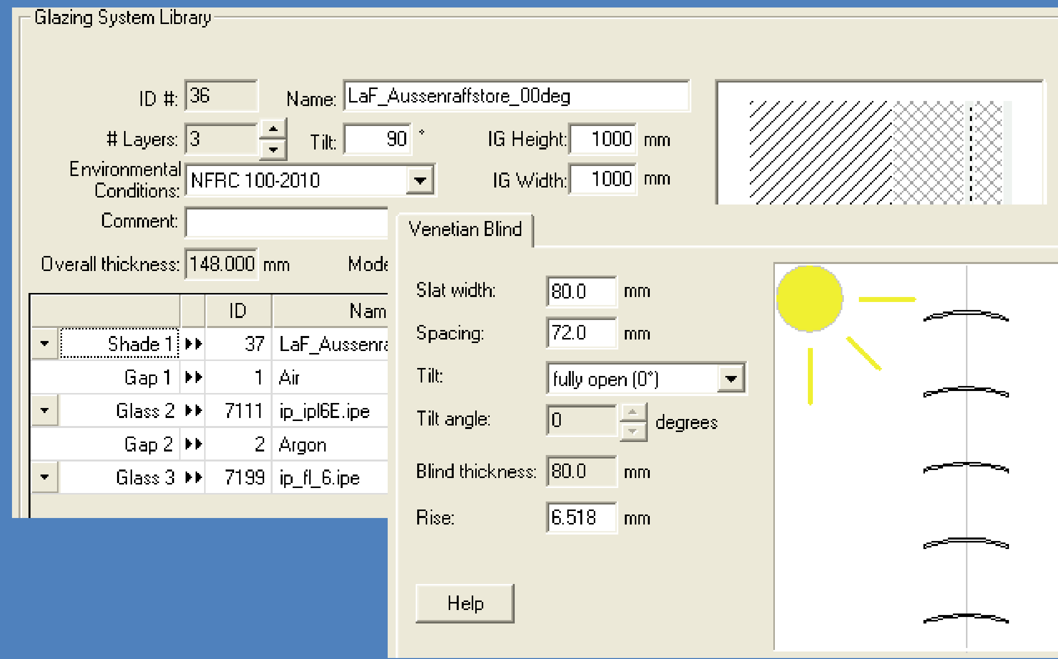
Reference System – Modeling

RADIANCE

```
# Optics5 - Export; optics2rad
void glass GC02-05-pane
0
0
3  0.808  0.872  0.842

GC02-05-pane polygon pane ...
```

```
void plastic gray
0
0
5 0.48 0.48 0.48 0 0

genblinds gray lamella 0.08 1.0 0 1 0 +r 0.126
!xform -t ... -a 15 -t ... -i 1 ...
```

WINDOW 6



ASAP

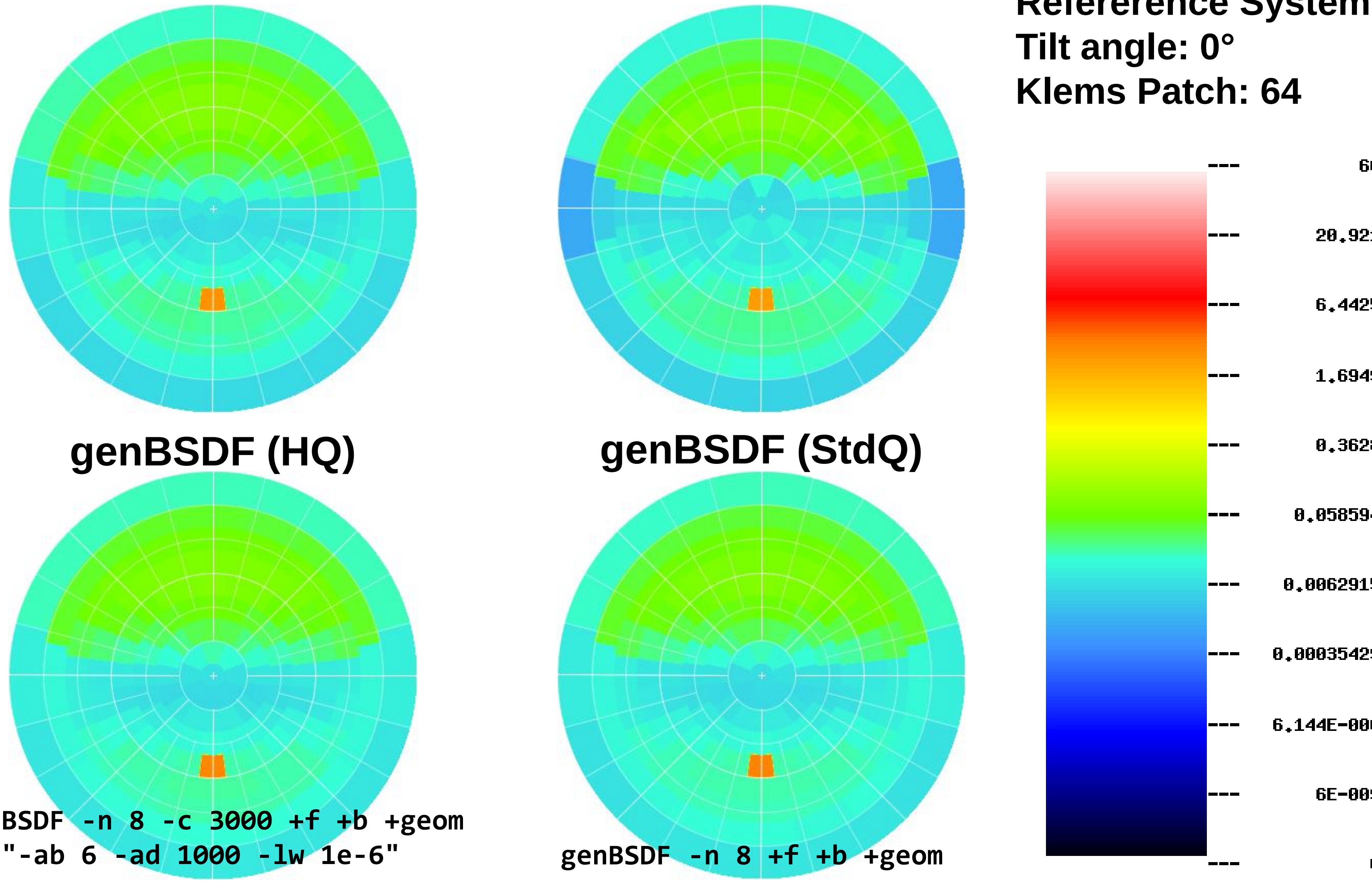
```
LAM_QX=LAM_PX-LAM_THICKNESS*SIN(LAM_AL0)
LAM_QZ=LAM_PZ+LAM_THICKNESS*COS(LAM_AL0)

EDGES
  ARC Y (-LAM_LENGTH/2) (LAM_PZ) (LAM_PX) (LAM_RADIUS) 0 (LAM_AL_DEG)
  SWEEP DIR (LAM_LENGTH) 0 1 0
OBJECT 'LAM.#1.REFL'
  INTERFACE 0 0 AIR AIR
  SCATTER RANDOM (_LAM_RHO) 1
  FRESNEL OFF
```

BSDF Simulation

Refererence System
Tilt angle: 0°
Klems Patch: 64

ASAP | **WINDOW6**

genBSDF (HQ) | **genBSDF (StdQ)**



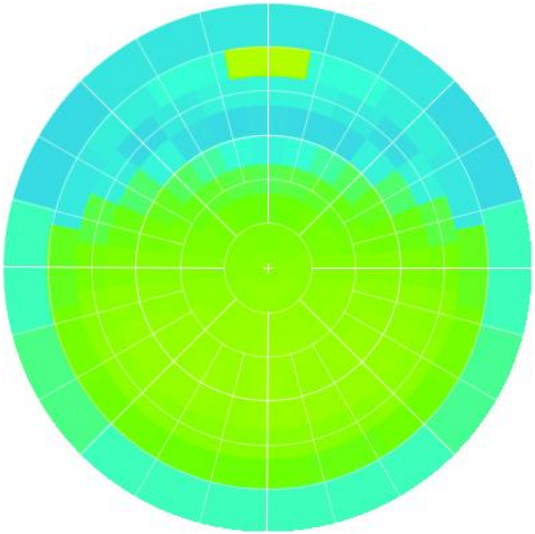

```
genBSDF -n 8 -c 3000 +f +b +geom
-r "-ab 6 -ad 1000 -lw 1e-6"
```

```
genBSDF -n 8 +f +b +geom
```

