Deciduous Trees in Climate-based Daylight Simulations

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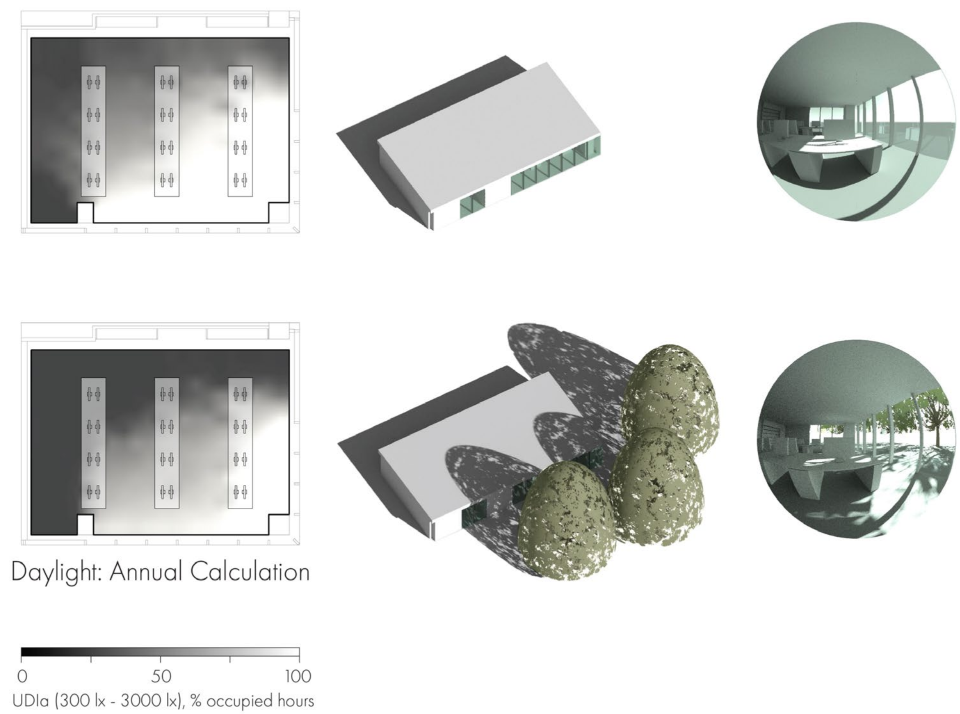


Impact of Trees

Benefits of Urban Trees

- **Environmental** (Heat island mitigation, shade, air cooling, and decreasing wind speed)
- **Economic** (lower energy consumption through passive heat gains and cooling load reduction)
- **Social and psychological**

In Building Performance Simulation

- Urban landscape trees can dramatically **reduce energy demand** in buildings
- Tree integrated simulation tools allows designers to assess and maximize **daylight availability**, **reduce glare** problems, and contribute to **passive heat gains and cooling load reduction**

Current Practice: Lighting

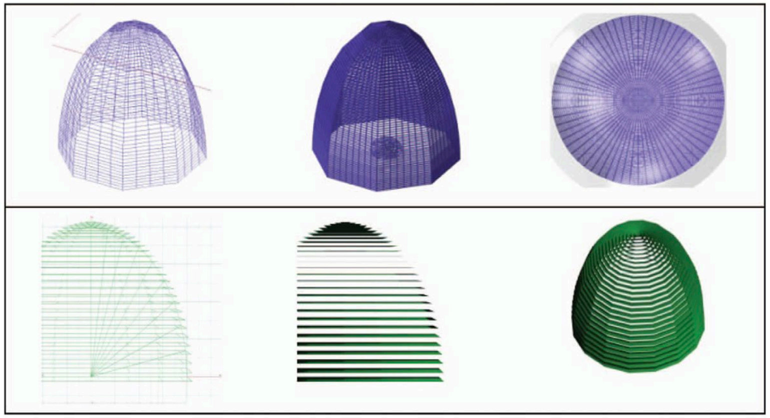
```
void trans tree_trans_only
0
0
7 1 1 1 0 0 0.45 1
```

19 % transmittance
55.3% reflectance

```
void trans tree_trans_reflect
0
0
7 0.28 0.7 0.37 0 0 0.8 1
```

19 % transmittance
11.3% reflectance

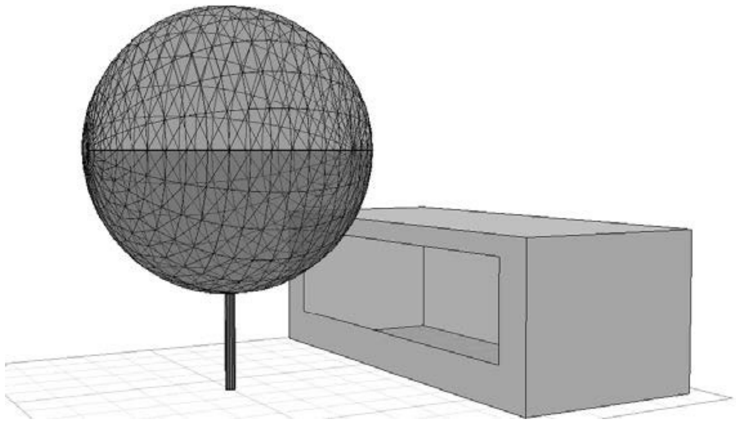
Priji Balakrishnan, & Jakubiec, J. A. (2015). *Quantifying Materials in Lighting Simulations*.



Al-Sallal, K. A., & Al-Rais, L. (2013). A novel method to model trees for building daylighting simulation using hemispherical photography. Journal of Building Performance Simulation, 6(1), 38–52. https://doi.org/10.1080/19401493.2012.680496

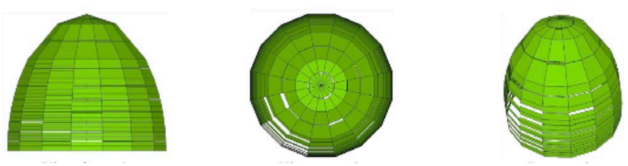
- Simulations simplify trees which are modelled as opaque geometries or with a uniform transmittance coefficient
- Various novel methods have been investigated such as mesh surfaces and louvred representations
- The IES Daylight Metrics Committee recommends that trees should be modelled as opaque solids with a reflectance of 20%
- Lighting simulation standards often do not provide guidance on modelling trees

Current Practice: Thermal

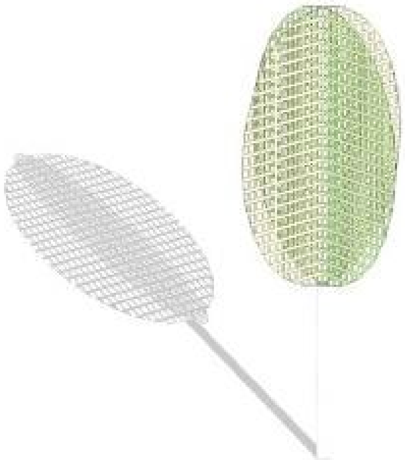


Szkordilisz, F., & Kiss, M. (2016). Passive cooling potential of alley trees and their impact on indoor comfort. Pollack Periodica, 11(1), 101–112. https://doi.org/10.1556/606.2016.11.1.10

- Methods similar to daylight models are used; opaque geometries or with a uniform transmittance coefficient.
- Other methods have been investigated such as intersecting planes, gap insertion method
- Tree models are derived with field measurements or collected literature
- Tree phenology schedules are sometimes used (see Simpson and McPherson)



Lima, E. de F. C., & Leder, S. M. (2017). Medição e modelagem simplificada da vegetação para simulação digital da iluminação natural. Ambiente Construído, 17, 233–252. https://doi.org/10.1590/s1678-86212017000400195

