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Thermo-optical properties of 3D-printed facades:
capturing material and geometrical complexity across scales

21st International Radiance Workshop

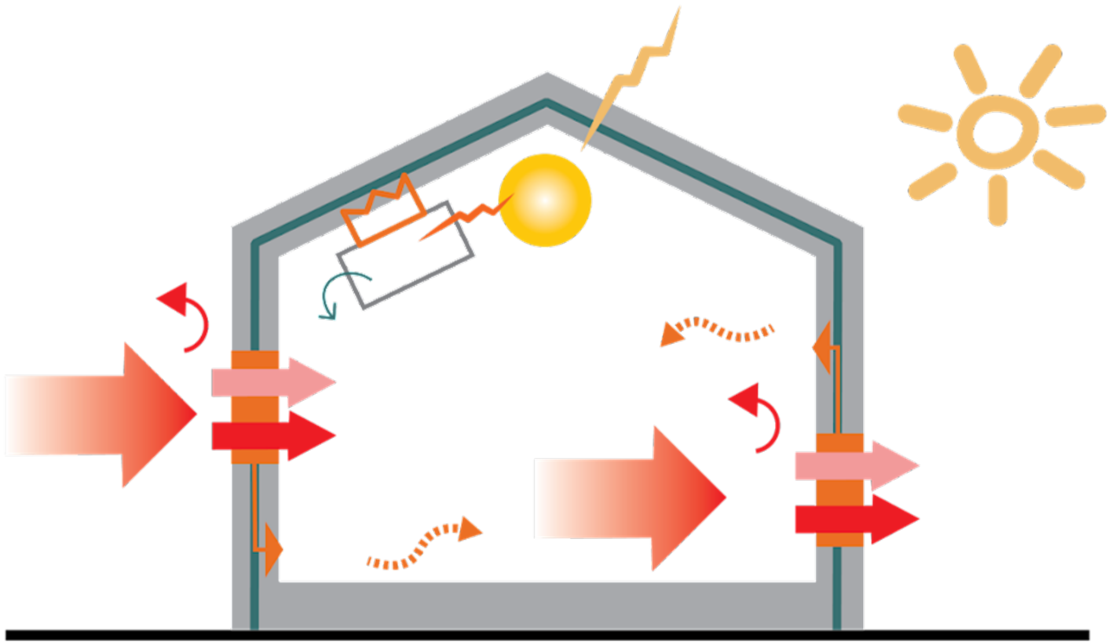
29 | 08 | 2023

National Centre of Competence
in Research
Digital Fabrication

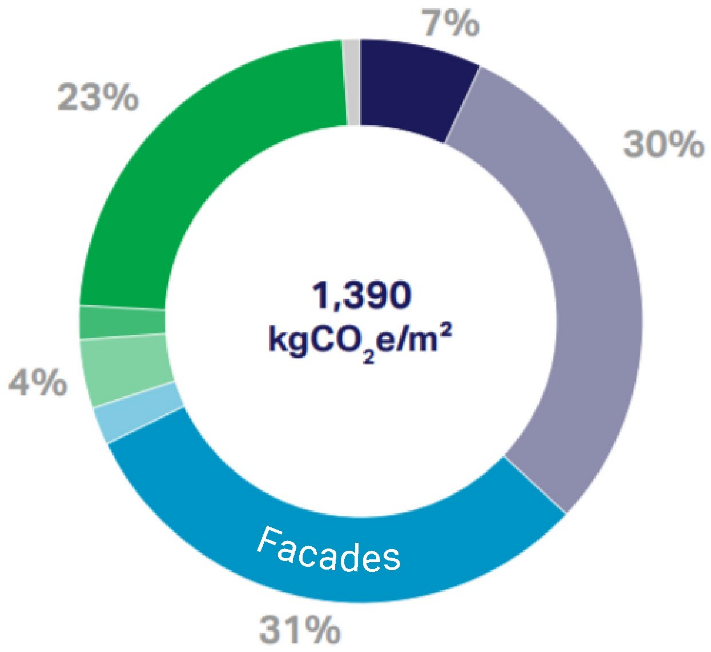
Architecture
and Building
Systems

Motivation

Role of facades in decarbonisation



Building life-cycle embodied emissions



Adapted from "Net-zero buildings Where do we stand? (2021), Arup and WBCSD

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Motivation

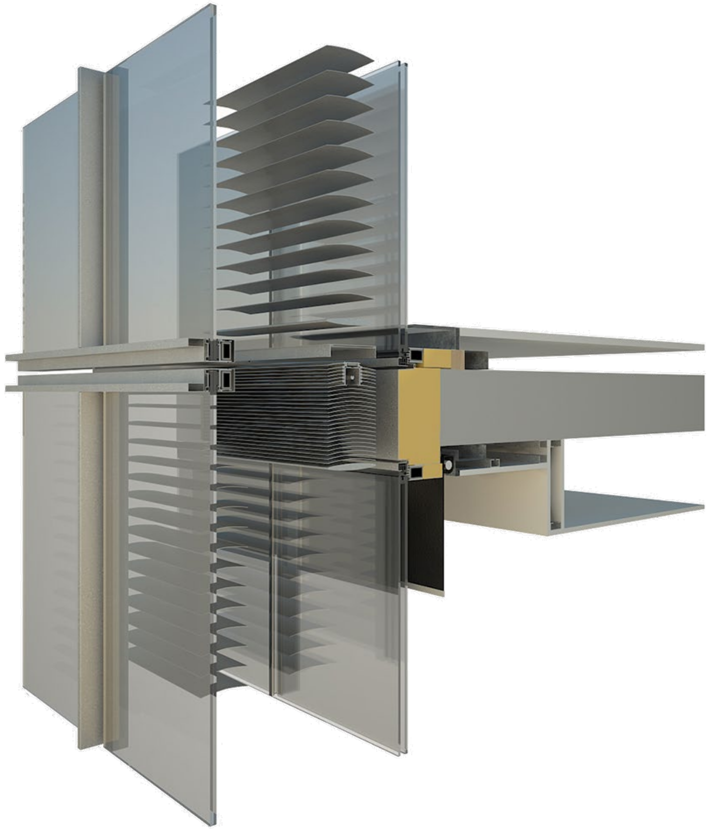
Role of facades in decarbonisation

Are there alterative approaches?

performance

maintenance

environmental impact



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Research Background

Large-scale polymer 3DP

- Mass customization: climate-specific design with tailored properties
- Geometrical complexity: performance integration and multi-functionality
- Additive process: minimal material waste
  Monomaterial: easy recycling

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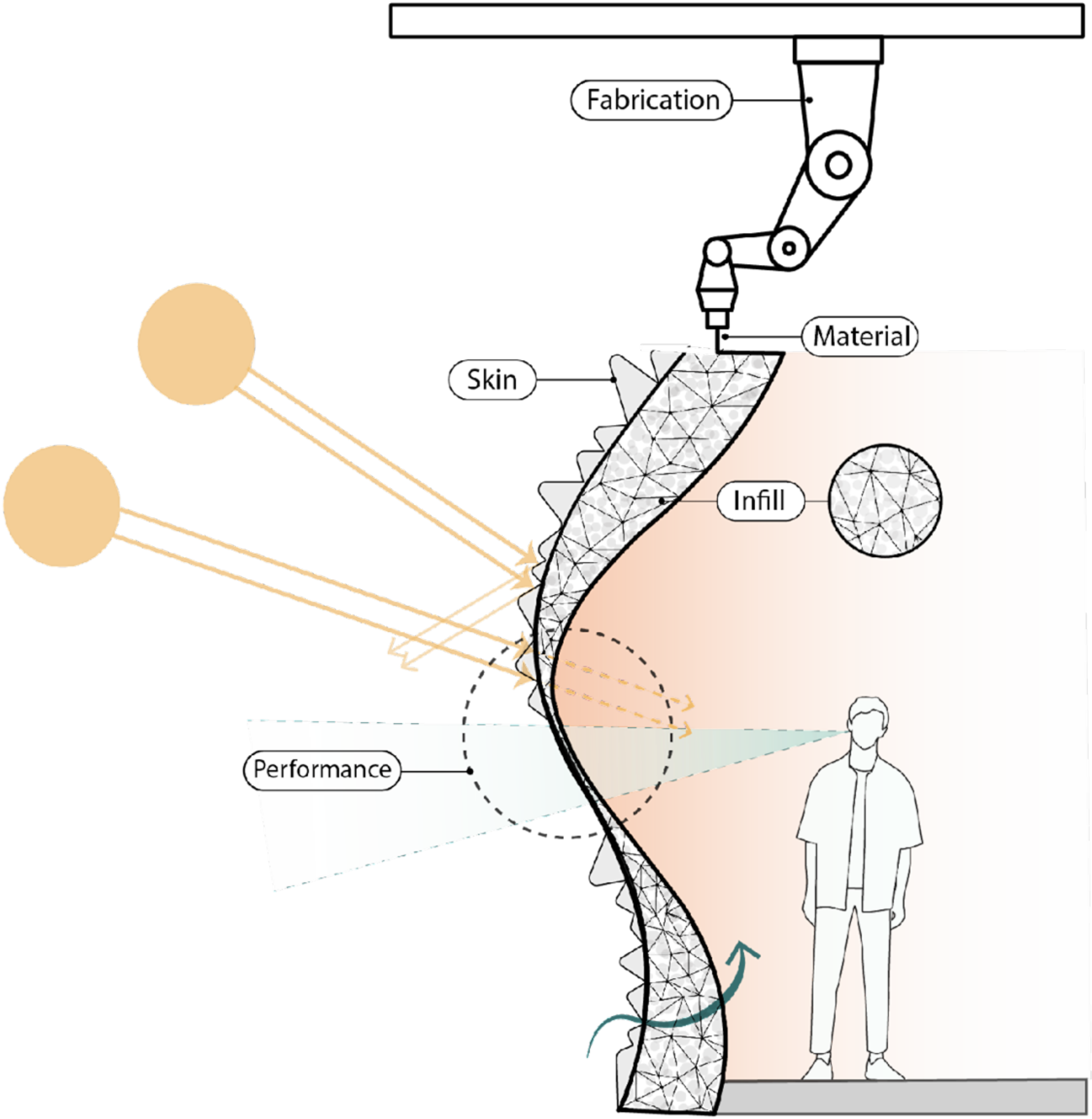
Research Project

Integrated 3D Printing Facade

- Relationship between performance, geometry and fabrication
- Focus on thermal and solar aspects as key functional requirements
- Modelling approaches for performance assessment and design integration