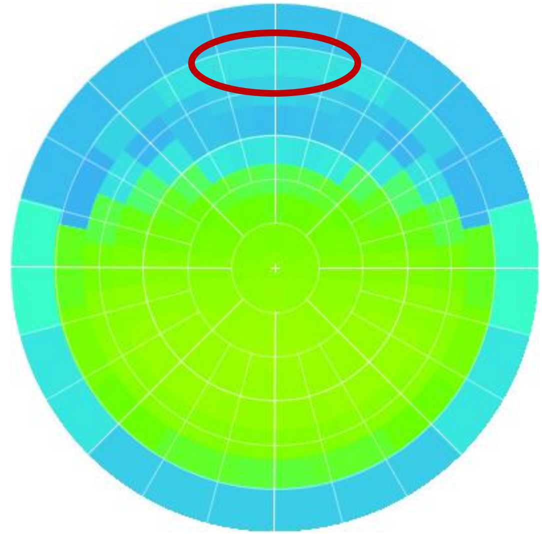
BSDF Simulation

Refererence System
Tilt angle: 45°
Klems Patch: 122

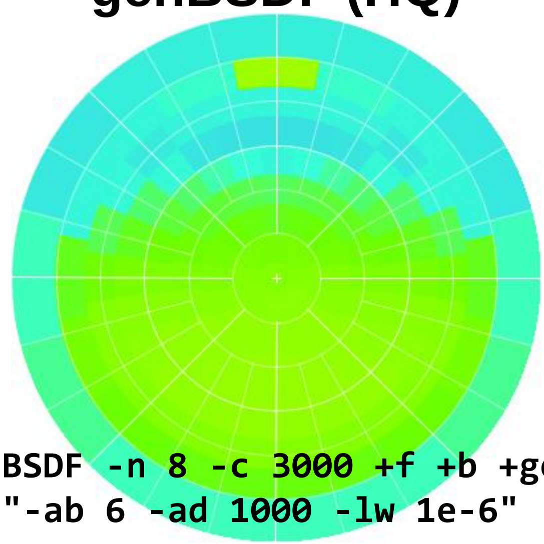
ASAP



WINDOW6

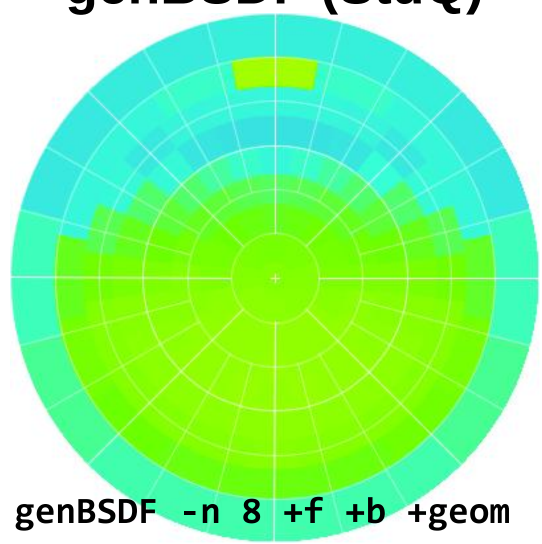


genBSDF (HQ)

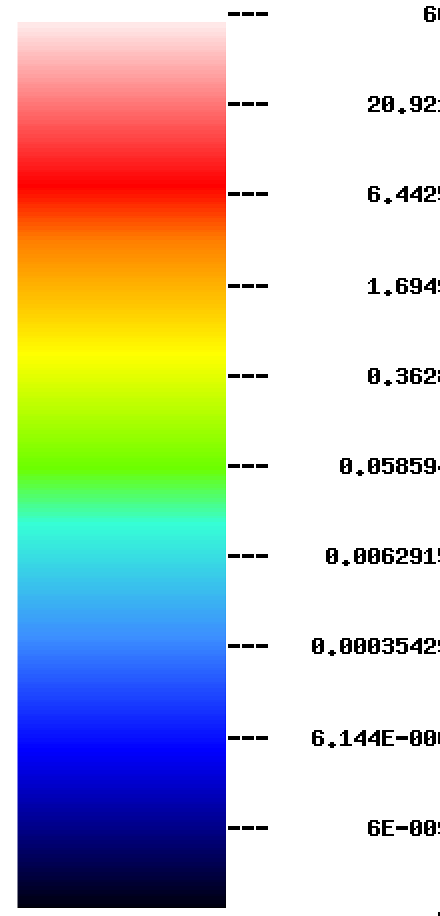


```
genBSDF -n 8 -c 3000 +f +b +geom
-r "-ab 6 -ad 1000 -lw 1e-6"
```

genBSDF (StdQ)



```
genBSDF -n 8 +f +b +geom
```



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Alar Lamella, specular part – Modeling

WINDOW 6

X

RADIANCE

```
# Optics5 - Export; optics2rad
void glass GC02-05-pane
0
0
3 0.808  0.872  0.842

GC02-05-pane polygon pane_in ...
```

```
void glass ip-fl-4
0
0
3 .965  0.985  0.976

ip-fl-4 polygon pane_out ...
```

```
void mirror m_up
0
0
3 0.91 0.91 0.91
```

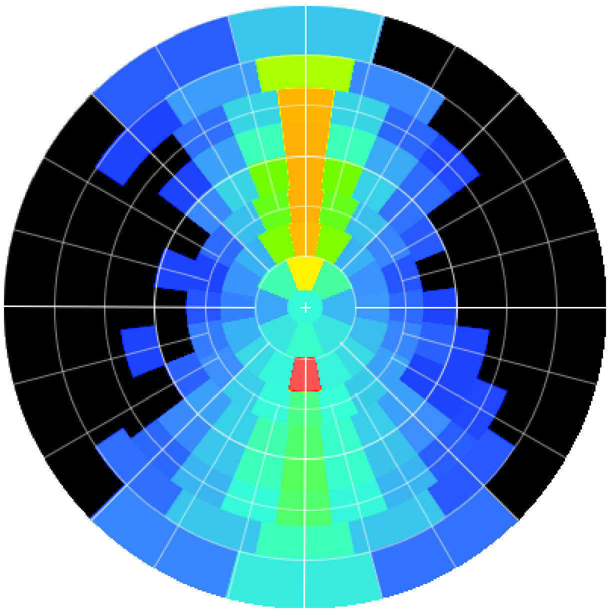
```
void metal m_back
0
0
5 0.83 0.83 0.83 0.999 0.05
```

```
gensurf m_up lam_up up.txt up.txt up.txt 150 1 -s > lam_up.rad
gensurf m_back lam_back back.txt back.txt back.txt 150 1 -s > lam_back.rad
```

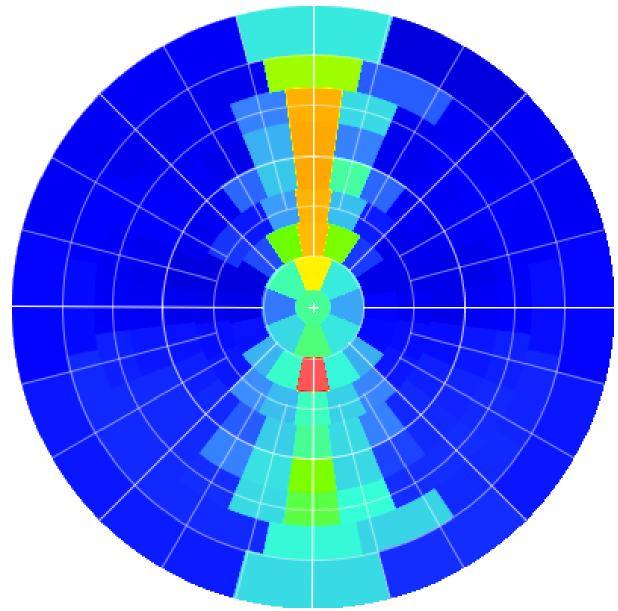
ASAP

```
  LINE  26.12583    4.244056    0.000000    31.09105    -4.355944    0.000000
  LINE  31.09105   -4.355944   0.  30.65803   -4.605944   0.
  COMPOSITE GAP -1
  ROTATE X 90 2@0
  SHIFT 0 (-LAM_L/2) 0
  SWEEP DIR (LAM_L) 0 1 0
OBJECT 'LAM.#1.REFL'
  INTERFACE COATING ALU
  ROUGHNESS MODEL 1
  FRESNEL OFF
```

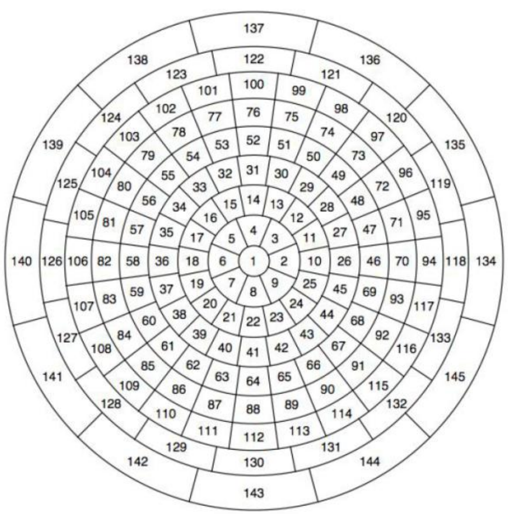
ASAP

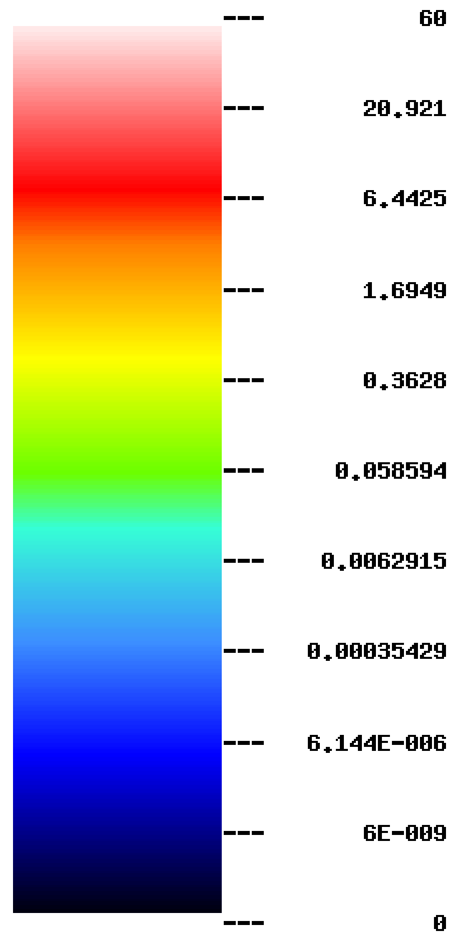


genBSDF



Alar Lamella
Tilt angle: 0°
Klems Patch: 122






```
genBSDF -c 3000 -n 8 +f -b -mgf
-geom -dim -0.5 0.5 500.0 553.6
-57.4 0
```