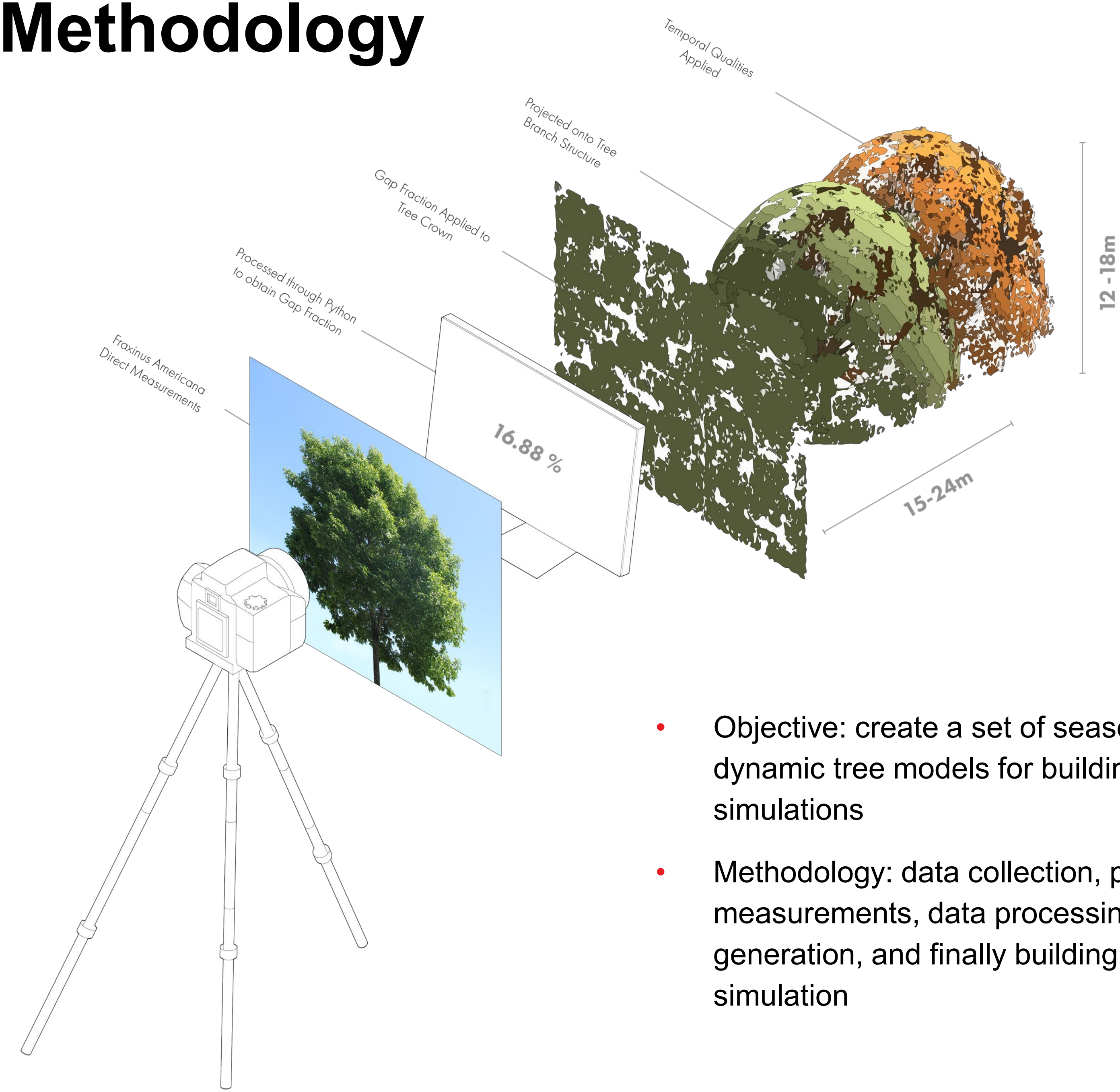


Hes, D., Dawkins, A., Jensen, C., & Aye, L. (2011). *A Modelling Method to Assess the Effect of Tree Shading for Building Performance Simulation*. 9.

Gaps in Current Practice

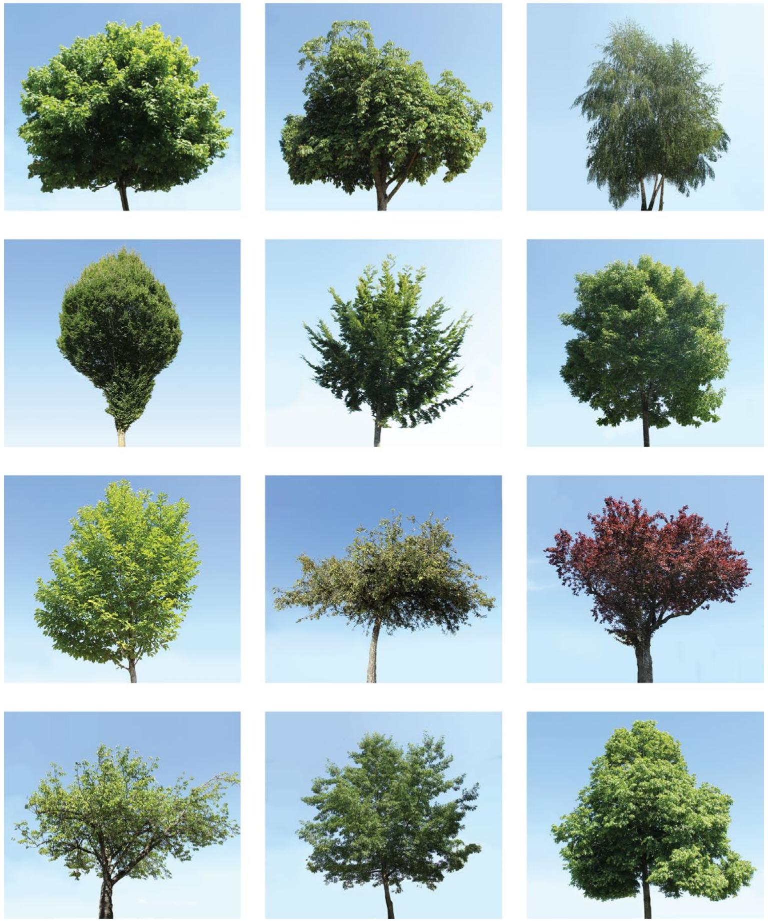
- Trees are formally complex, resulting in fluctuating light transmittance phenomena that vary with solar position and weather
- Deciduous trees are sophisticated due to tree phenology and leaf senescence that impact their foliage density and colour throughout the year
- These variable temporal effects of trees are often estimated or entirely ignored

Methodology



- Objective: create a set of seasonally varying, dynamic tree models for building performance simulations
- Methodology: data collection, physical measurements, data processing, model generation, and finally building performance simulation

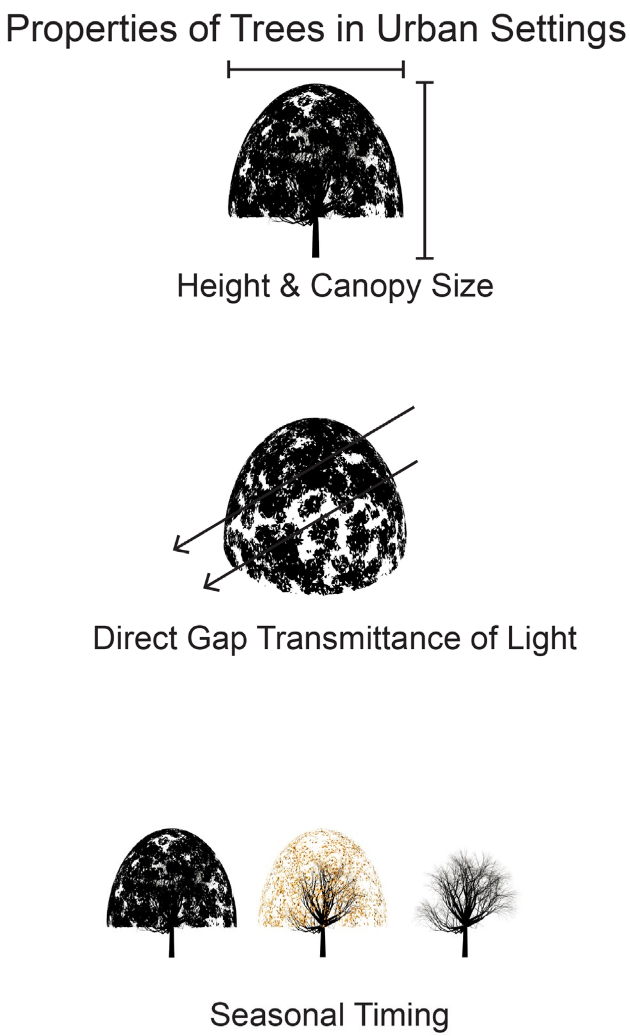
Tree Selection



- The twelve most common deciduous street trees in Vancouver, Canada were selected from the City of Vancouver Open Data Portal's Street Trees dataset.

Acer platanoides, Aesculus hippocastanum, Betula pendula, Carpinus betulus, Fagus sylvatica, Fraxinus americana, Magnolia kobus, Malus floribunda, Prunus cerasifera, Prunus serrulata, Quercus palustris, and Tilia x euchlora.

Data Collection and Scheduling



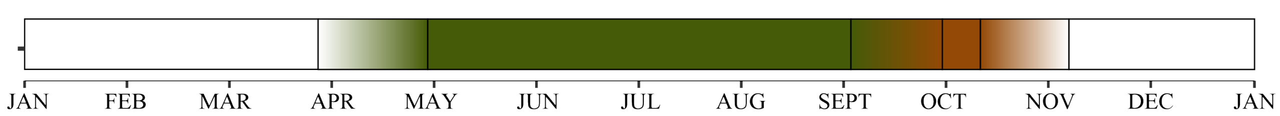
- Complex phenological properties of trees differ due to climate, changes in temperature, soil quality, and location
- The temporal schedules (timing of tree colour change, leaf drop, and leaf regrowth) were collected based on limited available data and used to create tree models
- Ranges on tree height and canopy sizes were collected

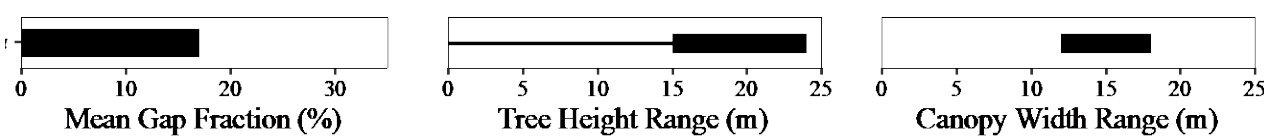
Example Goal (and Eventual Result)
Fraxinus americana / White Ash

Fraxinus Americana

Gap Transmittance =16.88 %
Dimensions
h = 15-24 m
w = 18 m

Annual Schedule
Leaf Growth = Mar 26 - Apr 28
Colour Change = Sept 3 - Sept 29
Leaf Drop = Oct12 - Nov 5