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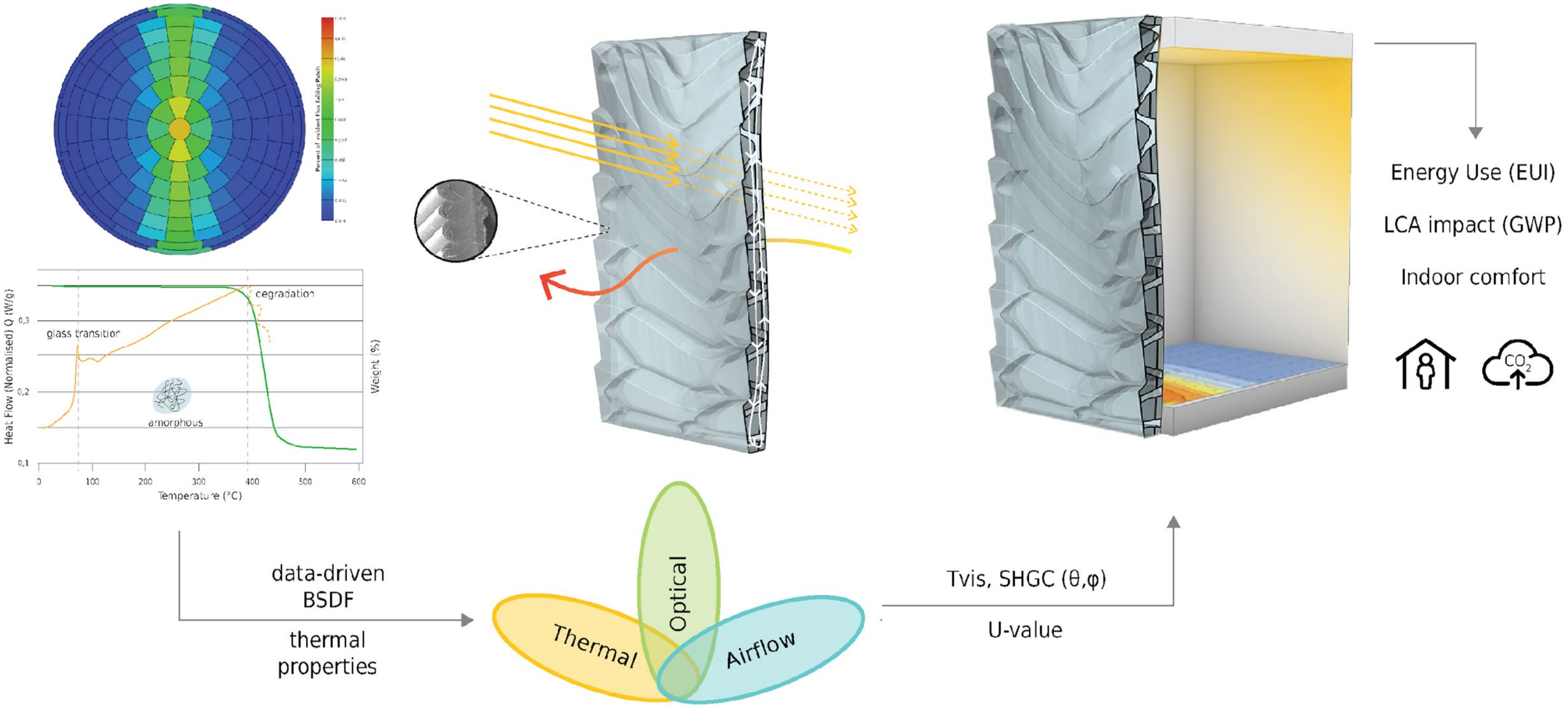
Methods

A Multiscale approach

MATERIAL
µm - mm
Material choice
Fabrication

COMPONENT
cm - m
Design
Geometry

BUILDING
m
Performance
indicators



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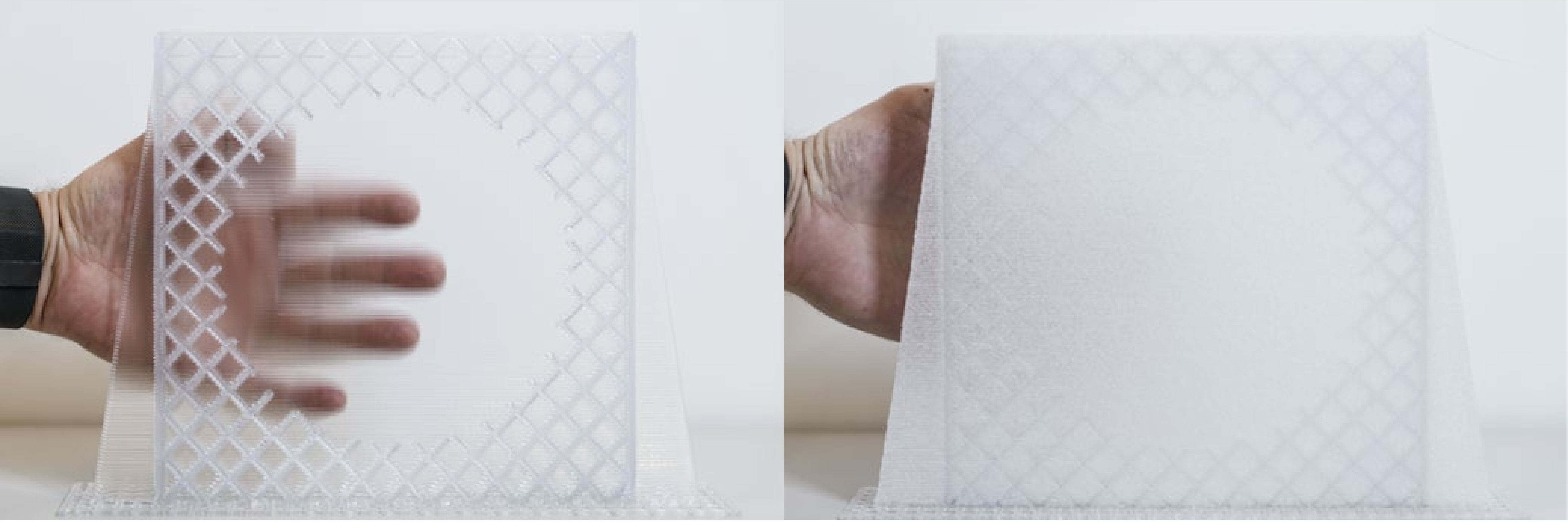
Material Scale

Fabricated with same material and printer



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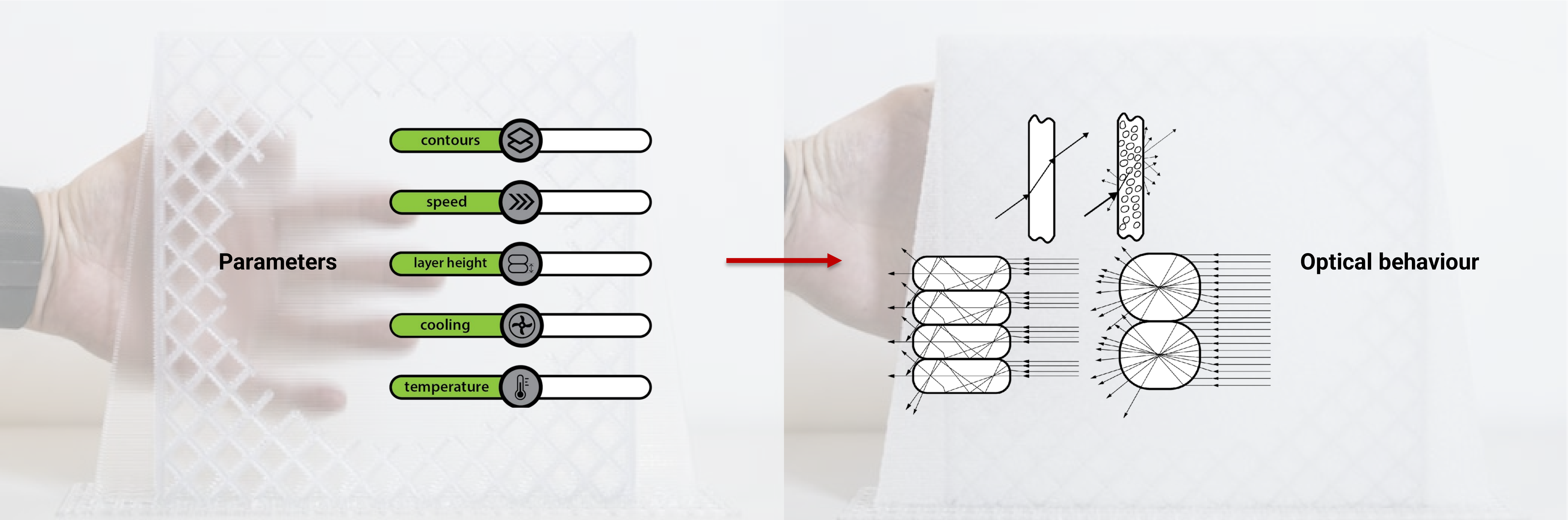
Material Scale