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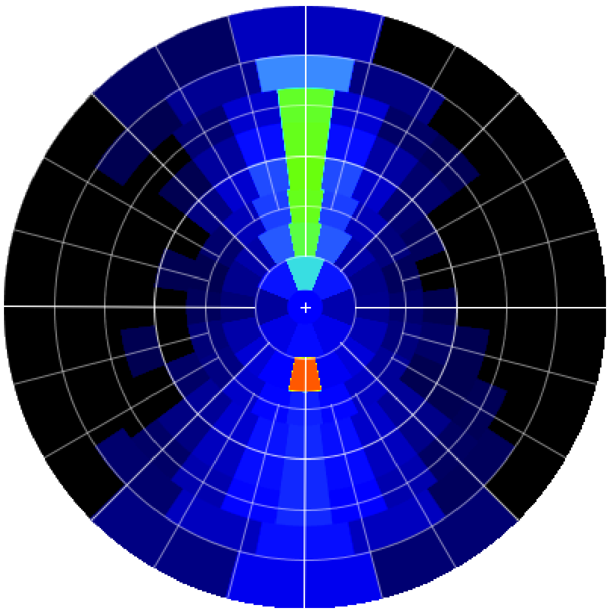
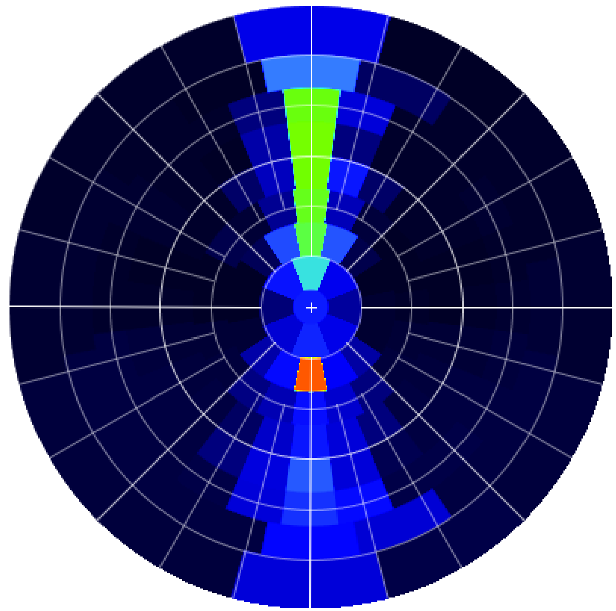
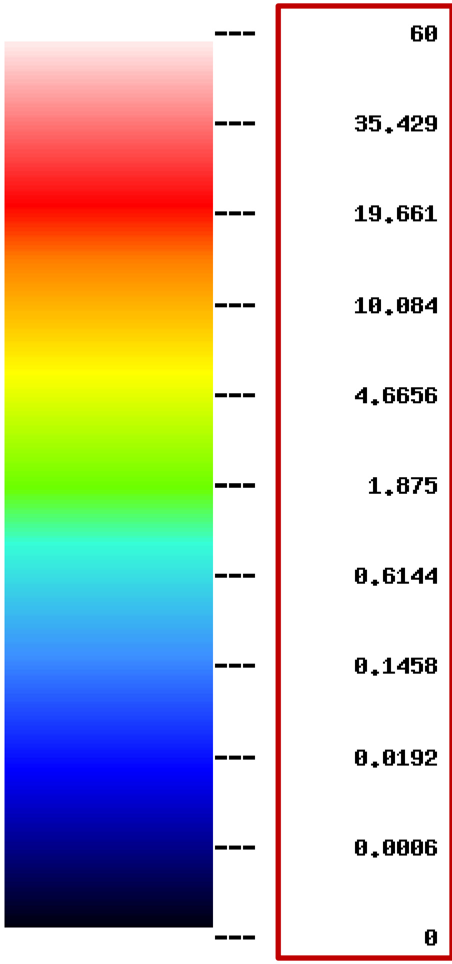
ASAP



genBSDF



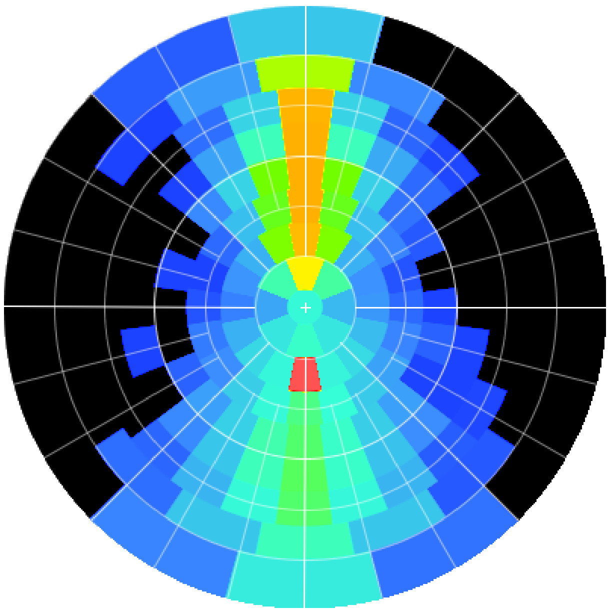
Alar Lamella
Tilt angle: 0°
Klems Patch: 122



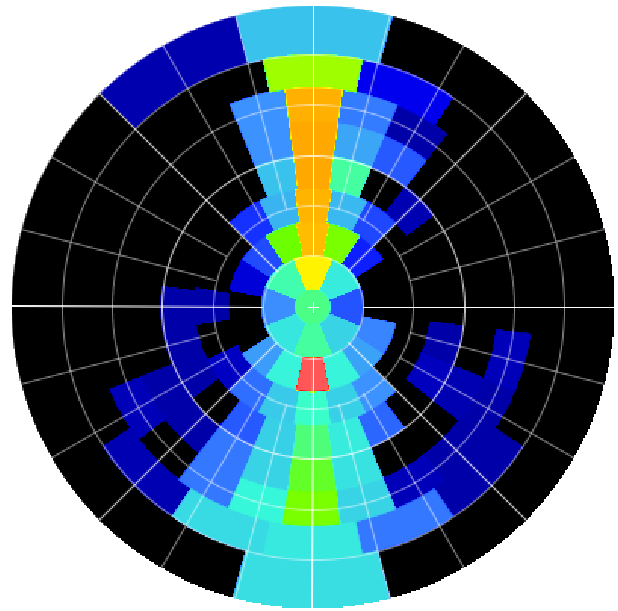
Solution 1:
change the scale …

```
genBSDF -c 3000 -n 8 +f -b -mgf
-geom -dim -0.5 0.5 500.0 553.6
-57.4 0
```

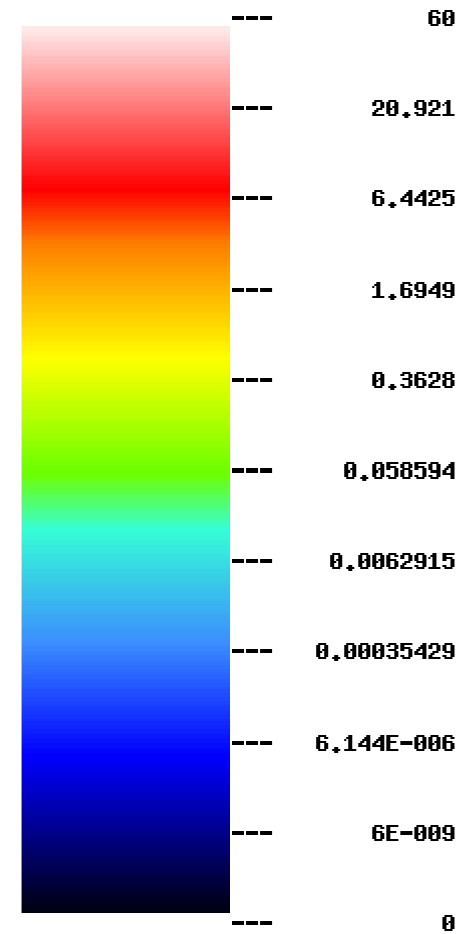
ASAP



genBSDF



Alar Lamella
Tilt angle: 0°
Klems Patch: 122



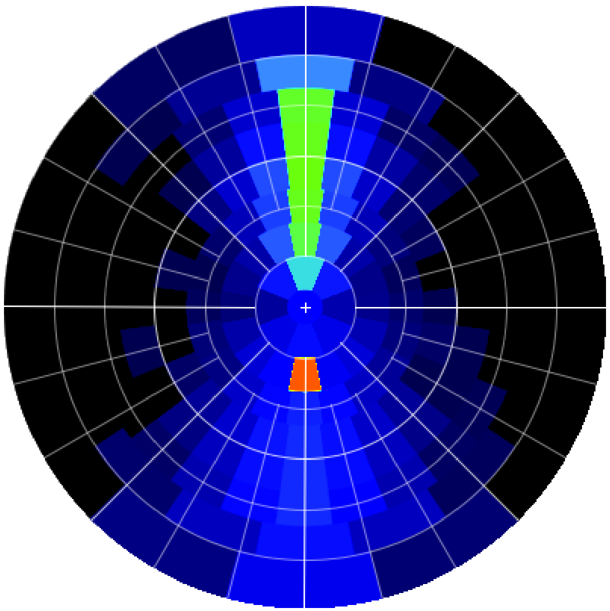
Solution 2:
change the material …

```
void metal m_back
0
0
5 0.83 0.83 0.83 0.999998 0.05
```