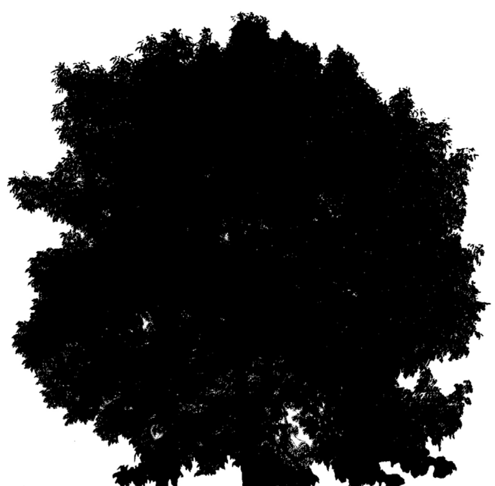




Tree Measurements

Photograph

Measured trees selected based on their background of an open sky with little to no surrounding obstructions



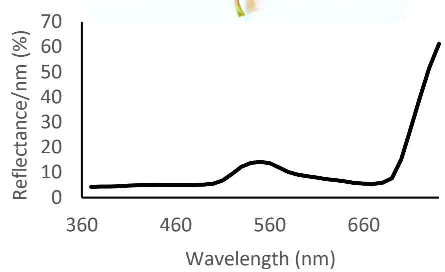
Flood fill

- For each species identified, five to seven individual trees were measured on clear, sunny days with no cloud cover and the sun high in the sky
- Each of the 154 measurements were processed using Balakrishnan and Jakubiec's flood fill algorithm (see 2015 workshop) to calculate the gap percentage of the tree canopy—the percentage of direct sky visible through the canopy bounds

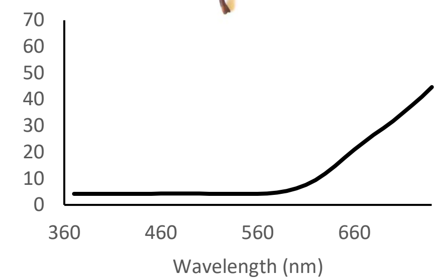
Leaf Colour Measurements

Example: *Acer platanoides* / Norway Maple

- Leaf reflective colour properties measured with a Konica Minolta CM-2500d spectrophotometer against a black backdrop



Summer colours
Reflectance 10.3%



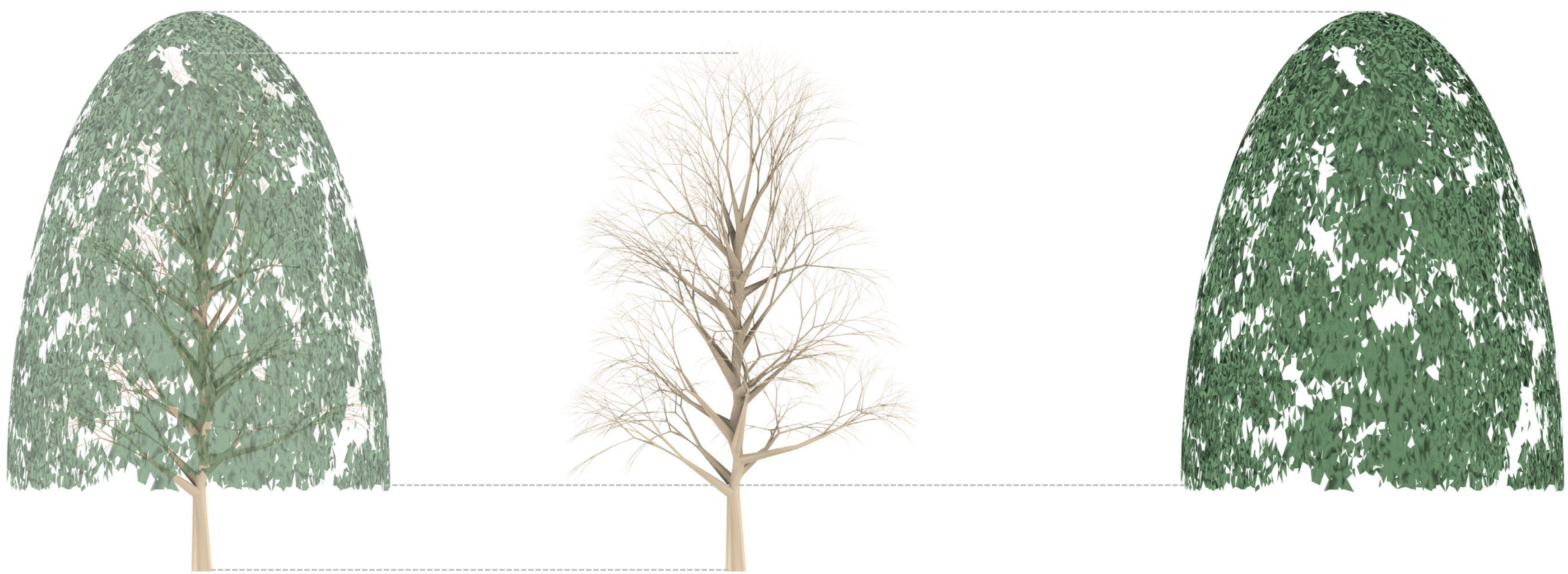
Autumn colours
Reflectance 5.6%

Tree Model Generation

Example: *Quercus palustris* / Spanish Oak

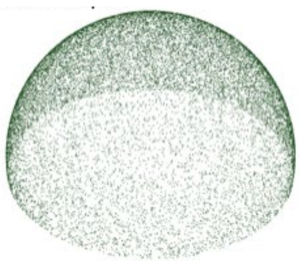
Tree branches are generated using a modified version of proctree.js based on analytical drawings of branch sizes and patterns.

Leaf canopies are based on hemispherical tree canopy generation method (Balakrishnan).