Fabricated with same material and printer



© Matthias Leschok

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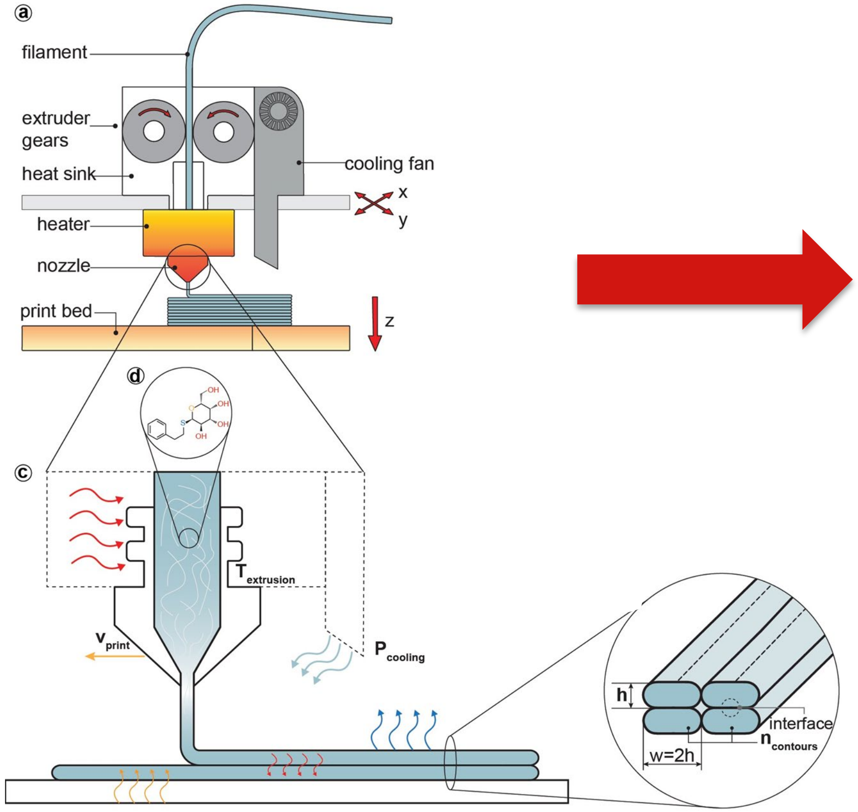
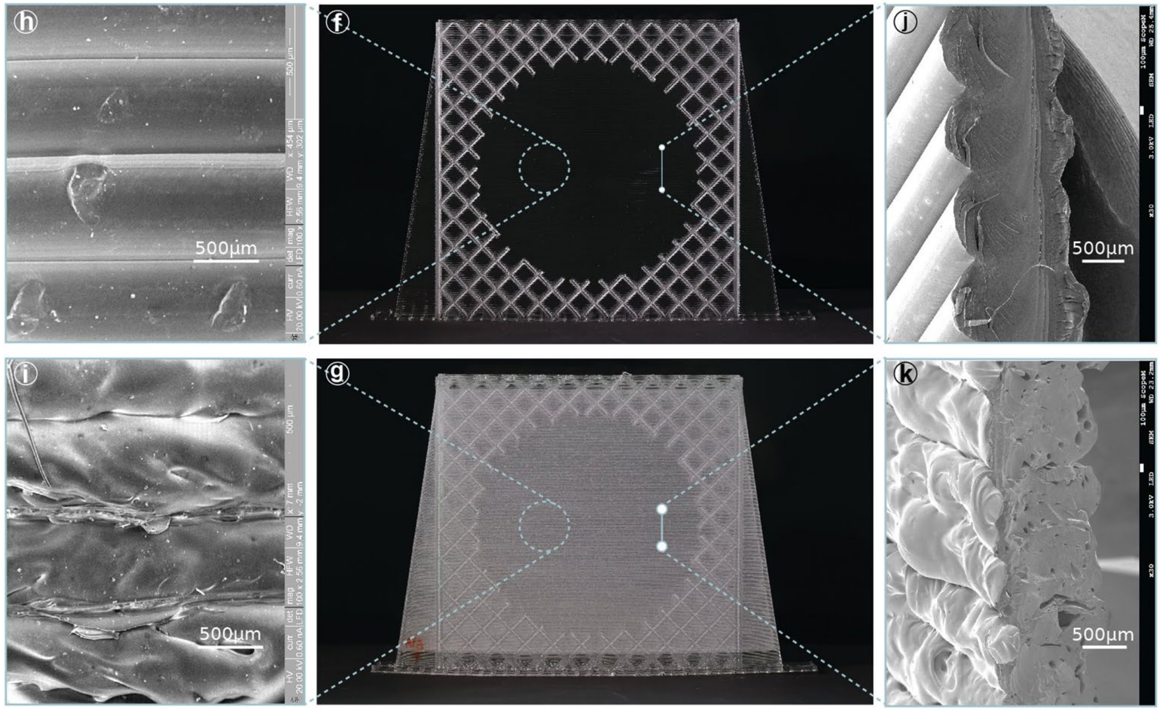
Material Scale

Fabrication



Morphology



Piccioni et al., 2023. https://doi.org/10.1002/admt.202201200

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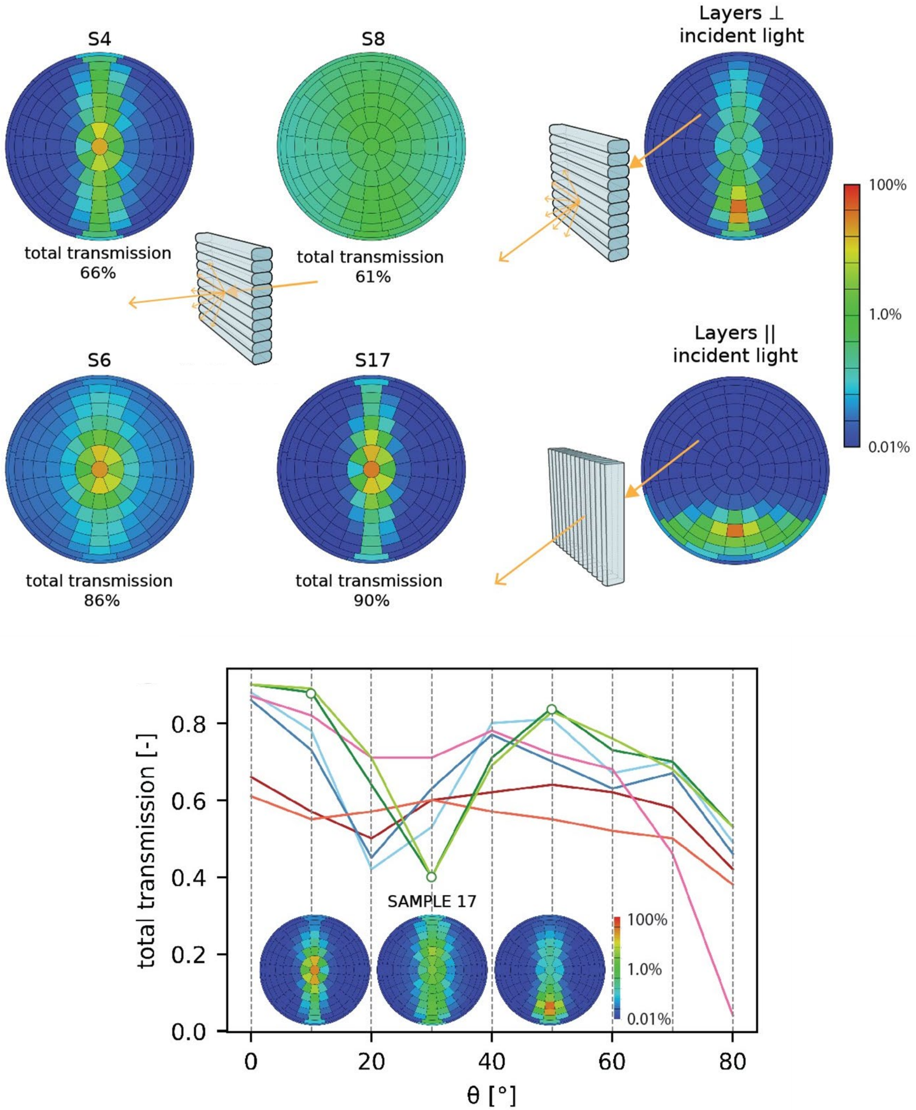
Material Scale

Optical characterisation through BSDF

Goniophotometer Laboratory, Research Group Envelopes and Solar Energy, HSLU
© Lars Grobe

- Scattered light transmission due to 3DP layers, depending on their orientation
- Angle-dependent behavior depending on layer cross sectional dimensions



Piccioni et al., 2023. https://doi.org/10.1002/admt.202201200

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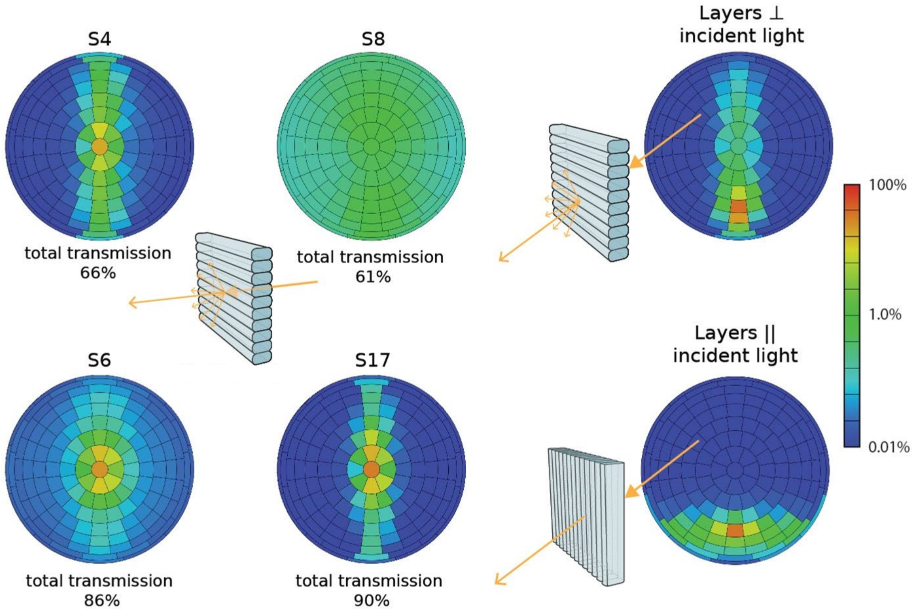
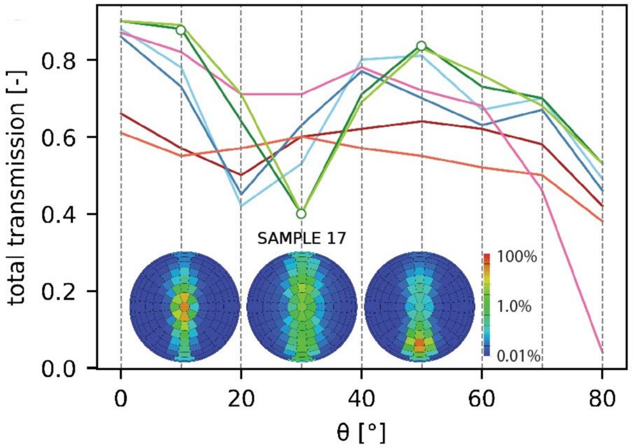
Material Scale

Optical characterisation through BSDF





- Can we describe this behavior with simulations?
- How can we use the material description for performance assessment at the component scale?
- What happens in parts with multiple 3DP surfaces? How do we model optical interactions?