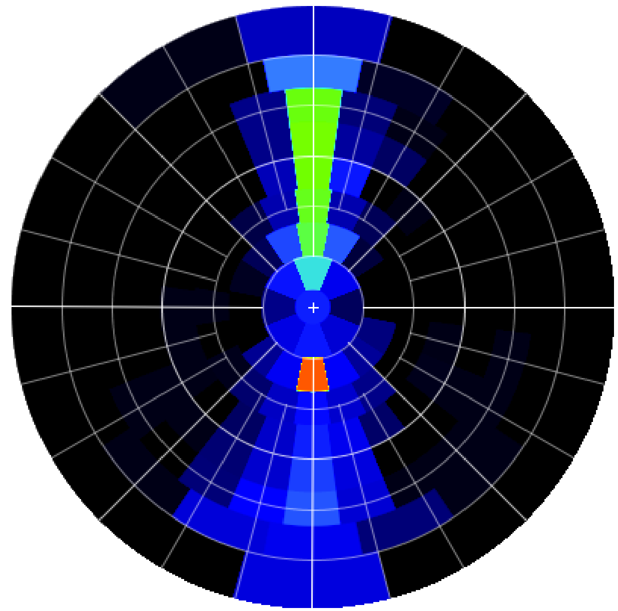
in rt/normal.c:

```
                                        /* diffuse reflection */
    nd.rdiff = 1.0 - nd.trans - nd.rspec;

    if (nd.specfl & SP_PURE && nd.rdiff <= FTINY && nd.tdiff <= FTINY)
        return(1);                      /* 100% pure specular */

    if (!(nd.specfl & SP_PURE))
        gaussamp(r, &nd);               /* checks *BLT flags */
```

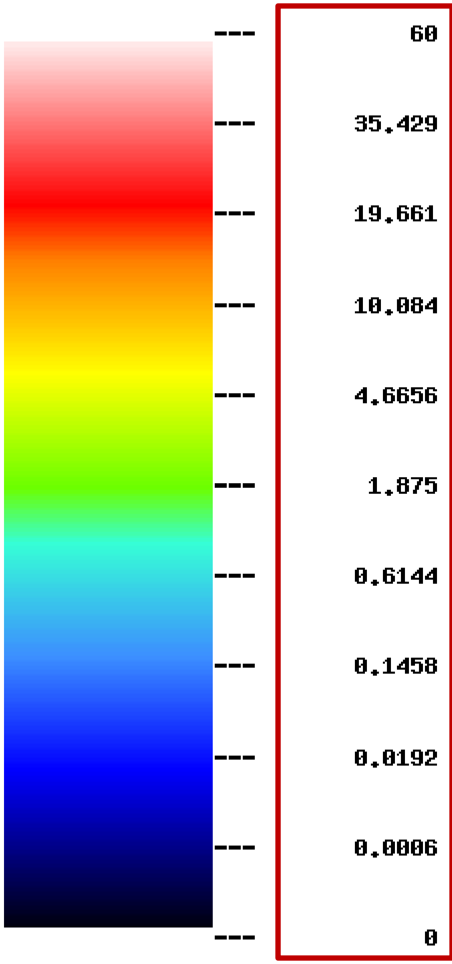
ASAP



genBSDF



Alar Lamella
Tilt angle: 0°
Klems Patch: 122



Solution 3:
change both …

```
void metal m_back
0
0
5 0.83 0.83 0.83 0.999998 0.05
```

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Three approaches to model thermal behavior (solar transmission and secondary heat flux) of daylight systems in TRNSYS:

"g-model": measured / simulated angular dependent SHGC (g-Value) $g_{total}(\varphi,\gamma)$ of overall system

"Fc-model": angular dependent "shading factor" of daylight system

$$Fc(\varphi,\gamma) = \frac{g_{total}(\varphi,\gamma)}{g_{window}(\varphi,\gamma)}$$

"Abs-model": Layer model with angular dependent

- absorption $\alpha(\varphi,\gamma)$
- transmission $\tau(\varphi,\gamma)$

and emission coefficients ε

For all approaches energy input through the system is separately calculated for beam, sky, and ground radiation.

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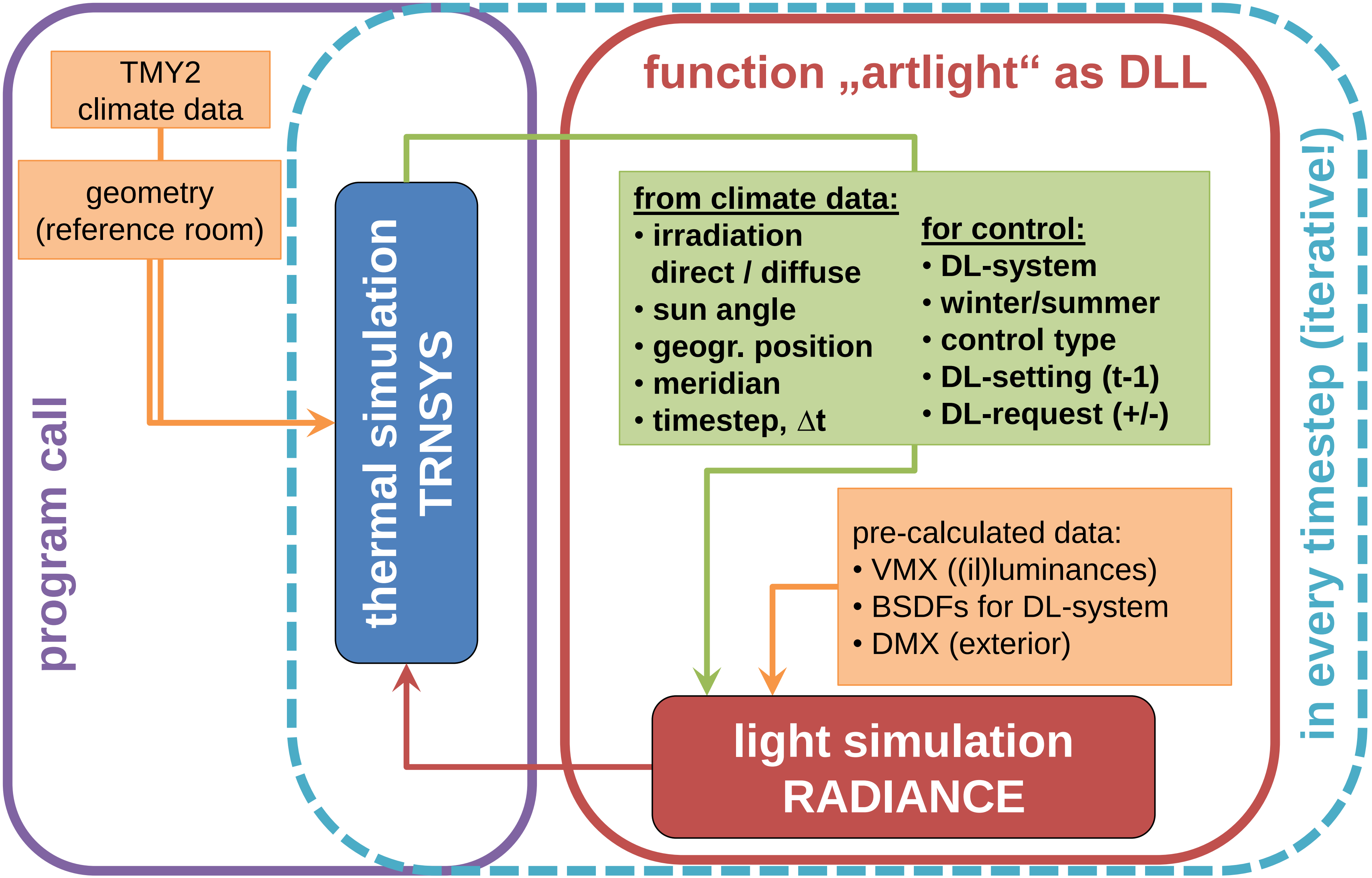
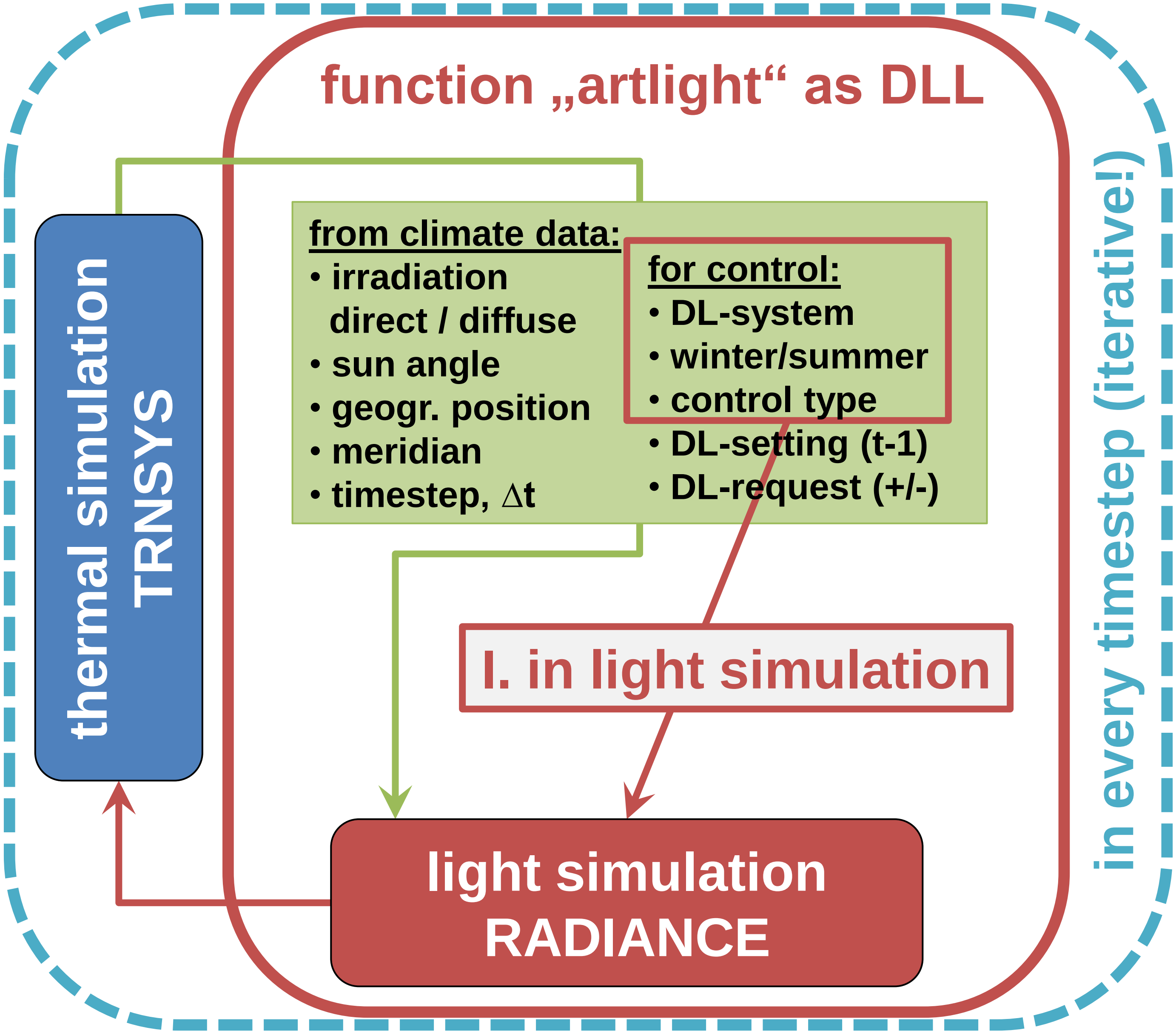