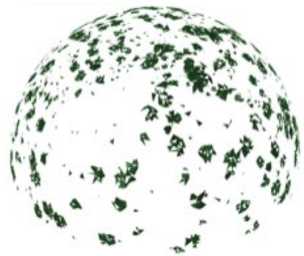


Full tree model *Branch model* *Canopy model*

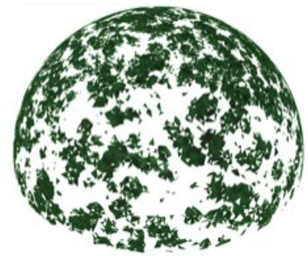
Canopy Generation



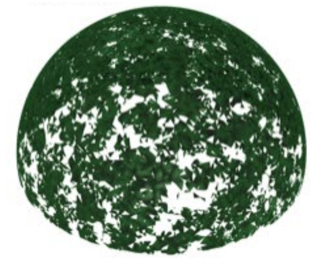
Points



10% area filled



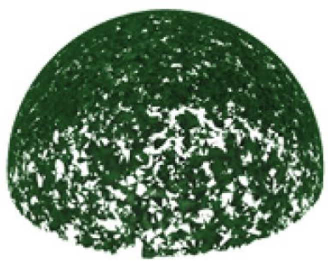
35% area filled



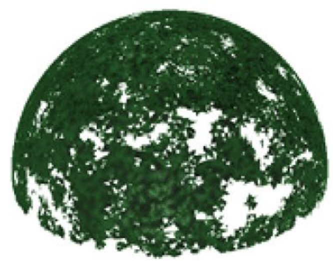
67.3% area filled
10.7% gap %

Gradual fill algorithm until

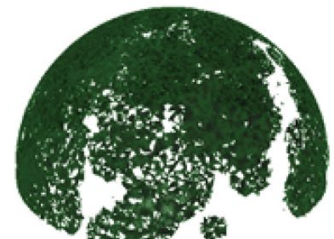
$$A_{fill} = A(1 - \sqrt{Gap\%})$$



CD = 2.0



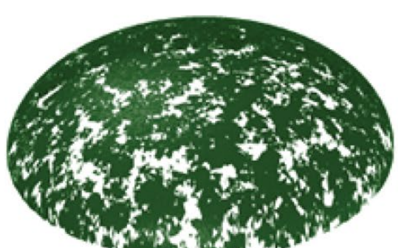
CD = 4.0



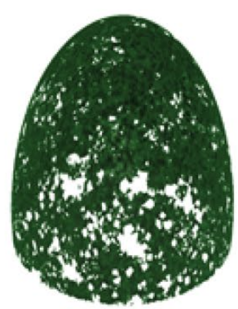
CD = 8.0

Different clustering densities

$$radius = CD\left(\frac{A}{n_{faces}}\right)^2$$



elipsoid oblate

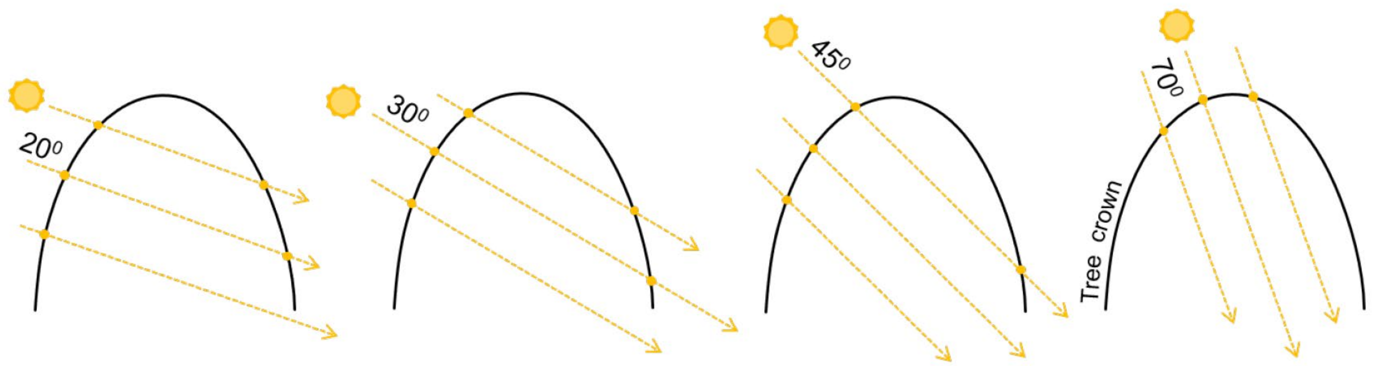


elipsoid prolate

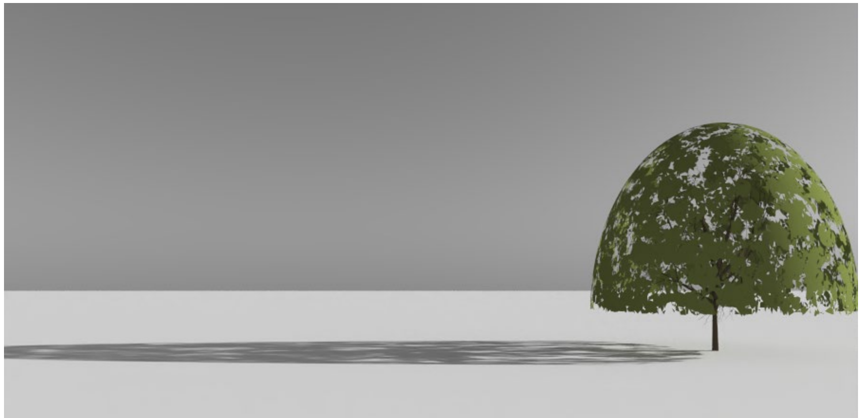
cone

Variety of shapes

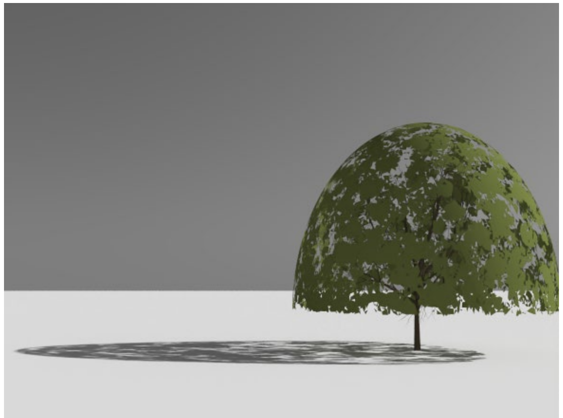
Transmission Concept



Direct light transmission varies with solar altitude and the fraction of light intersecting one or two surfaces of the tree canopy.



15° solar altitude

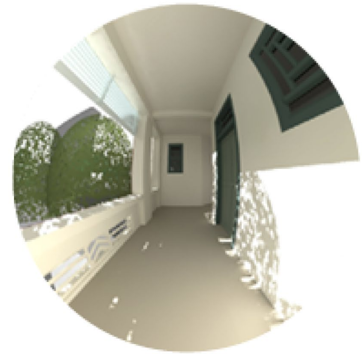


30° solar altitude

60° solar altitude (Magnolia kobus)