Piccioni et al., 2023. https://doi.org/10.1002/admt.202201200

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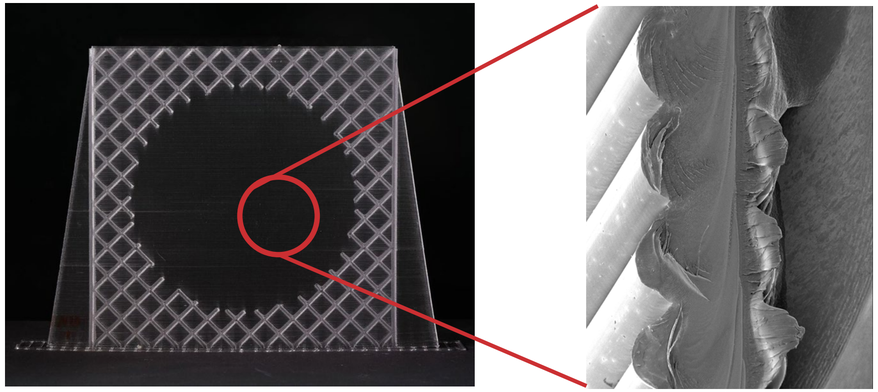
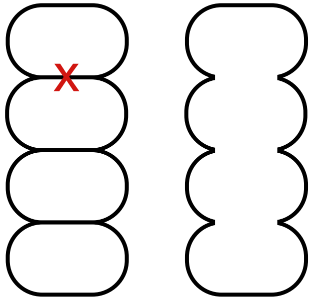
Material Scale

pabopto2BSDF vs genBSDF





- Geometry modelling in Rhino-Grasshopper (MSH2RAD)
- Dielectric material
  void dielectric PETG 0 0 5 .9 .9 .9 1.57 0
- genBSDF parameters
  +f +b
  -c 3000
  Klems resolution

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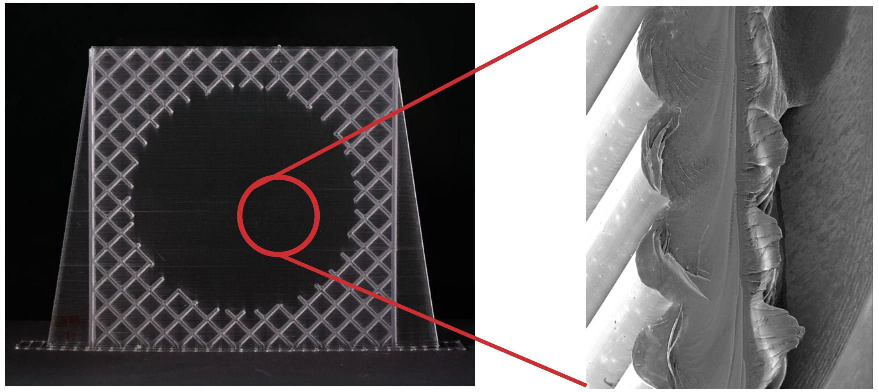
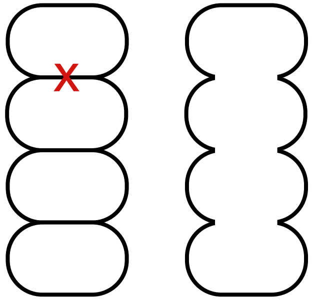
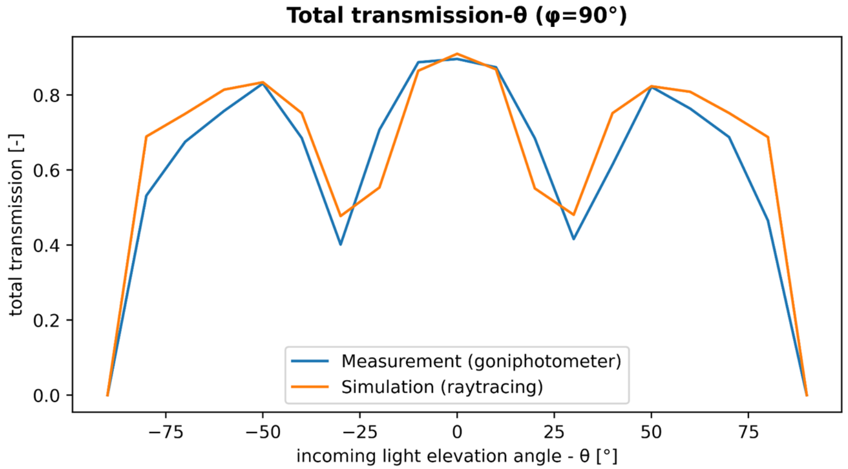
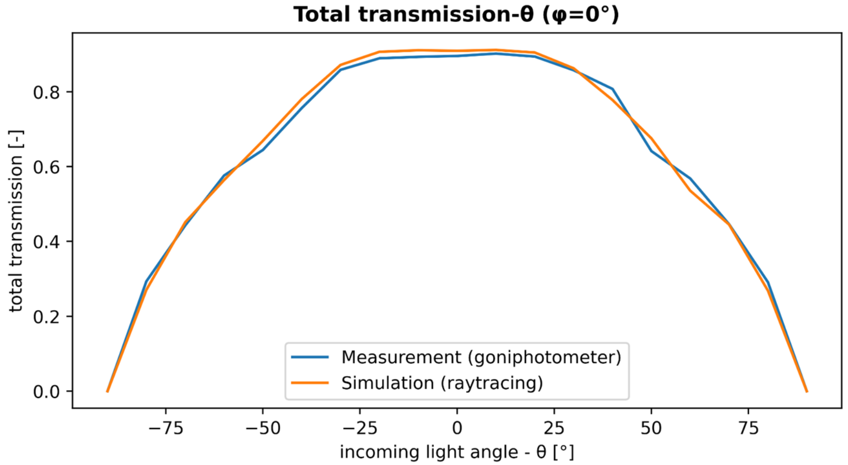
Material Scale

pabopto2BSDF vs genBSDF









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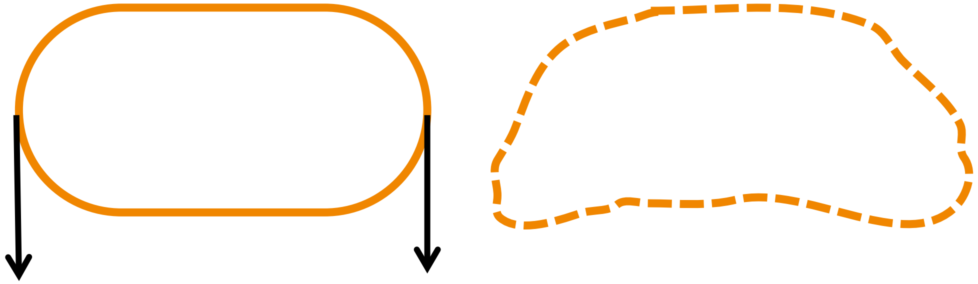
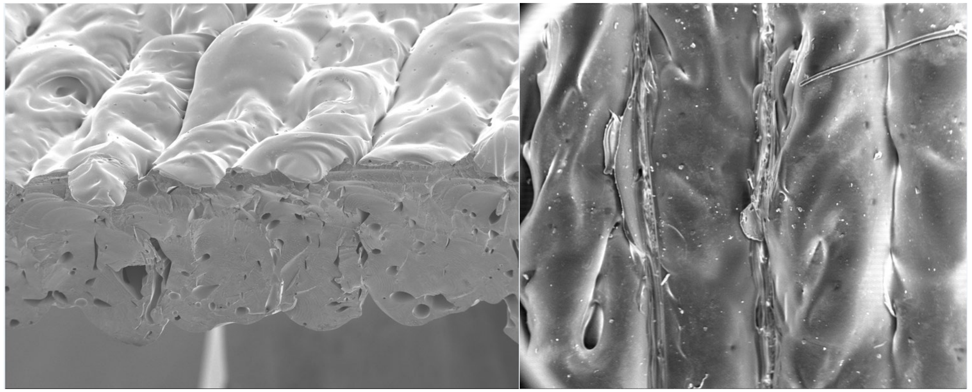
Material Scale