various control strategies possible:

e.g.:
- seasons
- light optimized (no TRNSYS interaction)
- energy optimized (full TRNSYS control)
- combined (thermal requests, light standards)
- …



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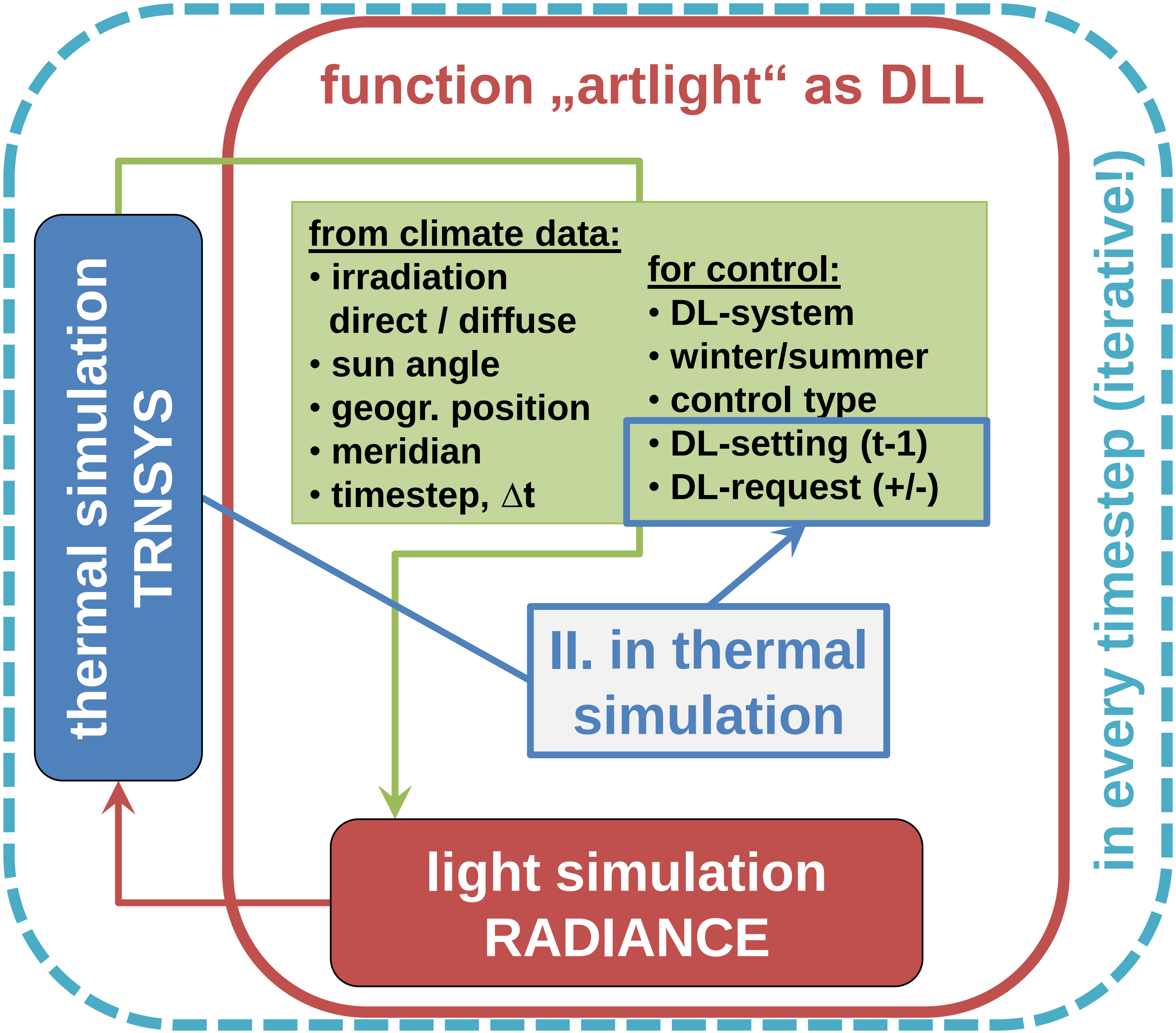
control from TRNSYS:

- iteration within timestep
- request for more/less gains
- depending on light control



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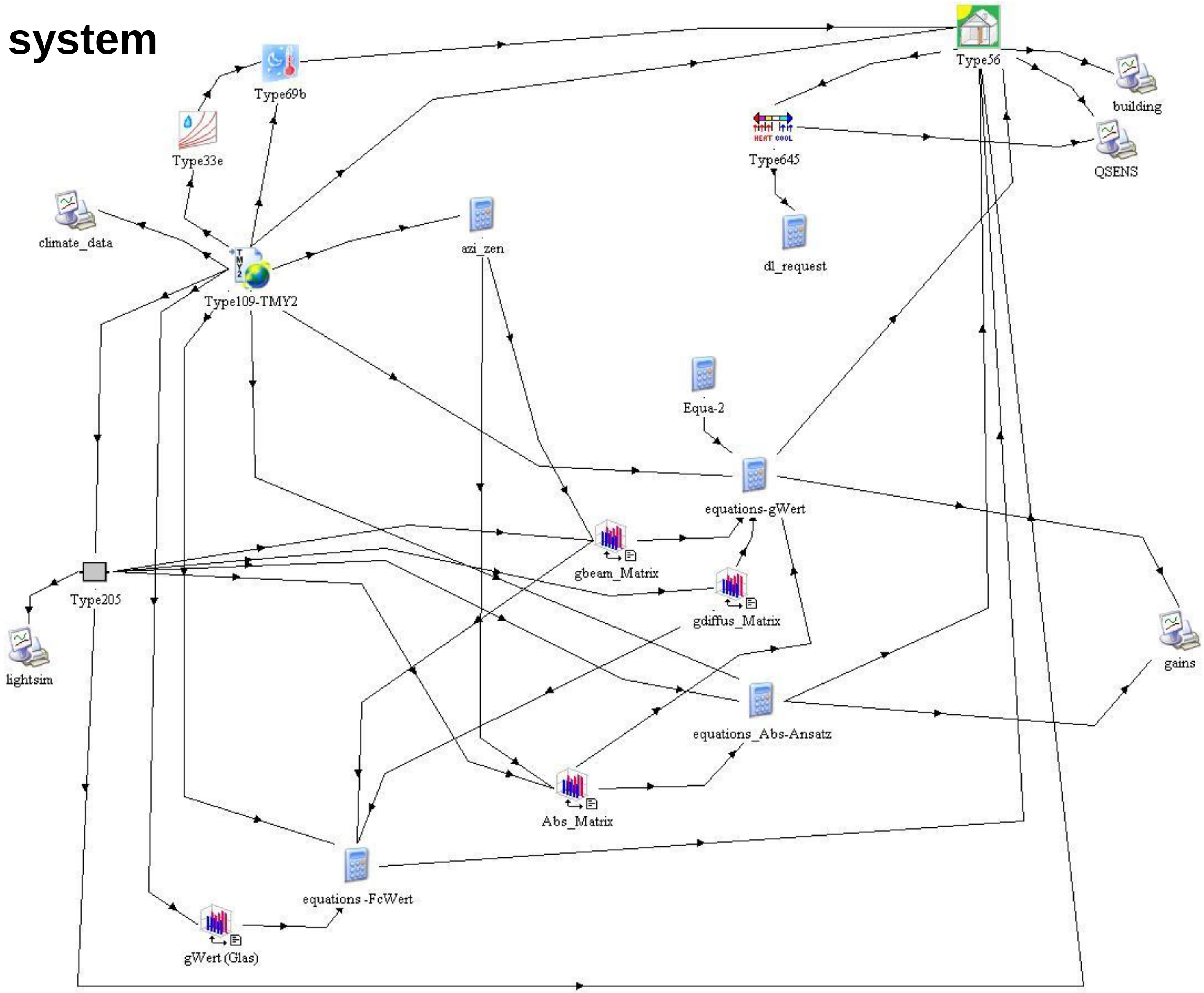
Reference system