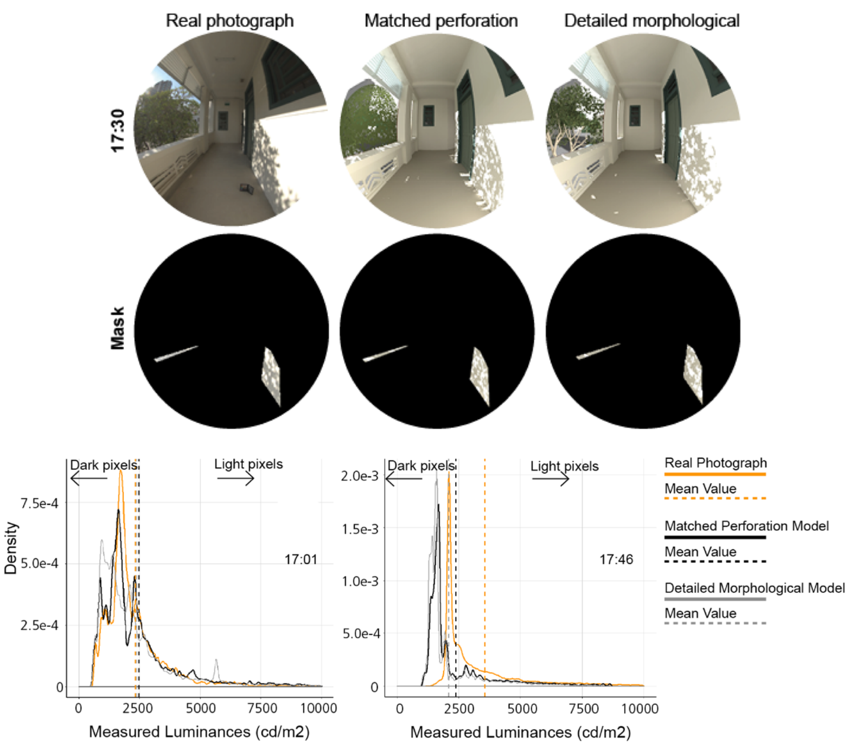
Validation of Shadow Casting

HDR photograph



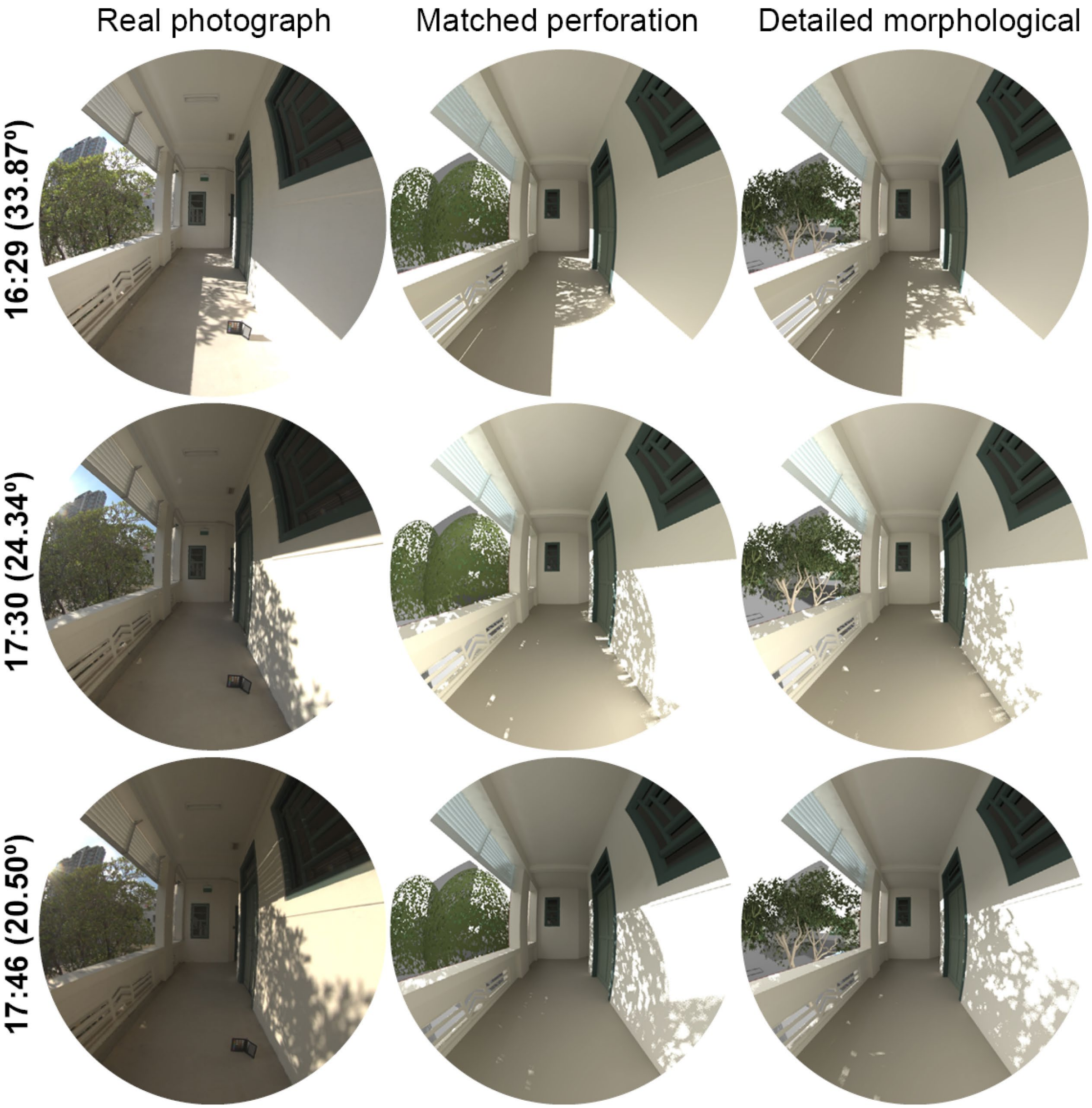
Radiance rendering

Community Centre in Singapore fronted by six Red Frangipani trees



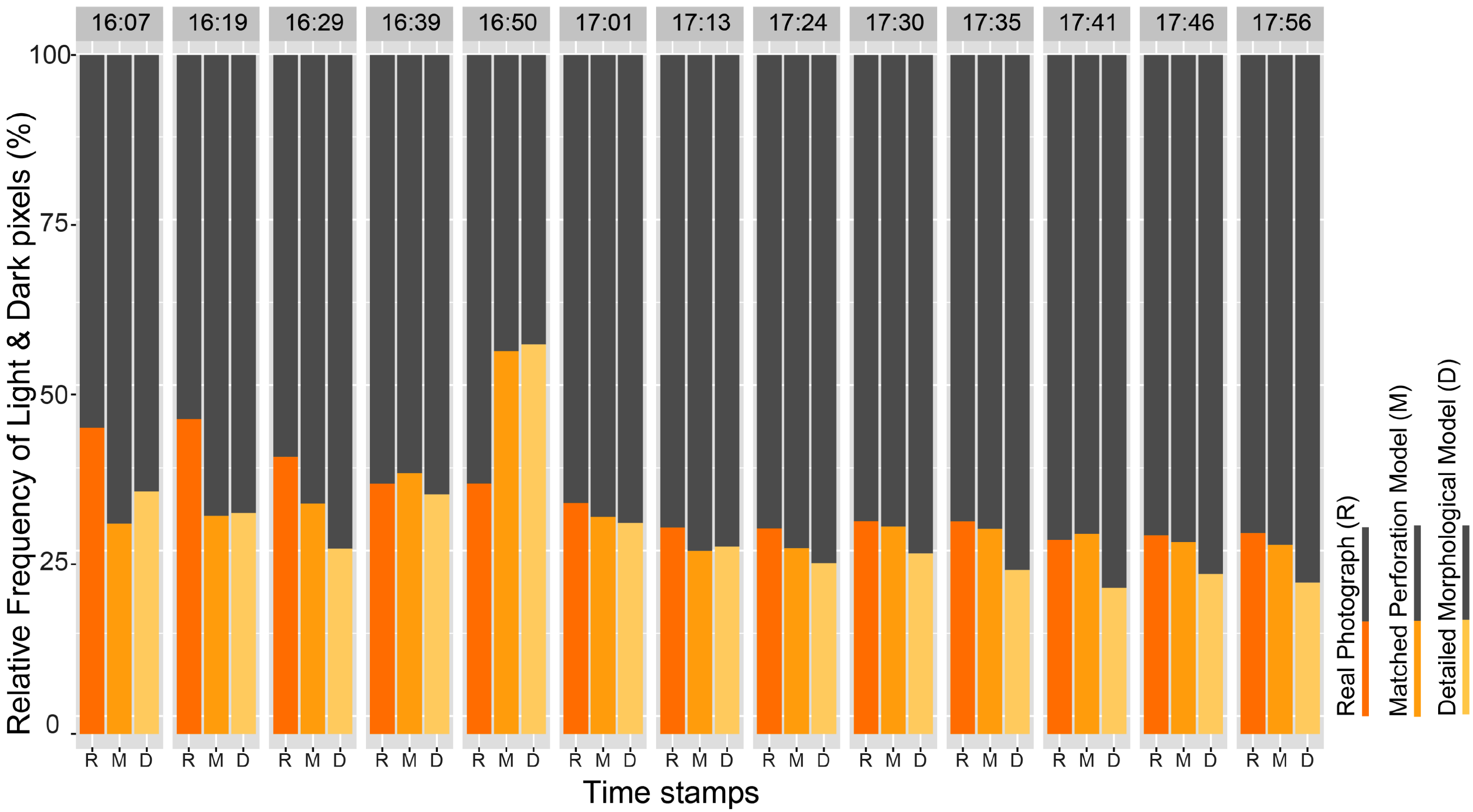
Shadow area calculated by masking and luminous threshold analysis

Validation of Shadow Casting



The solar altitude varied between 44.8° to 17.5° during two hours of measurements / simulations.

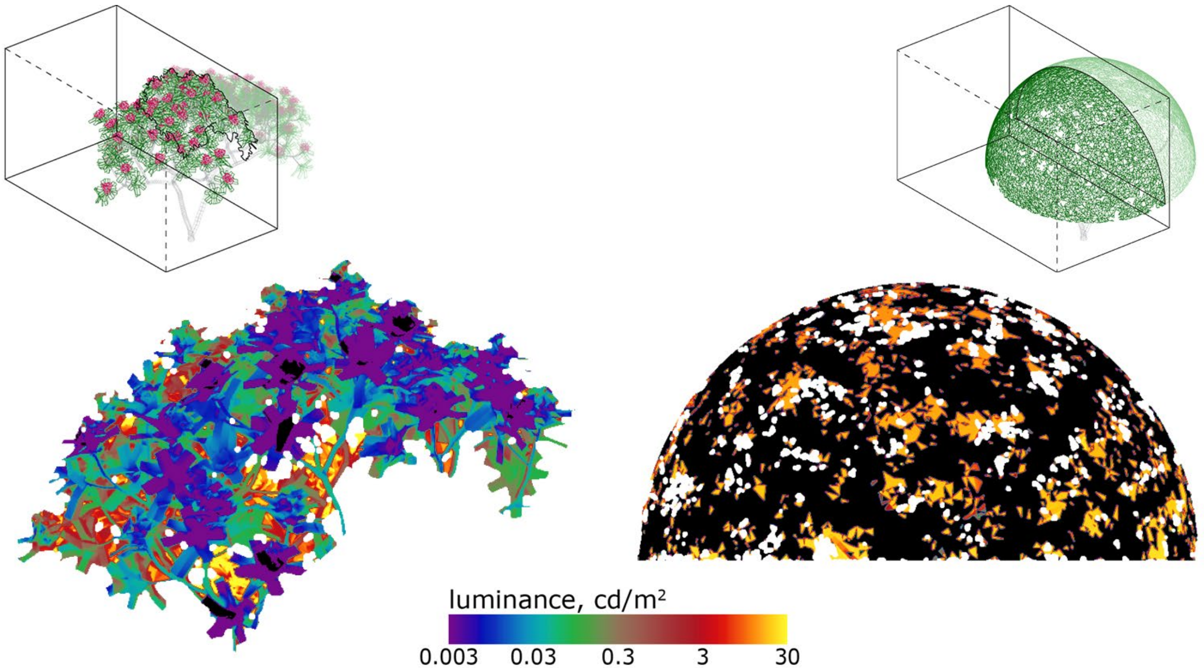
Validation of Shadow Casting



RMSE: 1.8% error in light/dark pixel areas compared to measured data

MBE: +3.8% more light pixel areas compared to measured data

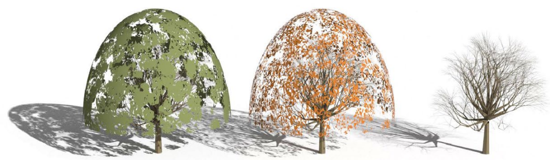
Indirect Transmission



0.089% indirect transmission *0.146% indirect transmission*

Indirect transmission is around 0.06-0.1 % of direct transmission under an overcast sky in this case.

Tree Model Generation



Fraxinus Americana

Gap Transmittance =16.88 %
Dimensions
h = 15-24 m
w = 18 m

Annual Schedule
Leaf Growth = Mar 26 - Apr 28
Colour Change = Sept 3 - Sept 29
Leaf Drop = Oct12 - Nov 5

Betula Pendula

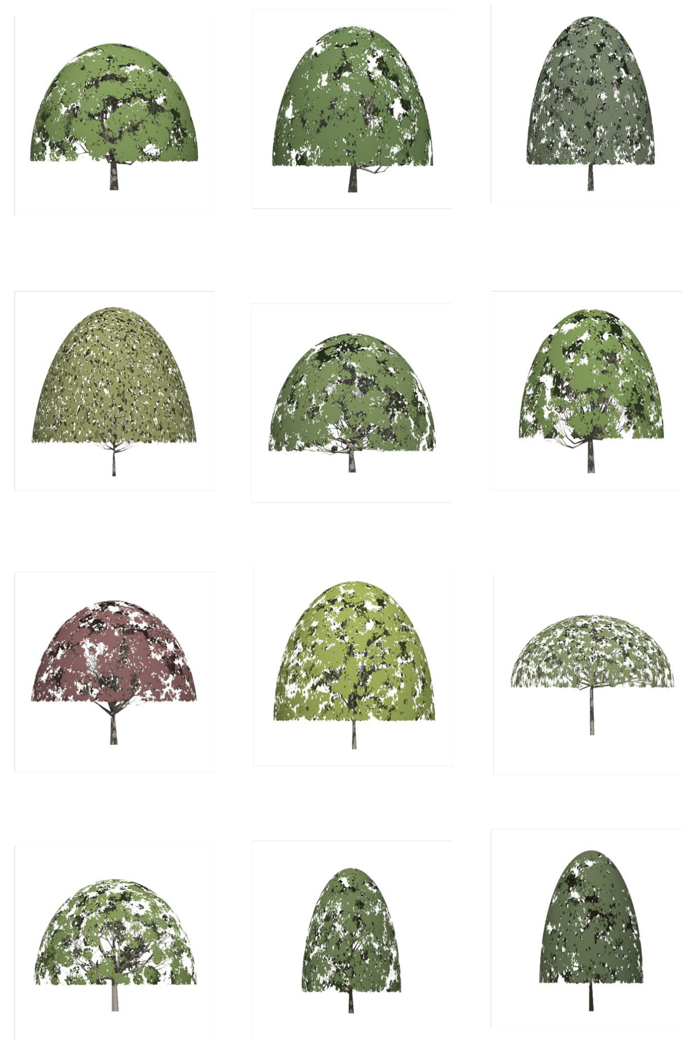
Gap Transmittance = 8.35 %
Dimensions
h = 12-15 m
w = 10 m