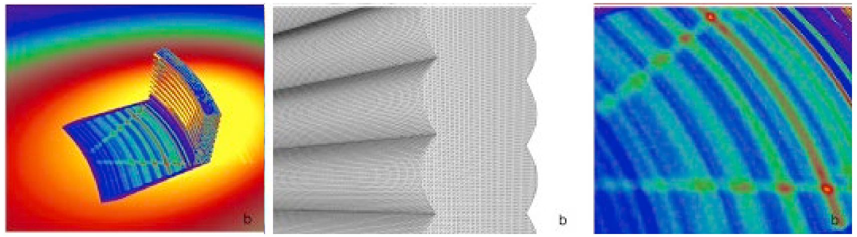
Gravity-induced deformation

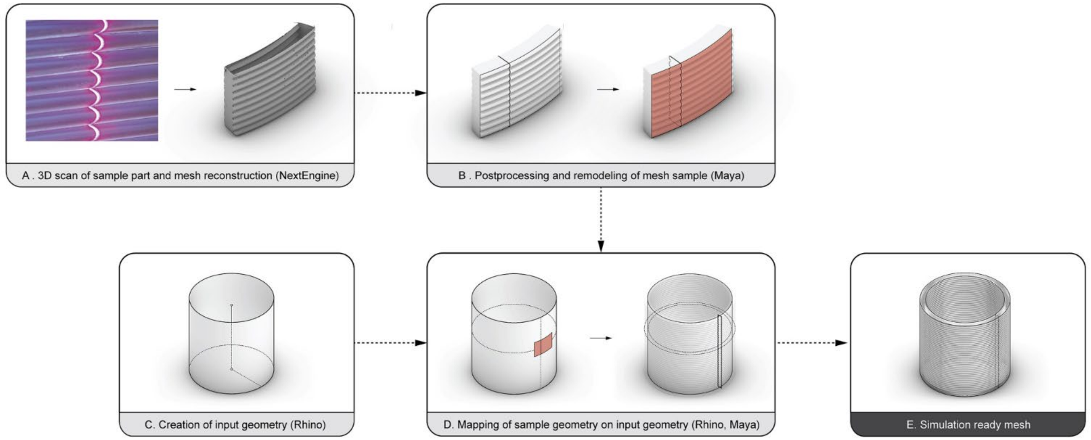


Fabrication-induced microstructures



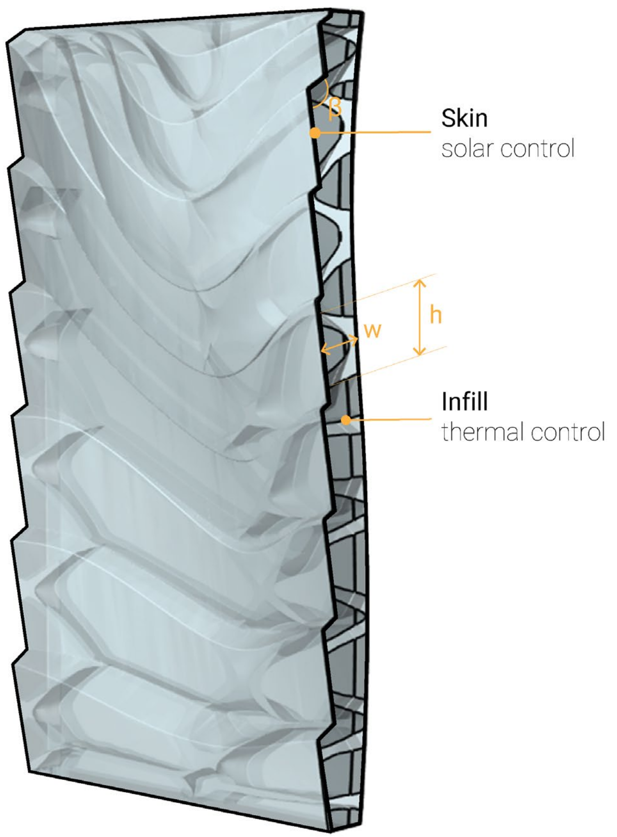
3D-scanned geometry as Radiance input



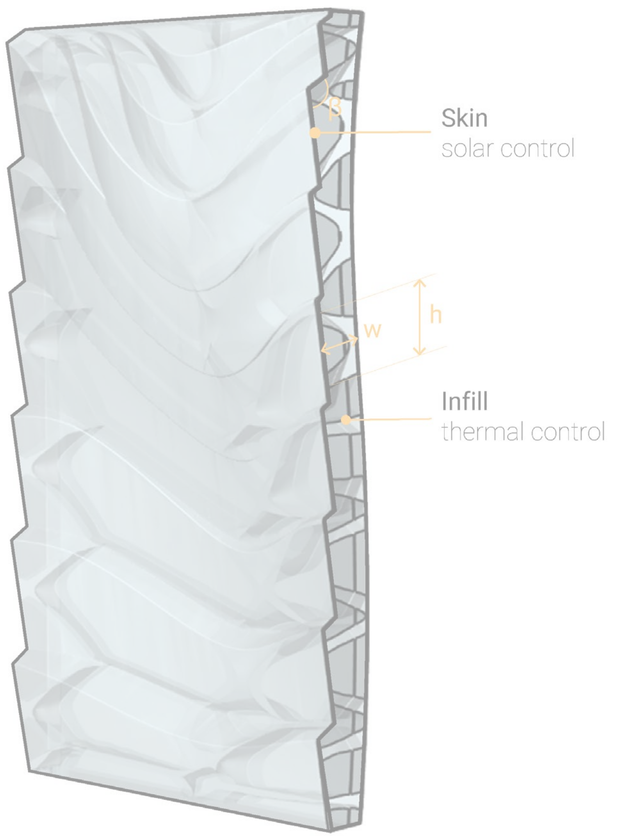


Weber et al., 2023. https://doi.org/10.1016/j.buildenv.2020.106957

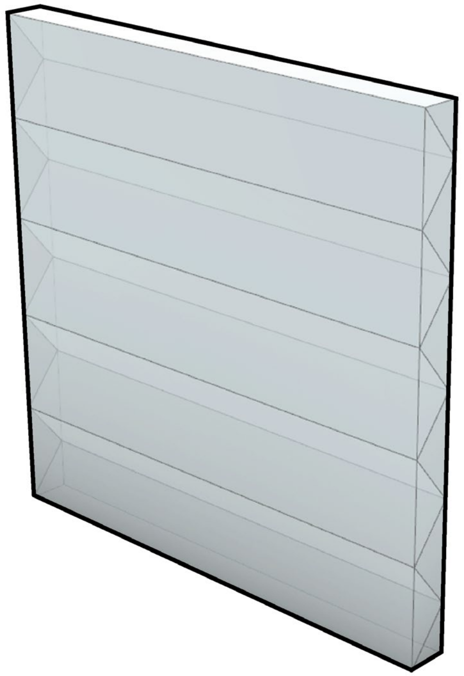
Component Scale

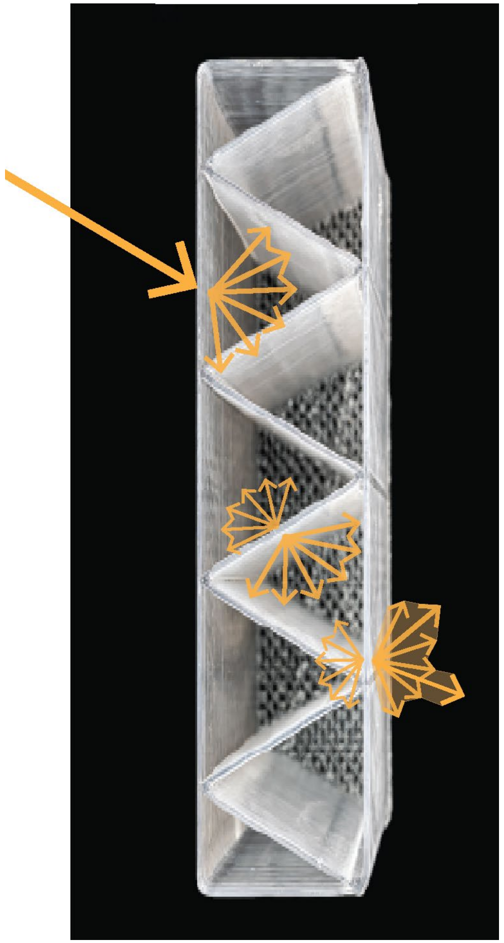


Component Scale



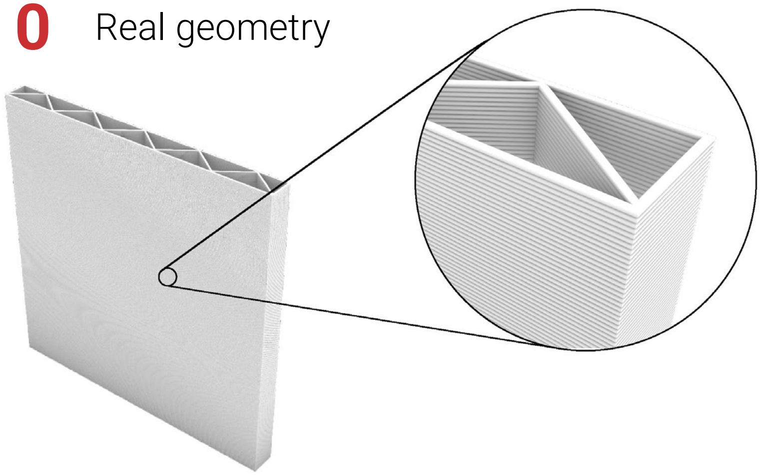
Simplified geometry





Component Scale

0 Real geometry



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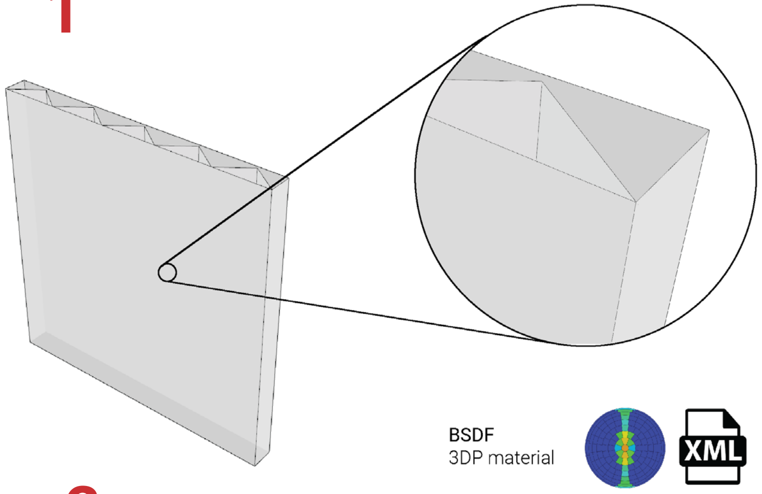

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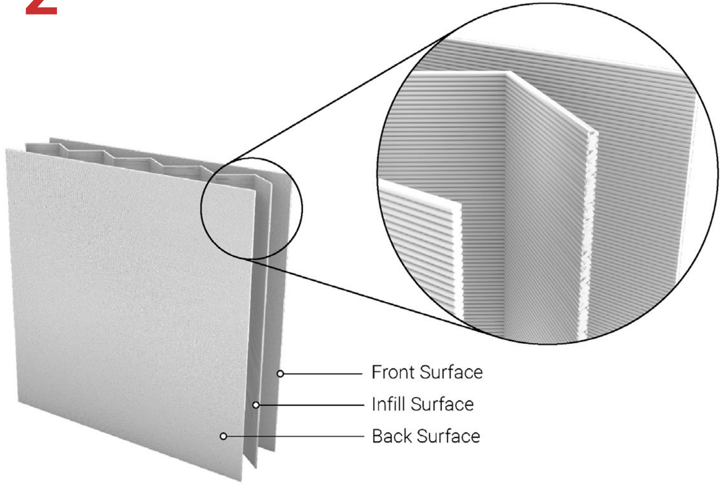