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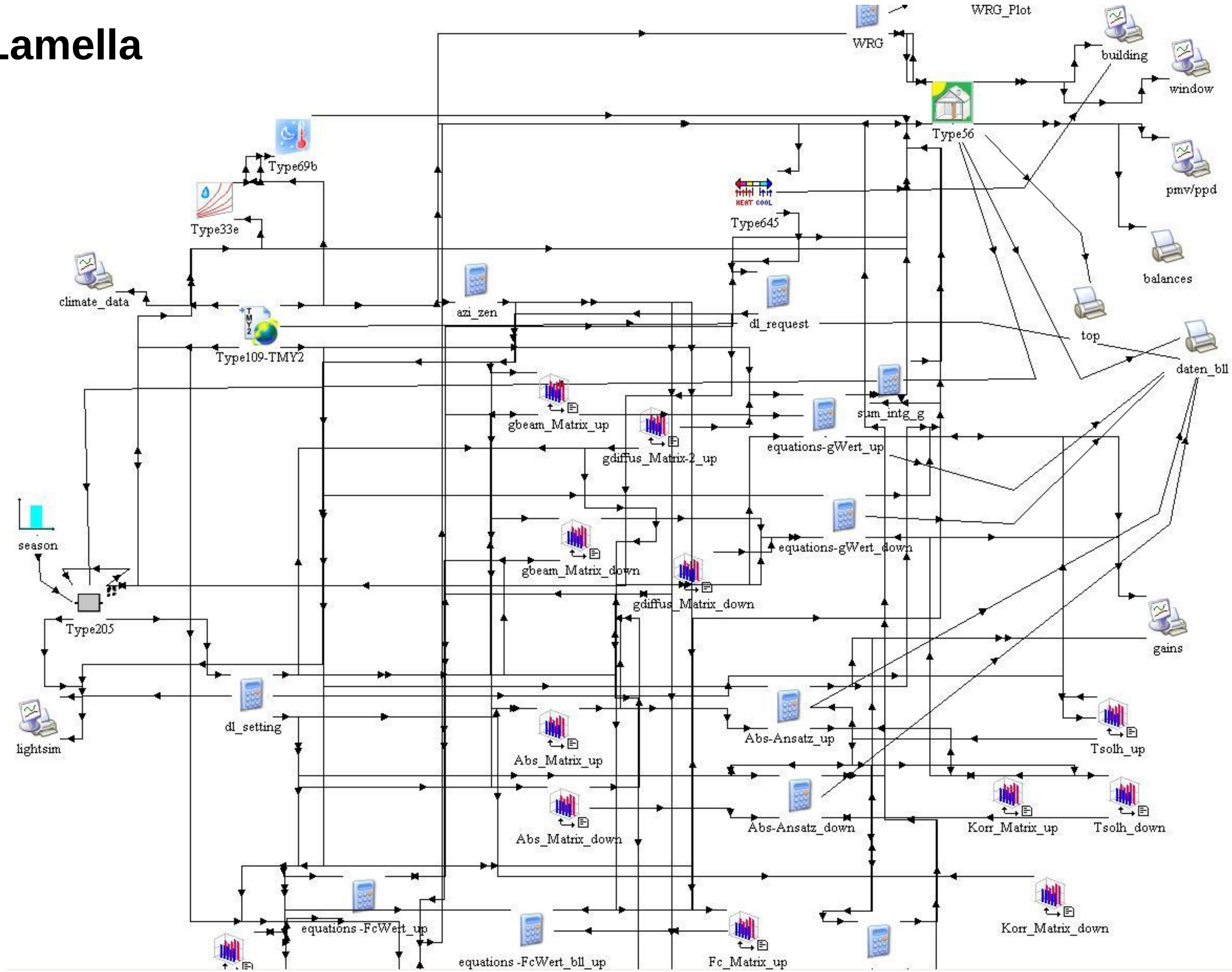
Alar Lamella



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Function call of „artlight“ (in DLL) from TRNSYS
→ RADIANCE simulations wrapped up in Python script artlight.py

FORTRAN 77

python™

artlight.py

Input

Phi_e_direct	irradiance direct-horizontal [W/m^2]
Phi_e_diffuse	irradiance diffuse-horizontal [W/m^2]
sun_gamma	sun altitude [deg] (horizon = 0, zenith = 90)
sun_phi	sun azimuth [deg] (N = 0, E = 90, S = 180, W = 270)
pos_gamma	position altitude [deg] (N = +)
pos_phi	position azimuth [deg] (E = +)
meridian	meridian [deg] (E = +)
season	winter = 0 / summer = 1
sim_time	simulation time ((60.0/dt) -- 8760.00)
time_delta	dt, length time step [min] (e.g. 5, 10, 30, or 60)
control	flag control strategy
dl-system	flag daylight system (1, 2, 3)
dl-setting	flag daylight system setting (integer)
dl-request	flag thermal request to daylight system (-1, 0, 1)

Output (in file result.tmp)

artlight	internal load [W/m^2] (-1 if error)
dl-setting	flag daylight system setting (integer)

Return values

0	simulation ok
1	same dl-setting as given as argument
-1	radiation or sun azimuth < 0
-2	control error
-3	gendaylit error
-4	genskyvec error
-5	dctimestep error

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Workflow of the light simulations in “artlight.py”

RADIANCE Three Phase DC Method

1. **light control – *dl_system.py***
   in: input from TRNSYS (irradiance, sun angle, time, daylight system, …)
   out: daylight system setting → BSDF for each part of the system
2. **generate Perez sky – *gendaylit***
   in: irradiance direct/diffuse, sun angle
   out: sky luminance distribution, sun description
3. **discretize sky into patches – *genskyvec***
   in: Perez sky luminance distribution, sun description
   out: luminances for sky patches (Tregenza [145] or Reinhart [580/2305])
4. **matrix multiplication for each part of the daylight system - *dctimestep***
   in: sky vector, pre-calculated DMX, BSDF, and VMX
   out: grid luminances L_i / illuminances E_i
5. **sum up results of single parts of the daylight system**
   in: luminances L_i / illuminances E_i
   out: overall luminances L / illuminances E
6. **calculated required artificial light and resulting internal gains**
   in: illuminance E
   out: internal gains caused by artificial light