Annual Schedule
Leaf Growth = Mar 26 - Apr 28
Colour Change = Oct 2 - Nov 3
Leaf Drop = Nov10 - Dec 8

Prunus Cerasifera

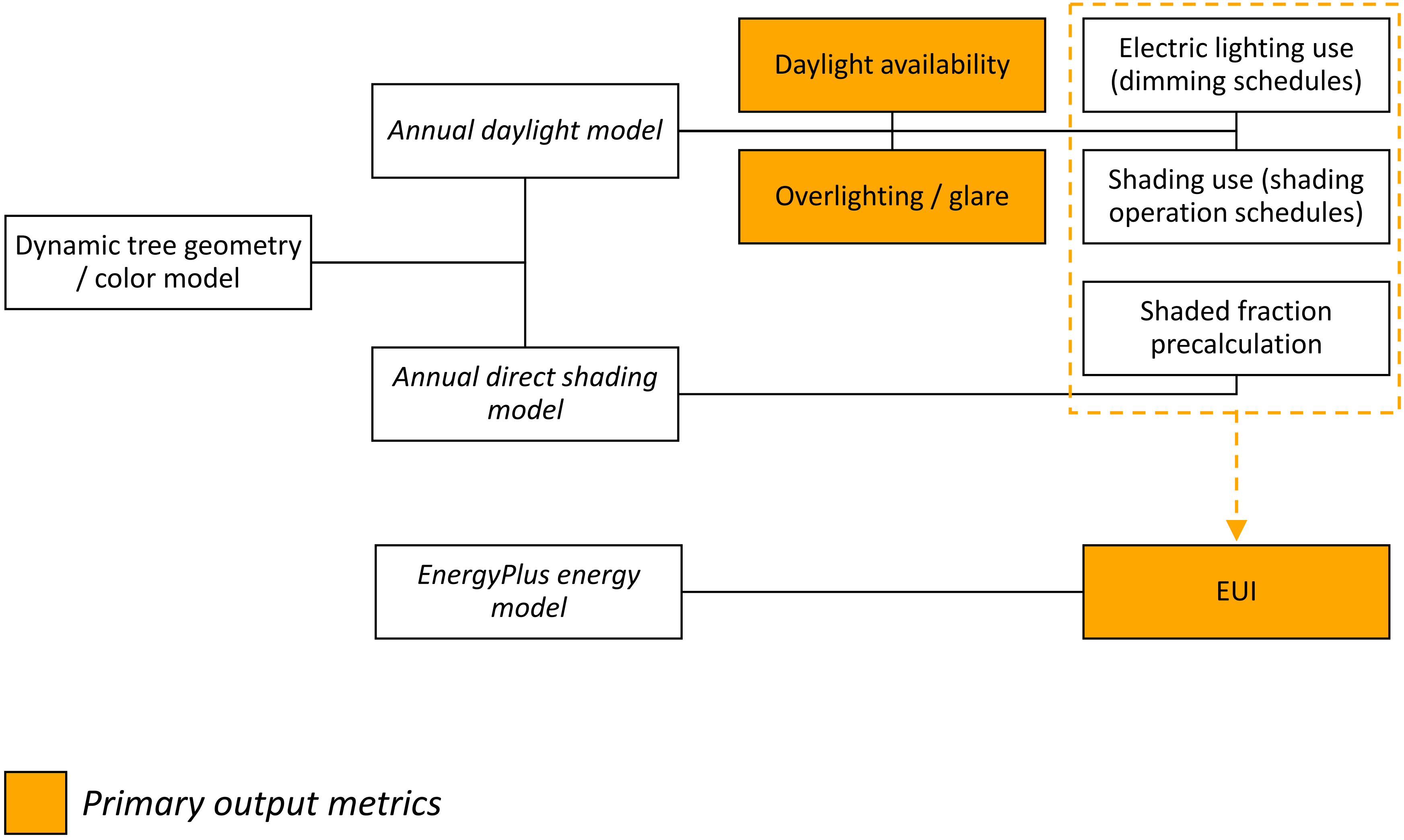
Gap Transmittance =16.22 %
Dimensions
h = 4.5-6 m
w = 7 m

Annual Schedule
Leaf Growth = Feb 26 - Mar 31
Colour Change = Oct 2 - Nov 3
Leaf Drop = Nov10 - Dec 8

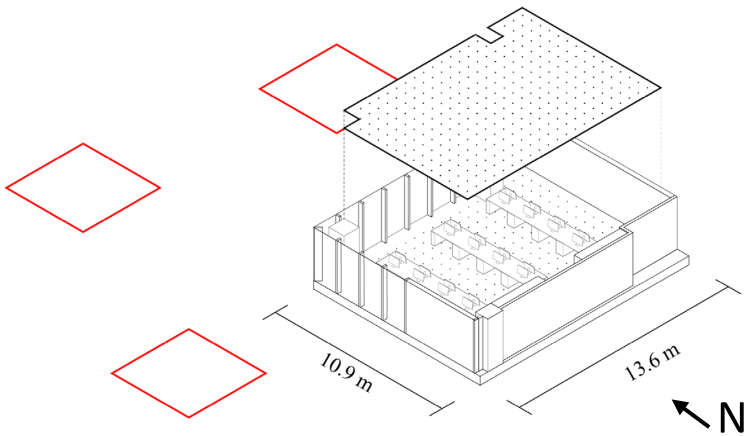


Simulation Process

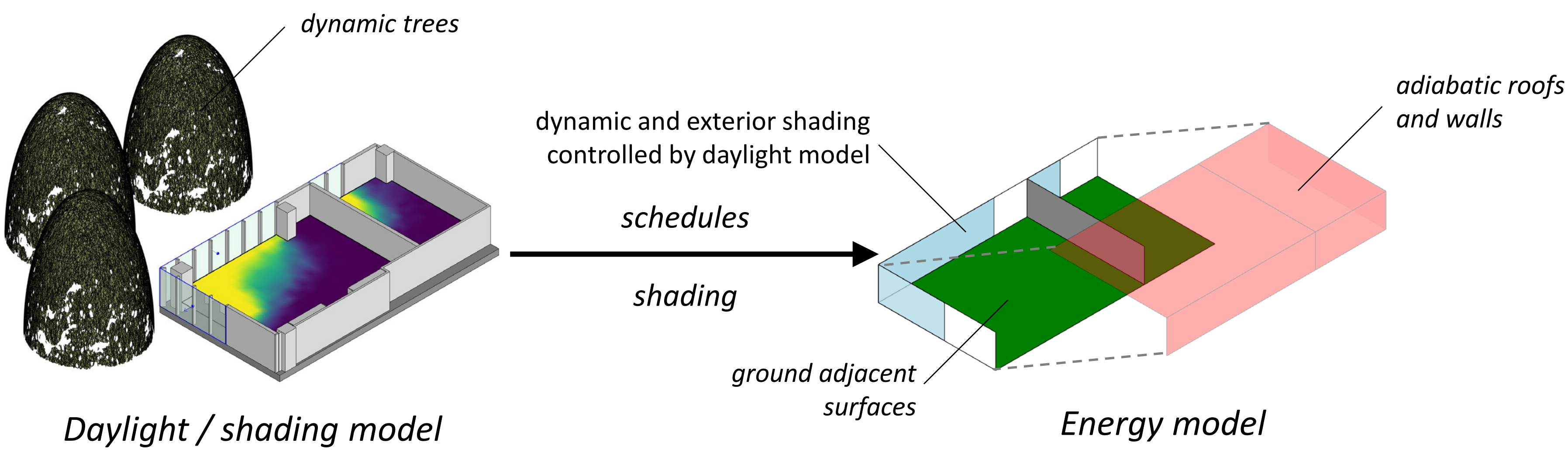
Combined Daylight / Shading / Electric Lighting / Energy Model



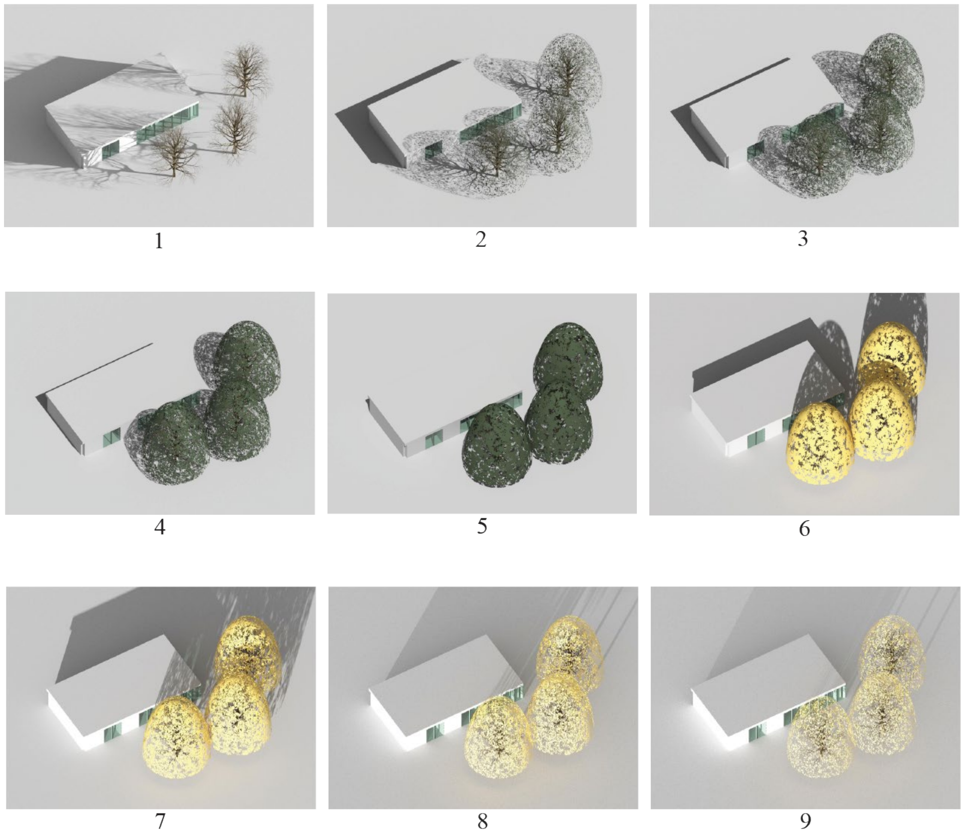
Combined Energy & Daylight Model



- Twelve different tree species were simulated, placed within the red squares in the diagram to the left.
- Dynamic foliage behaviour and differential geometry / canopy porosity lead to differences in:
  - Direct sunlight penetration and solar heat gains
  - Electric light utilization
  - Blind / window shade utilization
- Impactful on daylight, energy, peak loads, and heating / cooling load balance!