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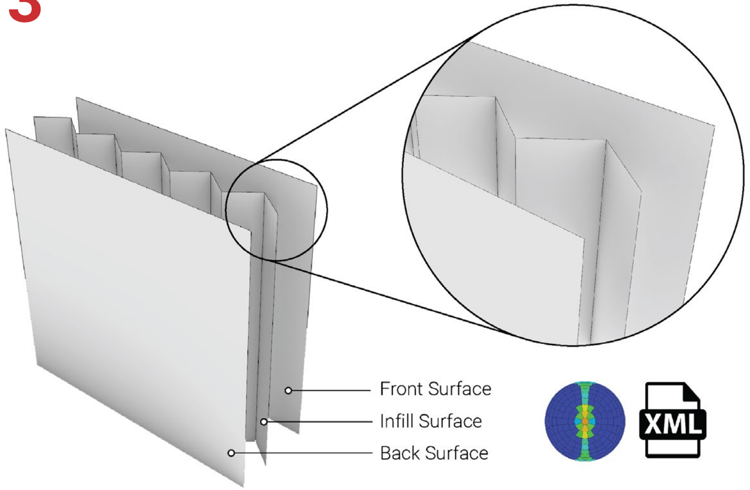
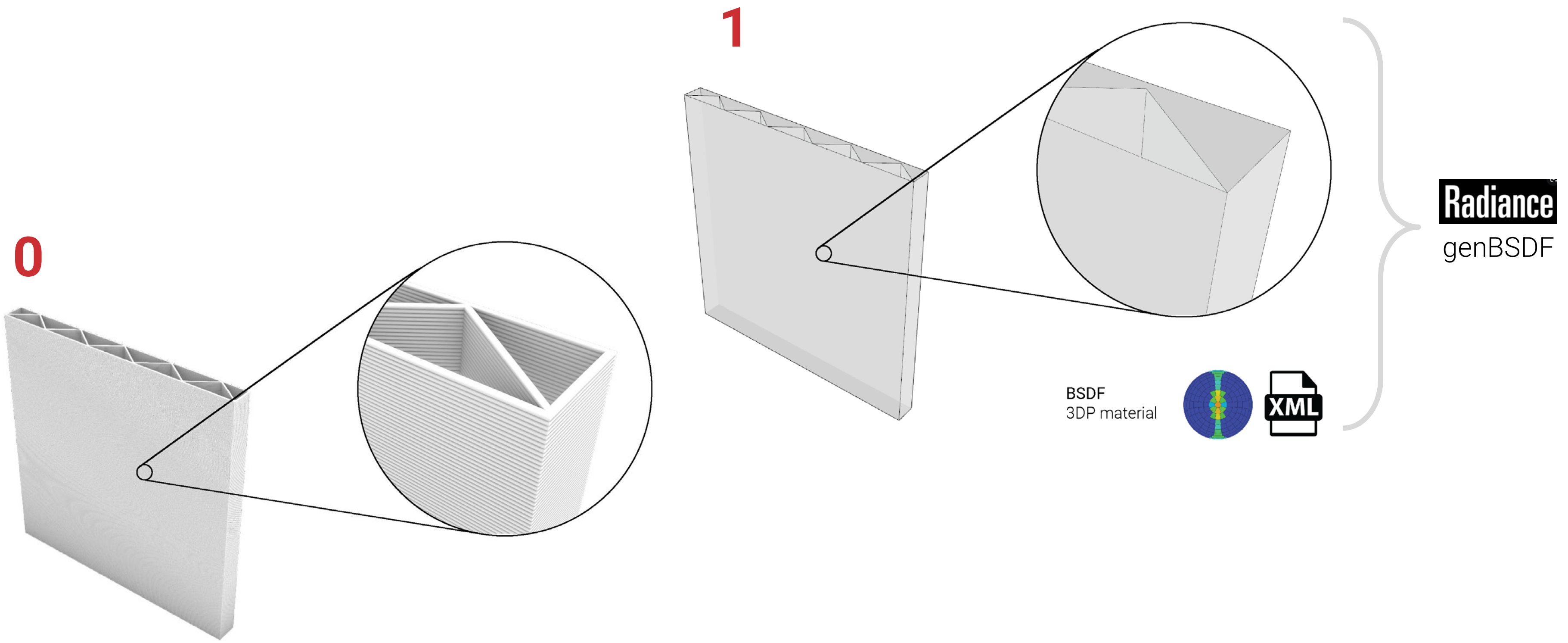
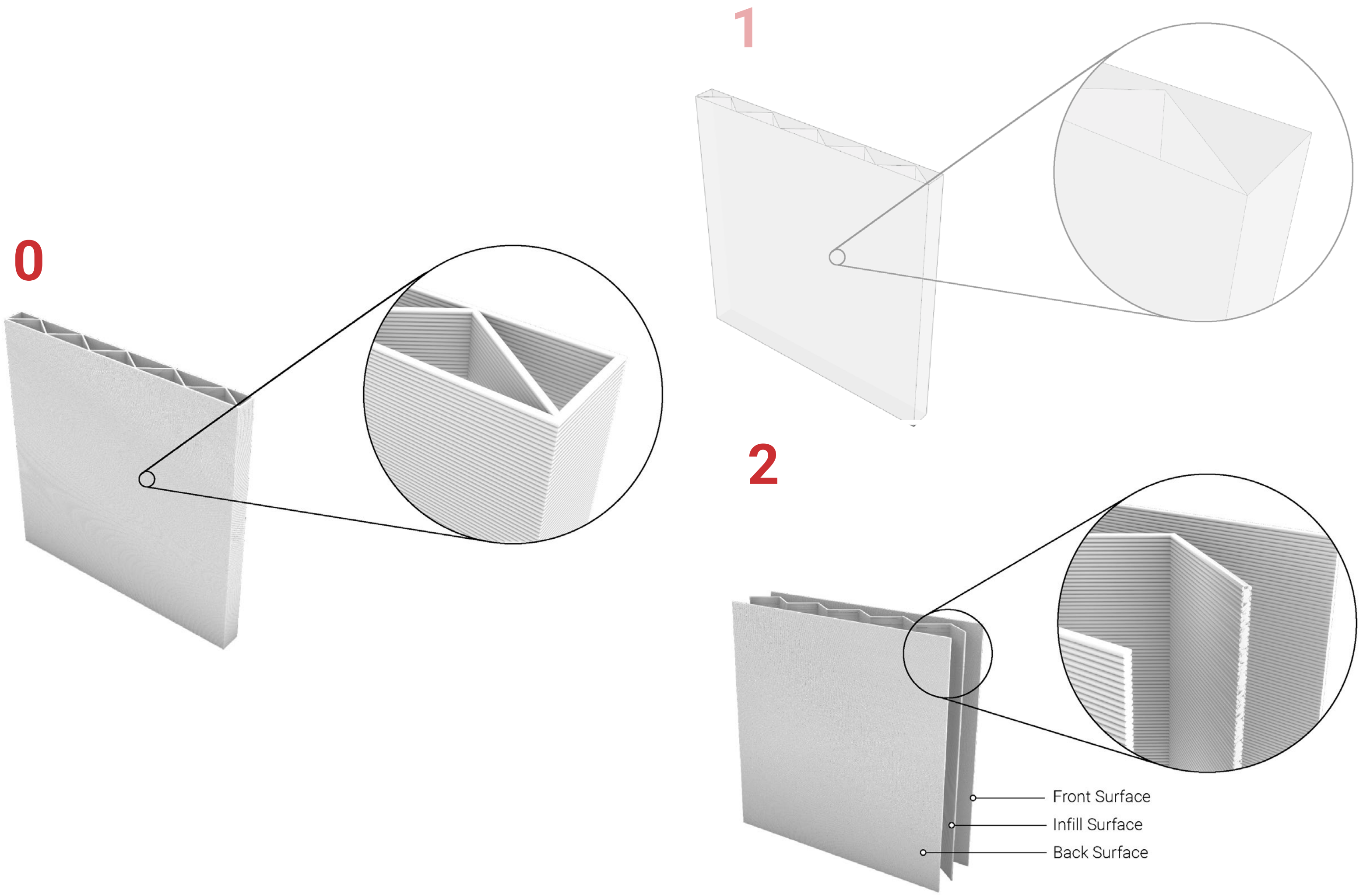
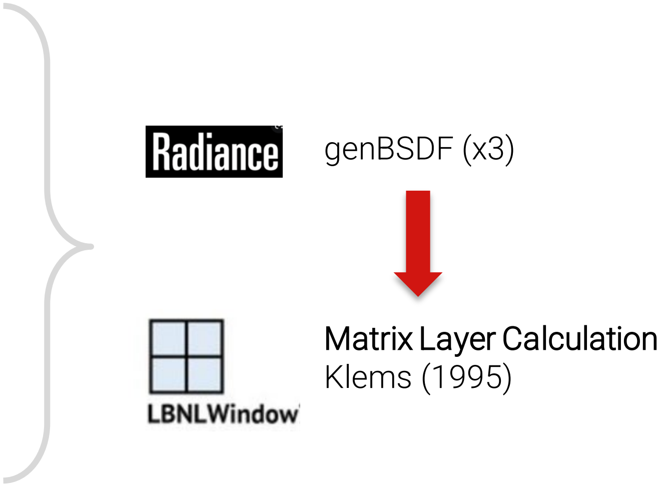


Component Scale



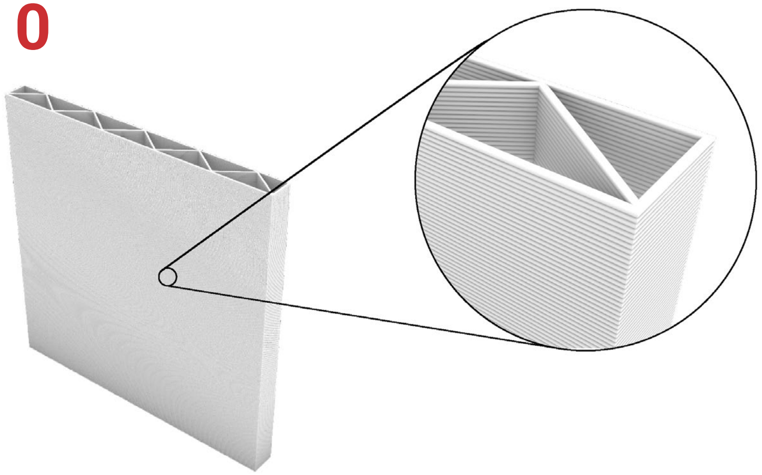
Component Scale





Component Scale

0



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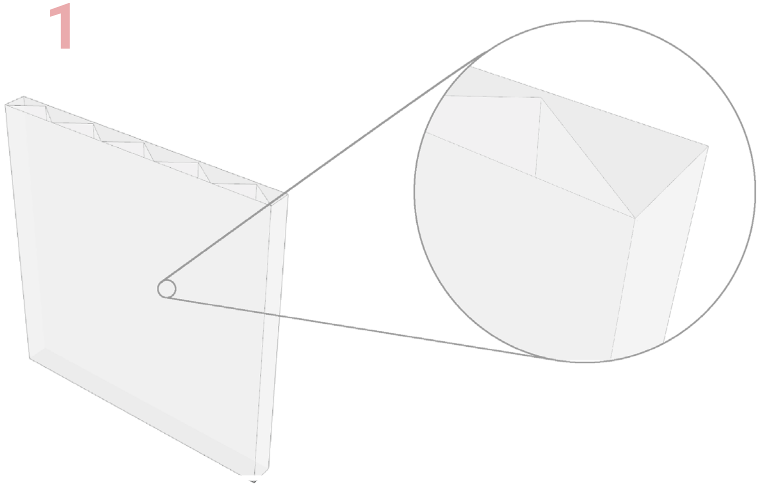