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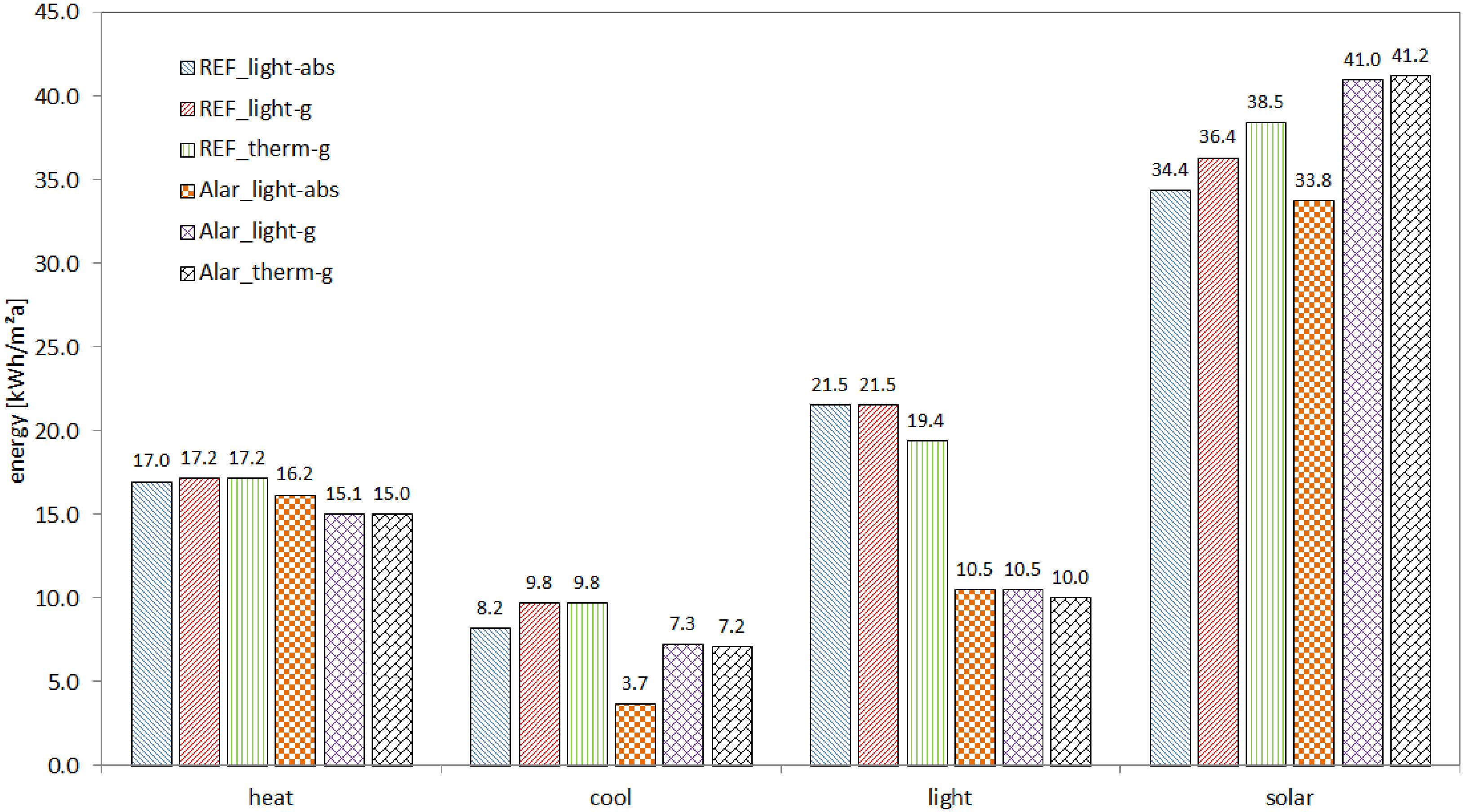
Annual energy balance



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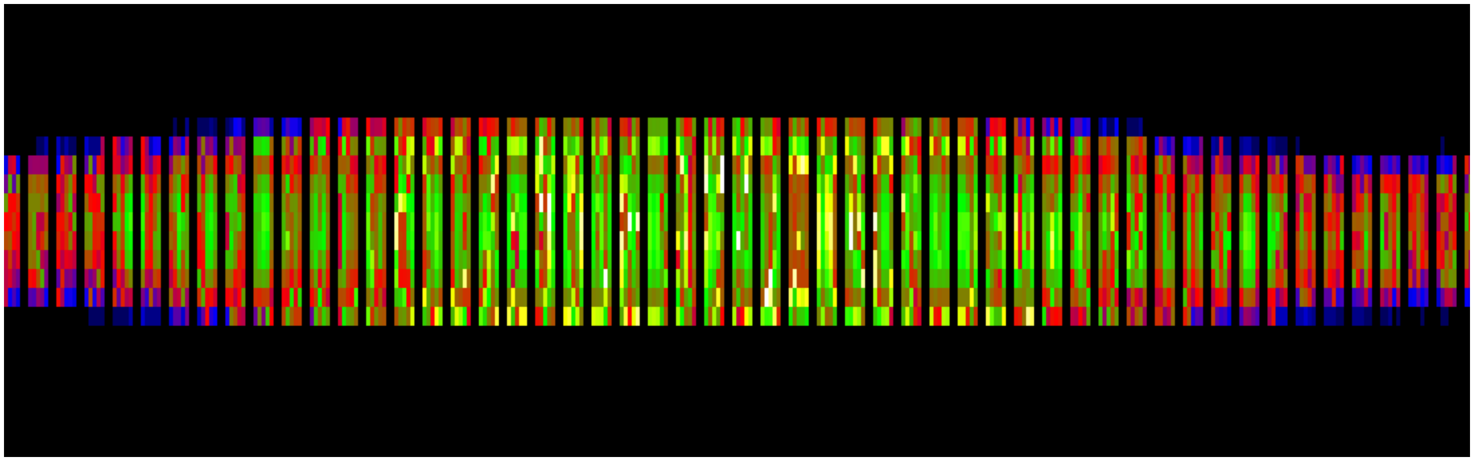
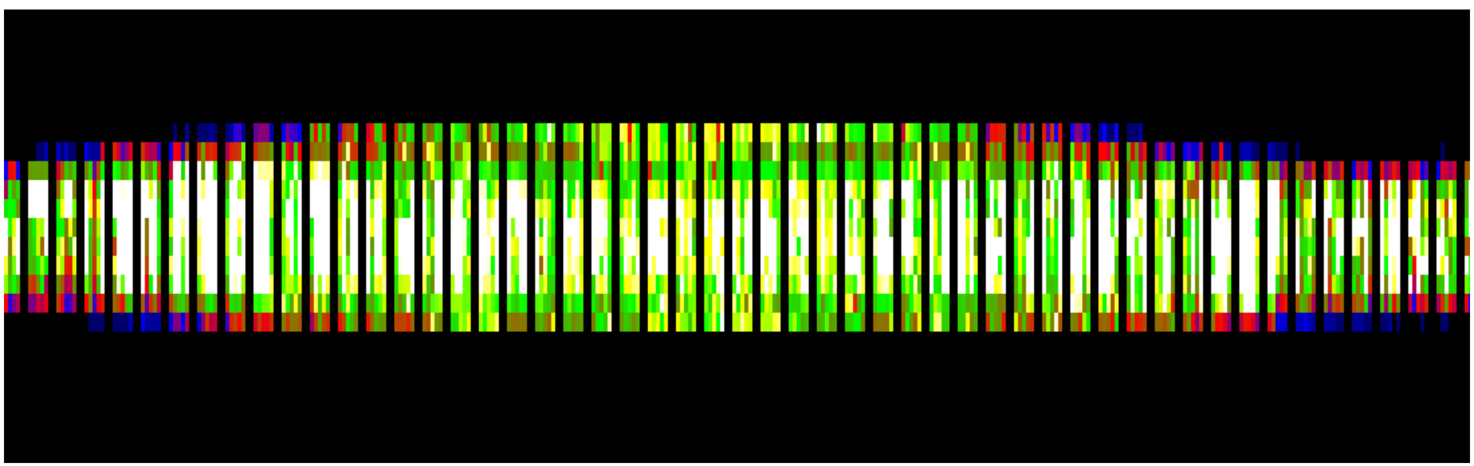
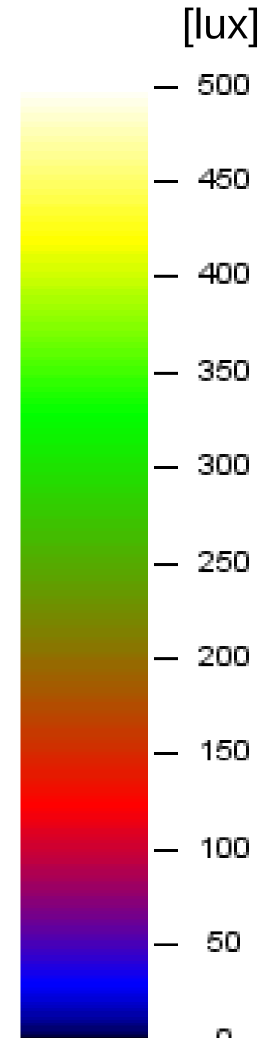
Mean illuminance on workplane during office hours



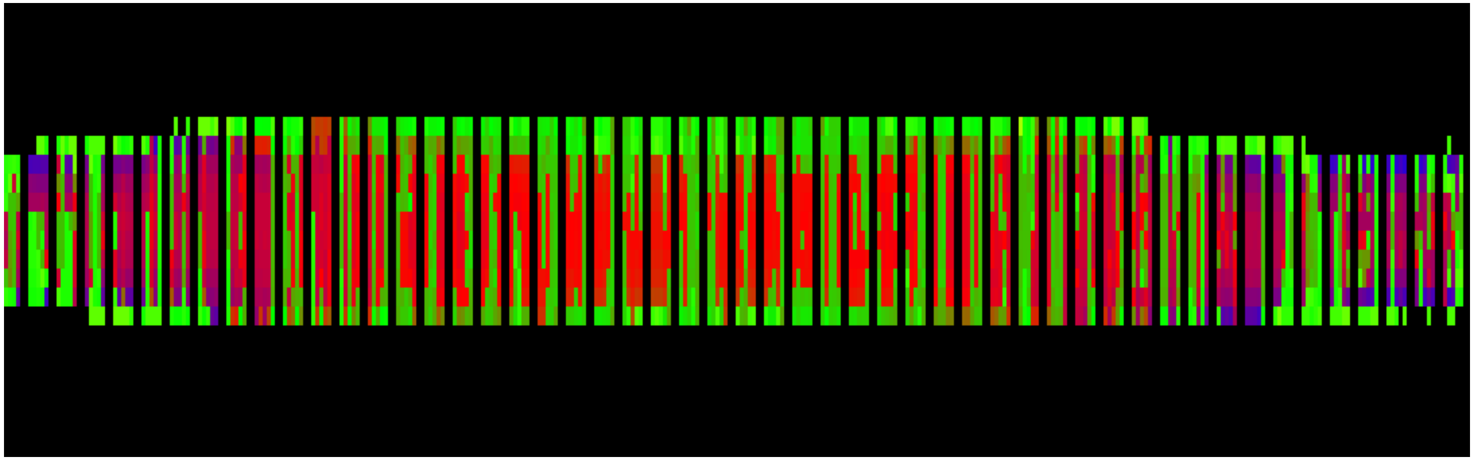
Reference system (venetian blinds)