Dynamic Tree Models, Visually
Example: *Betula pendula* / Silver Birch

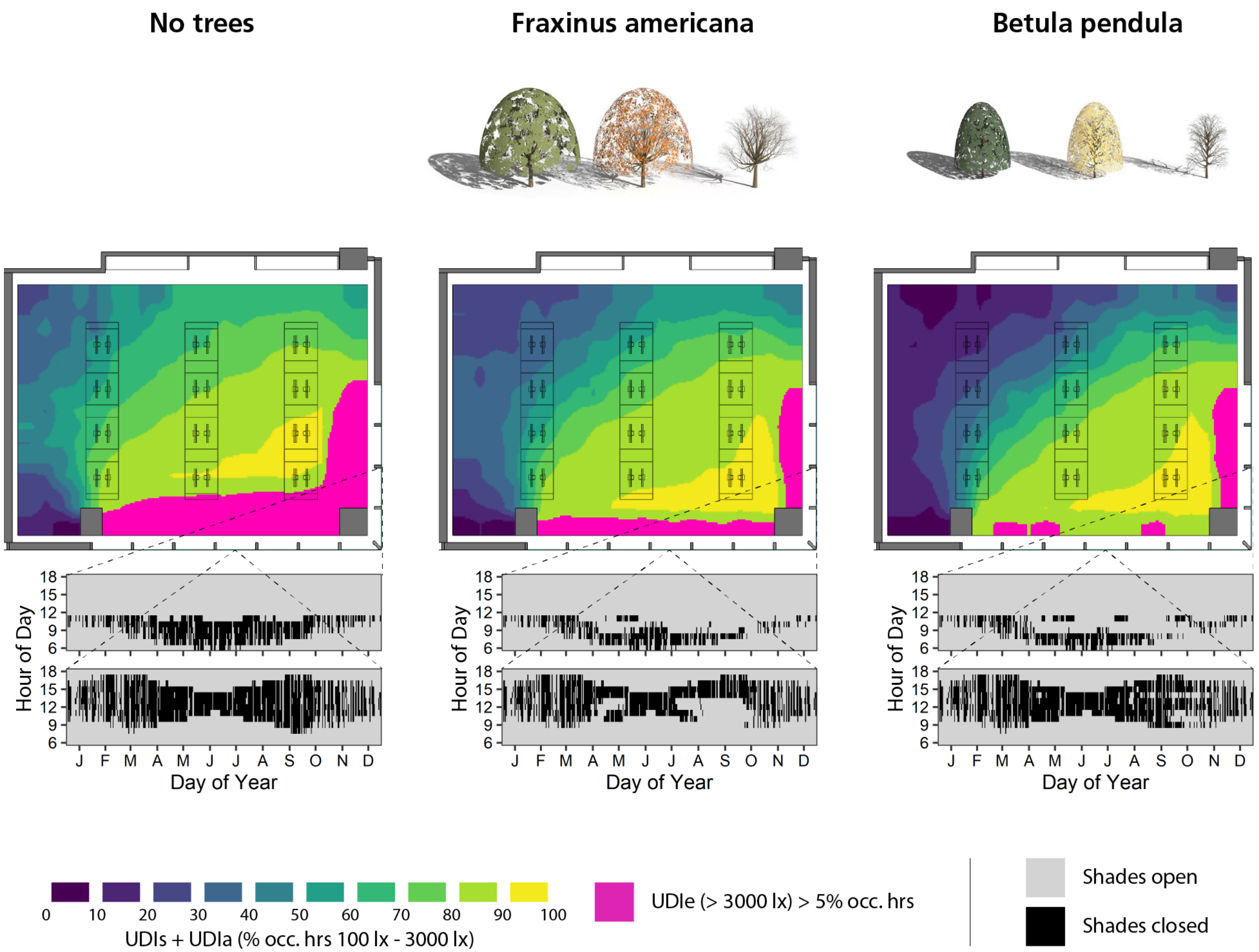


Example of dynamic tree foliage behaviour
Winter → Summer → Autumn

- For example, the Silver Birch:
  - 2-4: grows its leaves from April to May
  - 5: is green from May to October
  - 6: turns yellow from October to November, and
  - 7-9 & 1: loses its leaves from November to December
- (For other details, thermal/lighting material specifications, operational parameters, etc., please see our paper!)

Results & Analysis

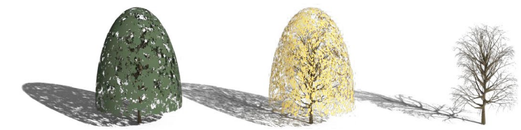
Results

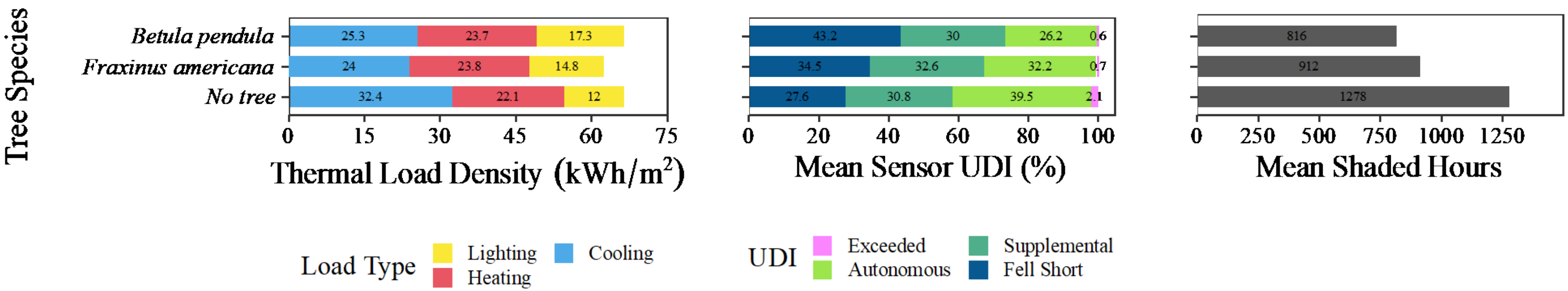


- Shade utilization and daylight levels vary meaningfully with the inclusion of trees compared to a baseline model *and* between tree species.
- Range of shade deployment: 462 hours
- Range of 'autonomous' (300 – 3,000 lx) and 'supplemental' (100 – 300 lx) daylight levels: 13.4%

Results

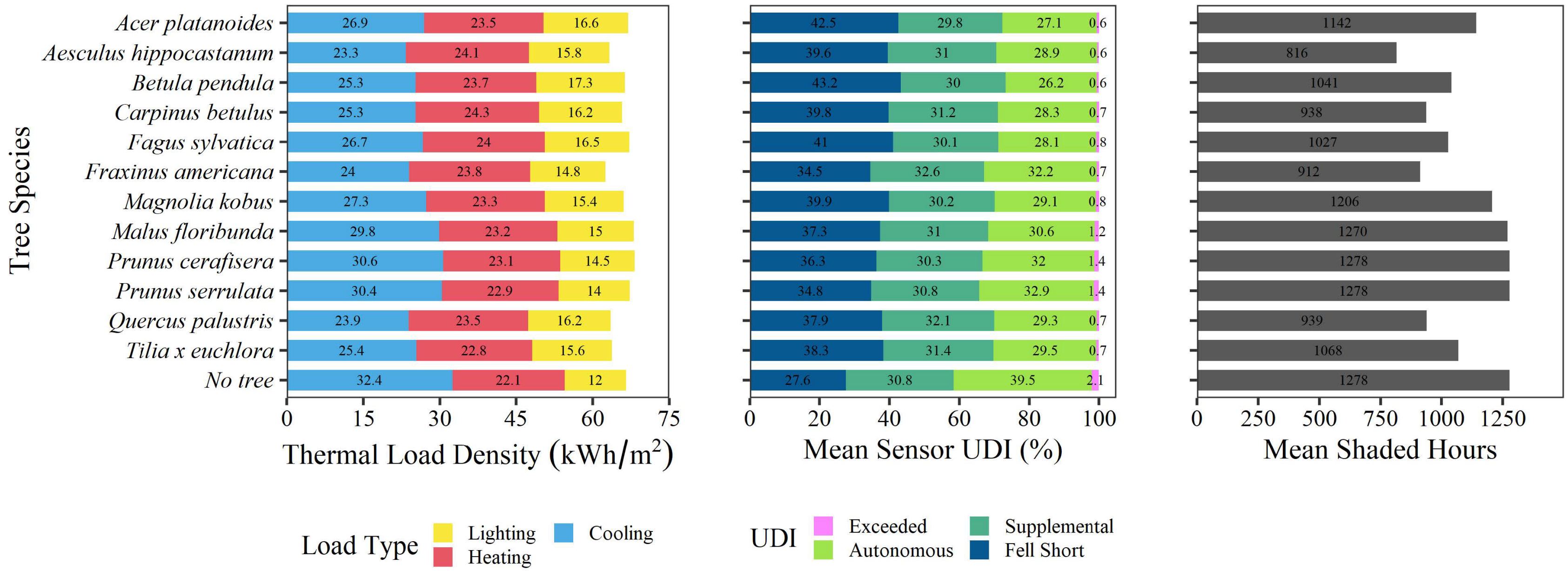
No trees **Fraxinus americana** **Betula pendula**