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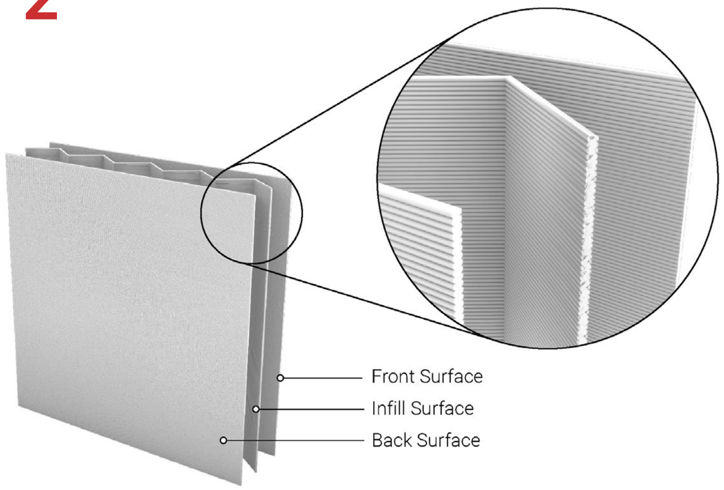
Gap 1	▸▸	1	Air		0.0
Glass 2	▸▸	00000	Dummy Glass		0.1
Gap 2	▸▸	1	Air		0.0
Shade 3	▸▸	00007	3DP Infill_Vertical_Cavities		76.0
Gap 3	▸▸	1	Air		0.0
Glass 4	▸▸	00000	Dummy Glass		0.1
Gap 4	▸▸	1	Air		0.0
Shade 5	▸▸	00006	3DP Flat Sheet_Horizontal		6.0

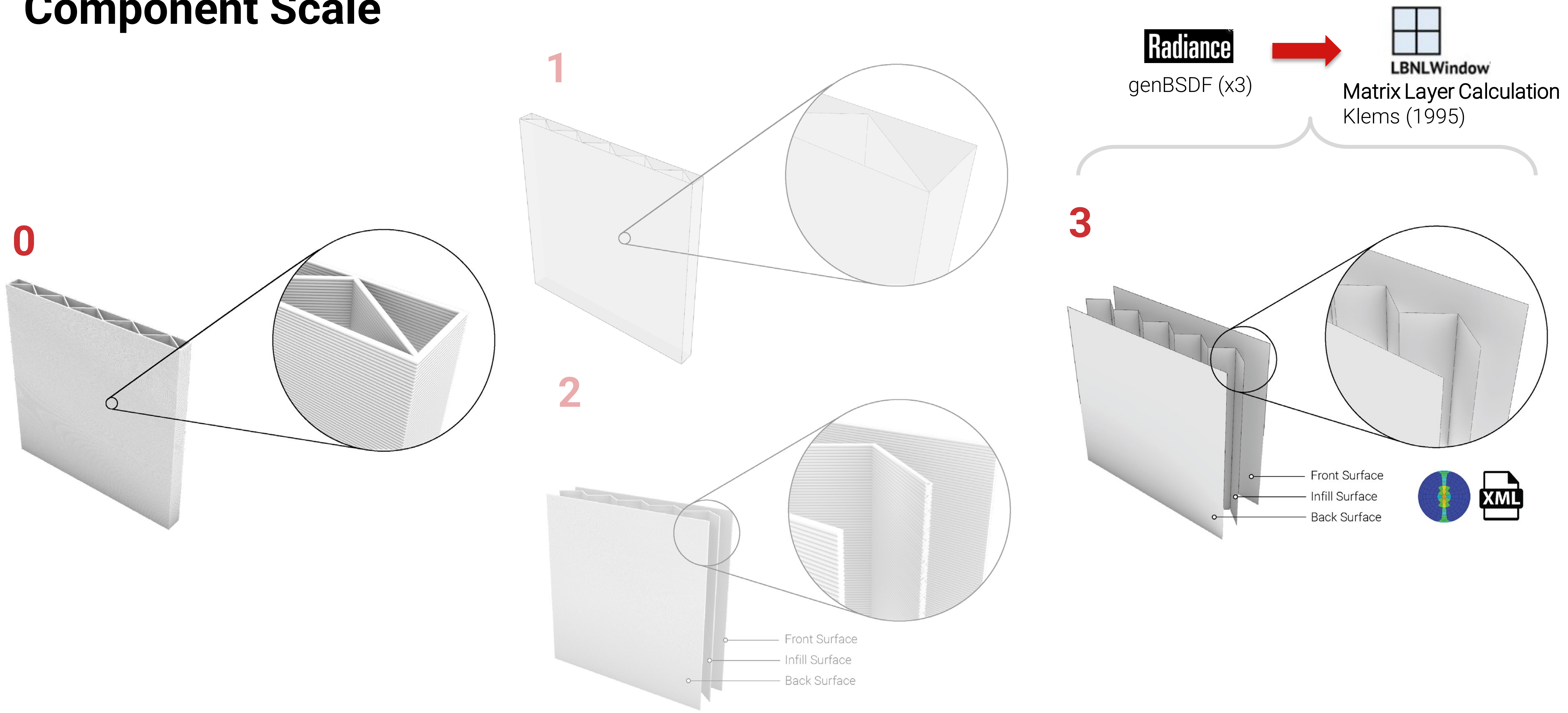
2



Radiance genBSDF (x3)

LBNLWindow Matrix Layer Calculation
Klems (1995)

Component Scale



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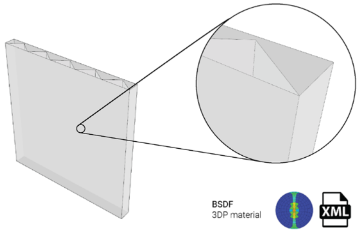
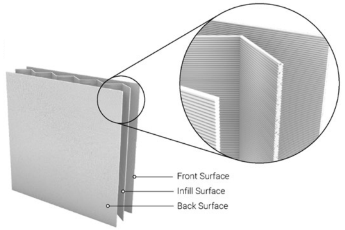
Component Scale



Approach 1

Pros:
Simple model generation
Fast runtime

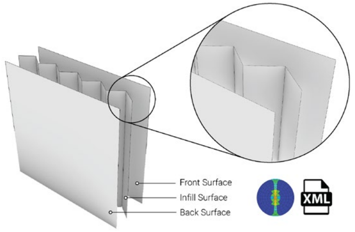
Cons:
Missing full component description (thermal properties)



Approach 2

Pros:
Full component description in WINDOW (SHGC, U-value)