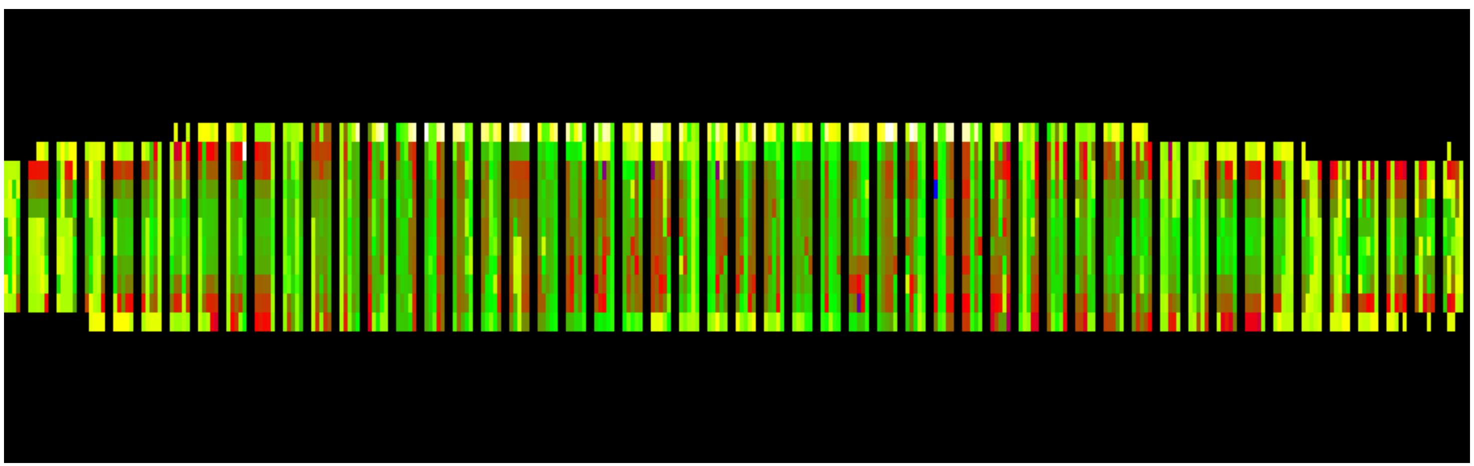
„Alar Lamella“



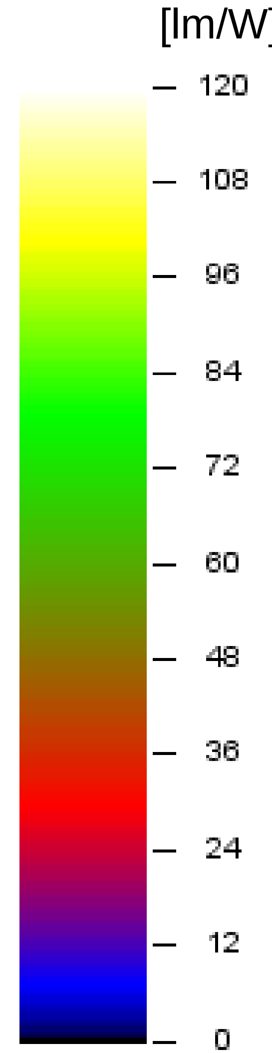
“Luminous efficacy”of daylight system



Reference system (venetian blinds)



„Alar Lamella“



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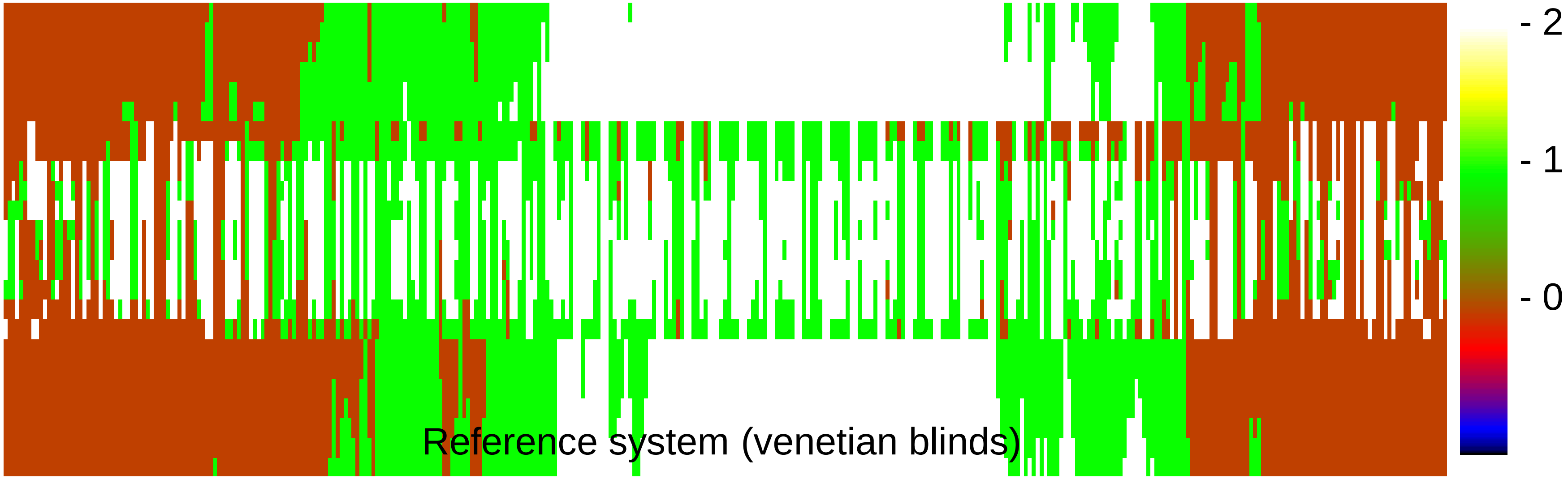
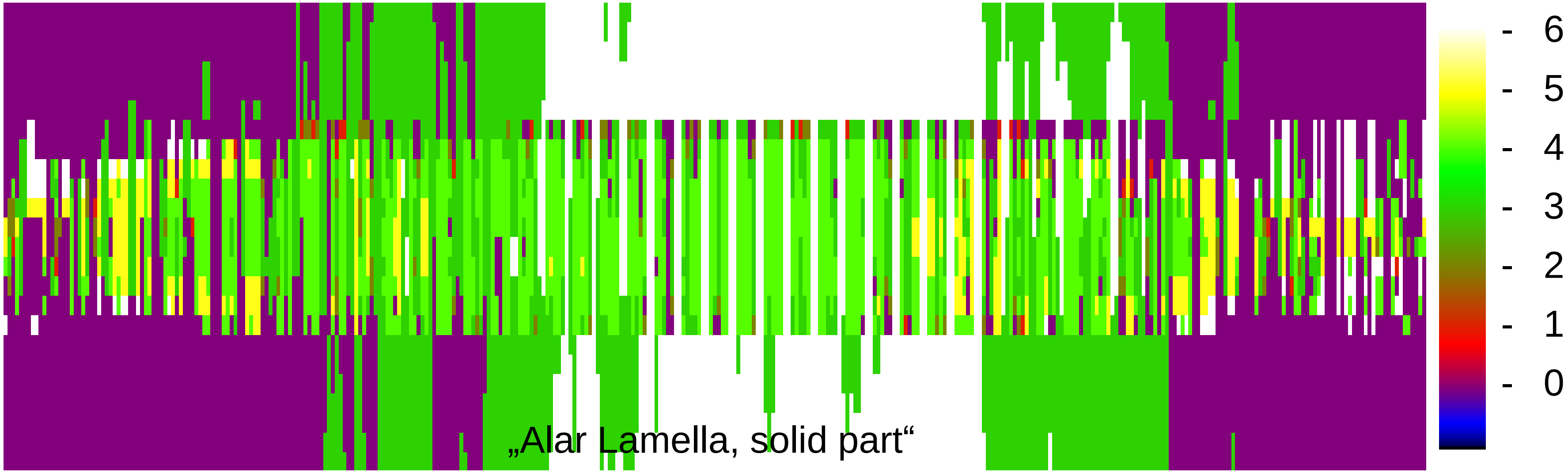
Settings of daylight systems



Reference system (venetian blinds)



„Alar Lamella, solid part“

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Consortium:

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M. Hauer, D. Neyer, D. Geisler-Moroder, C. Knoflach, W. Streicher and W. Pohl, “Combined Thermal and Light Simulation Method for Daylight Utilization” ISES Solar World Congress, 28 August – 2 September 2011, Kassel, Germany.

Thanks for your attention!

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