- Total thermal load density range: 5.68 kWh/m^2
  - But some varied disparities arise when loads are broken down:
    - Cooling range: 9.1 kWh/m^2
    - Heating range: 2.2 kWh/m^2
    - Electric lighting range: 5.3 kWh/m^2

Thermal Load Density, Mean Sensor UDI, and Mean Shaded Hours

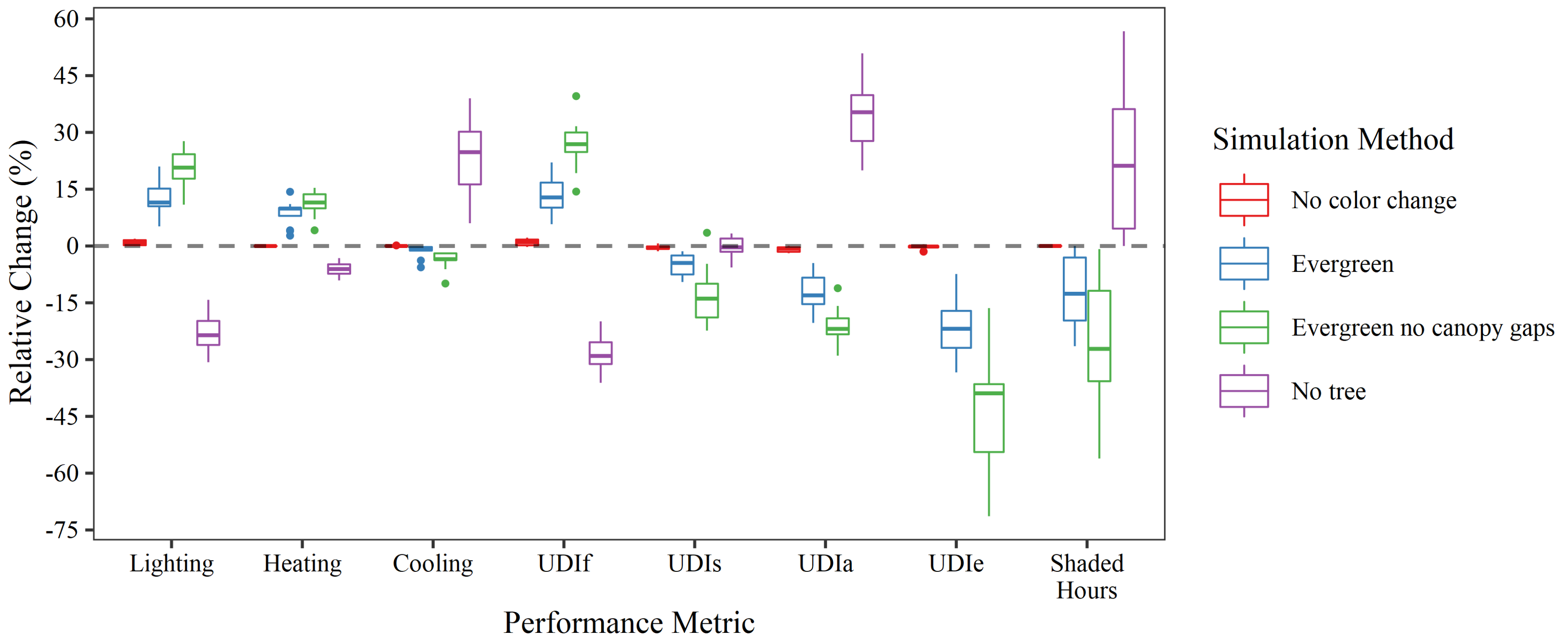


- *F. americana* is the best performing with a load density of 62.5 kWh/m², 5% less than the mean and 6% less than no tree at all.
- The 'No tree' simulation has the highest mean UDIs+a of 70.3%, while the *F. americana* performed the second best with a UDIs+a of 64.8%.
- The *F. americana* model has blinds closed only 913 h, a 28.7% reduction compared to the 'No tree' simulation.

What happens with simplification?

$$Variance_{simple-tree} = \frac{100 \cdot R_{full-tree}}{R_{simple-tree} - R_{full-tree}}$$

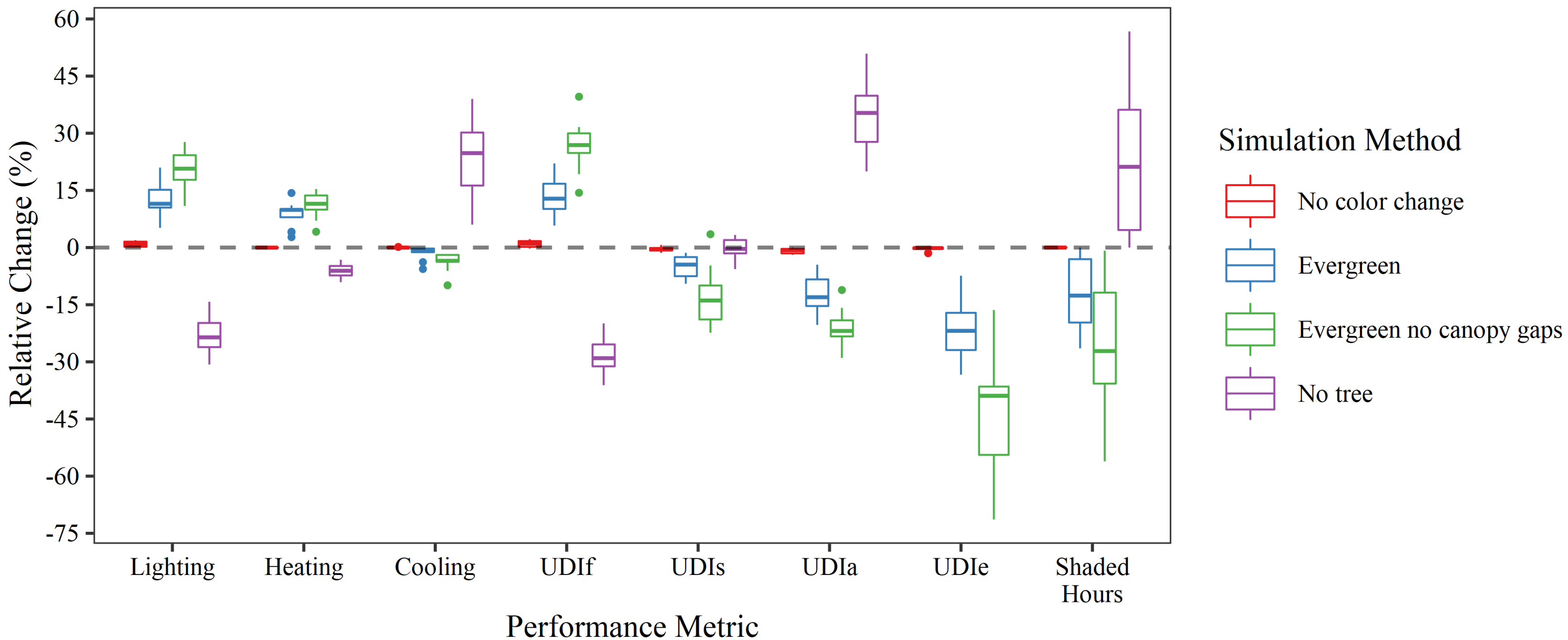
- What if we run the model with…
  - No color change?
  - Evergreen rather than deciduous trees?
  - Evergreen trees with no canopy gaps (opaque)?
  - No tree at all?



What happens with simplification?

- *Colour change has almost no effect*
- Evergreen tree models with canopy gaps increase lighting and heating, while decreasing mean UDIs and mean UDIa
  - Evergreen opaque trees with no canopy gaps have similar, but more extreme, results
- With no trees, simulations reverse these trends, decreasing lighting and heating, increase cooling loads, and significantly increasing mean UDIe

* For the UDIe calculations, No tree is not depicted as it exceeds the bounds of the figure



Future Research Topics

- Implementation in accessible daylight simulation tools.
- Reduction in simulation time.
  - Implementation of dynamic exterior objects into generalizable Radiance-based tools (example: trees, snow).
- Measurement of more trees.
- Implementation of growth models (sapling to mature tree).

Questions?

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J. Pan & J. A. Jakubiec. *Simulating the Impact of Deciduous Trees on Energy, Daylight, and Visual Comfort: Impact Analysis and a Practical Framework for Implementation*. 2022. eSim, Ottawa.

P. Balakrishnan & J. A. Jakubiec. *Trees in Daylight Simulation – Measuring and Modelling Realistic Light Transmittance Through Trees*. 2022. LEUKOS (In press).

Thank You