Cons:
Complex model generation
Long runtime per layer
Convoluted workflow

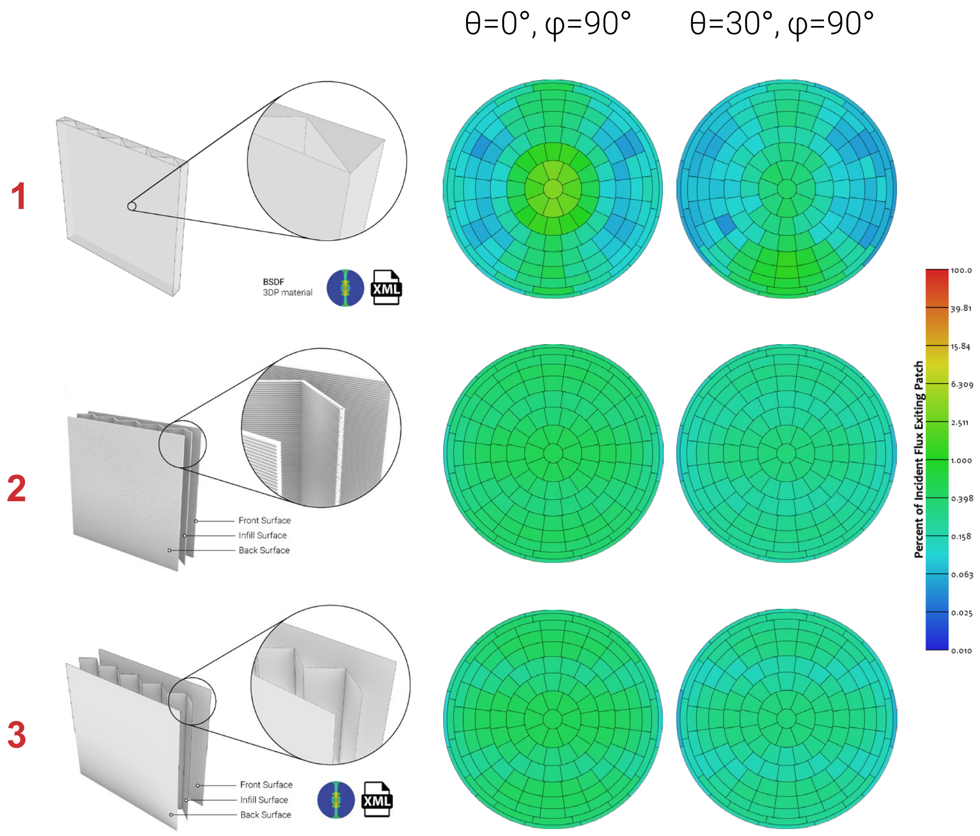


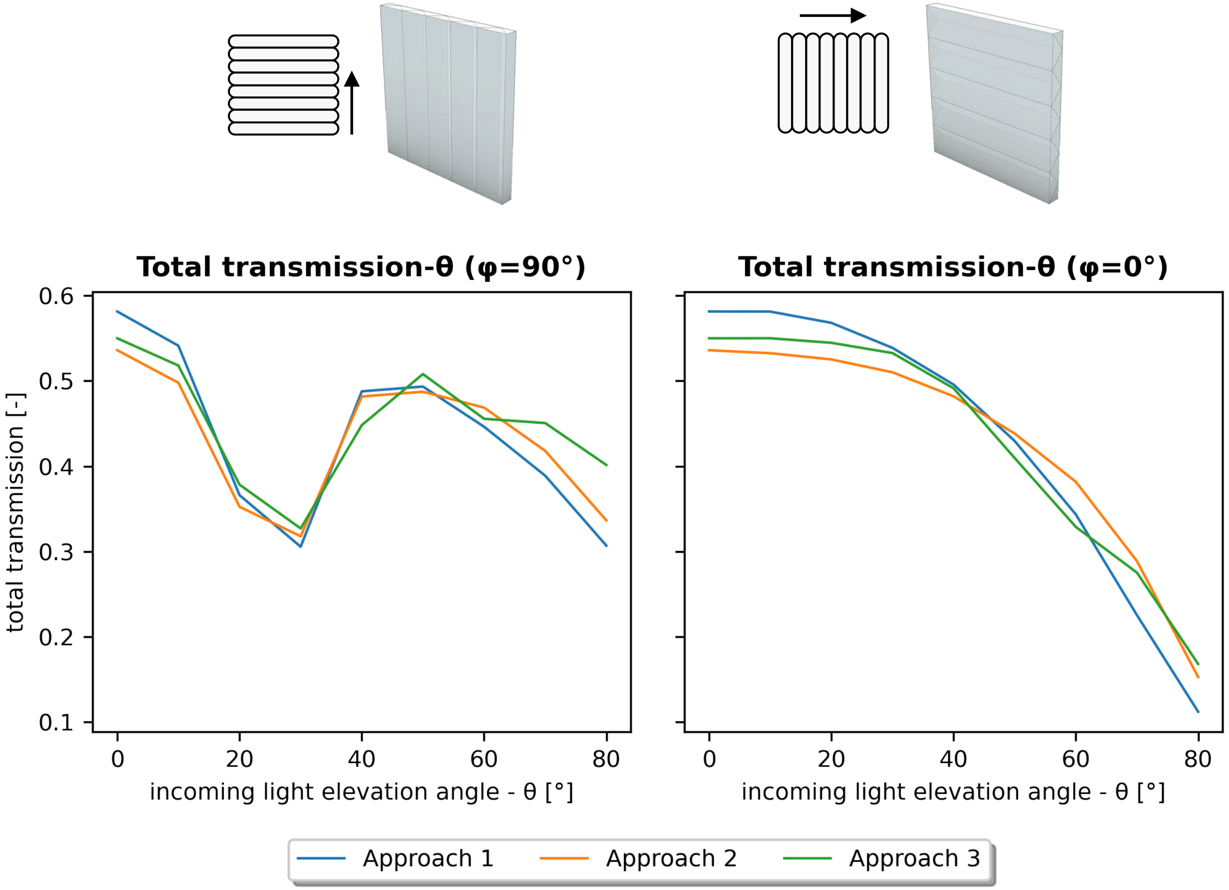
Approach 3

Pros:
Fast runtime per layer
Full component description in WINDOW (SHGC, U-value)

Cons:
Convoluted workflow

Component Scale



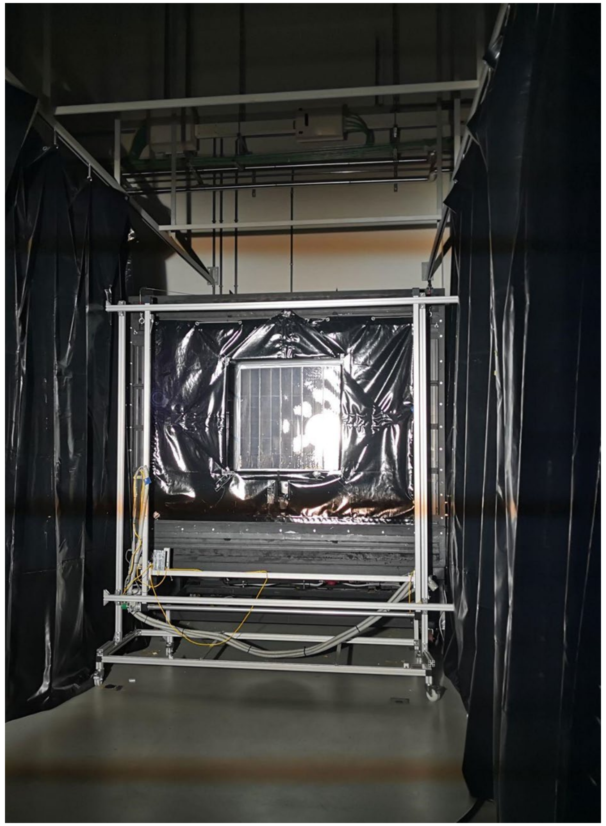


Component Scale

Solar-thermal characterisation

- Description of angle-dependent SHGC
- Integrating knowledge about thermal properties
- Validation of Radiance + Window modelling approach

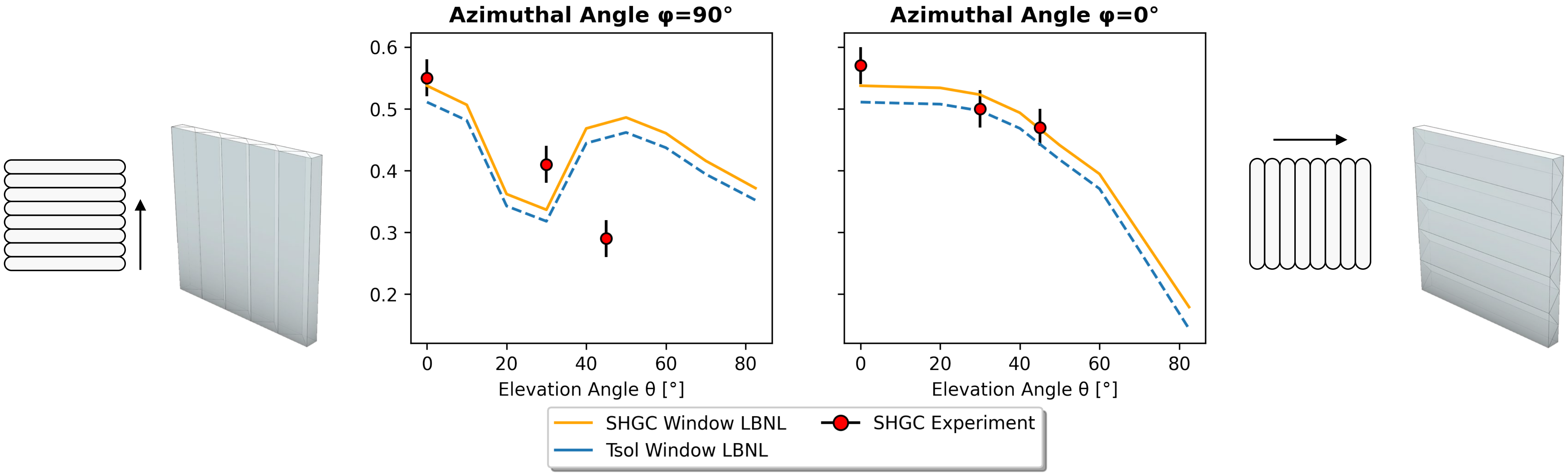
3DP façade sample fabricated at the Robotic Fabrication Lab in ETH Zürich



Sample installed at the G-value Lab in EURAC, Bolzano

Component Scale

Solar-thermal characterisation



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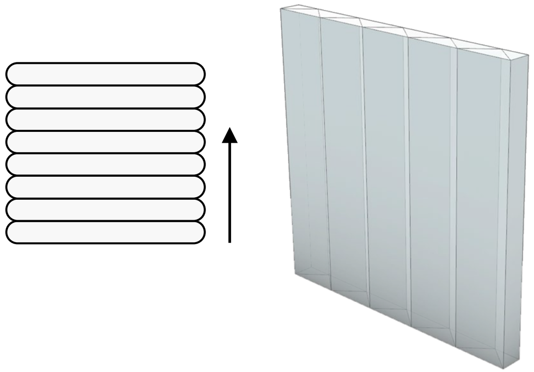
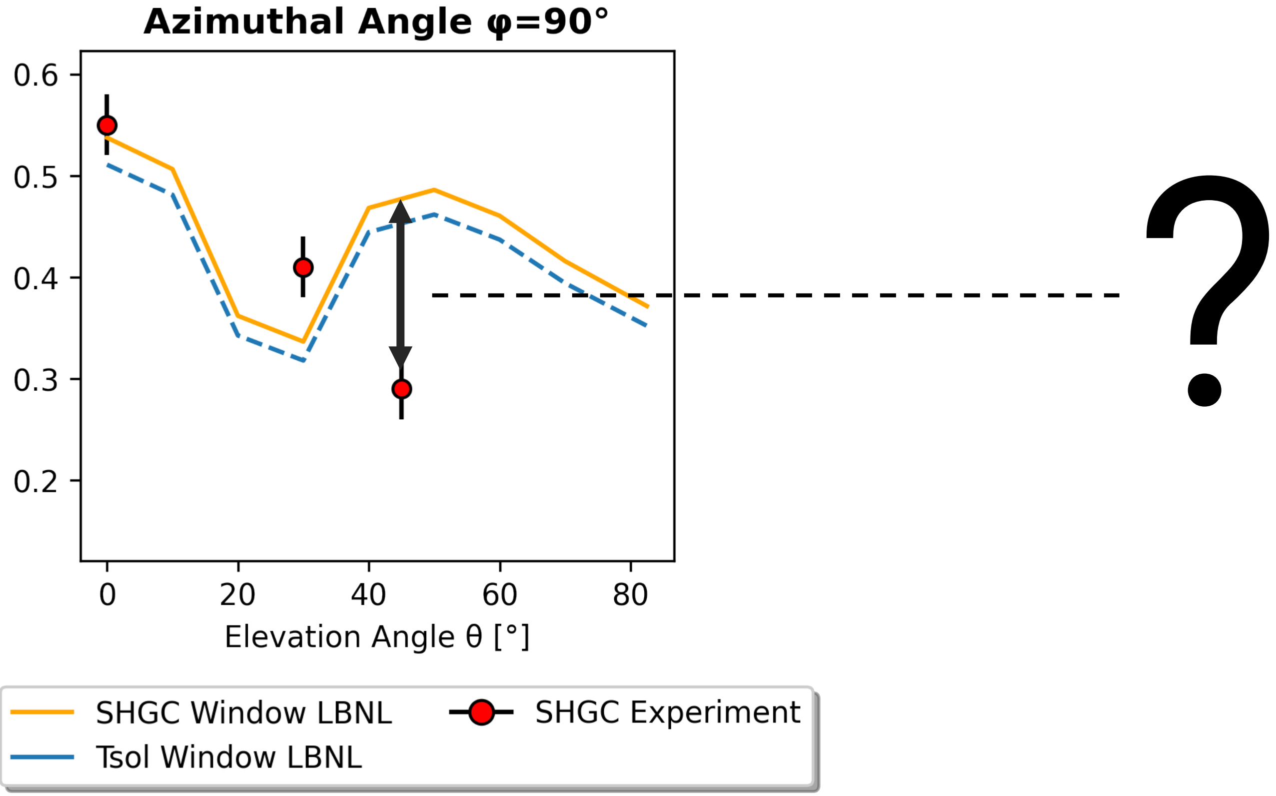
Component Scale

Solar-thermal characterisation





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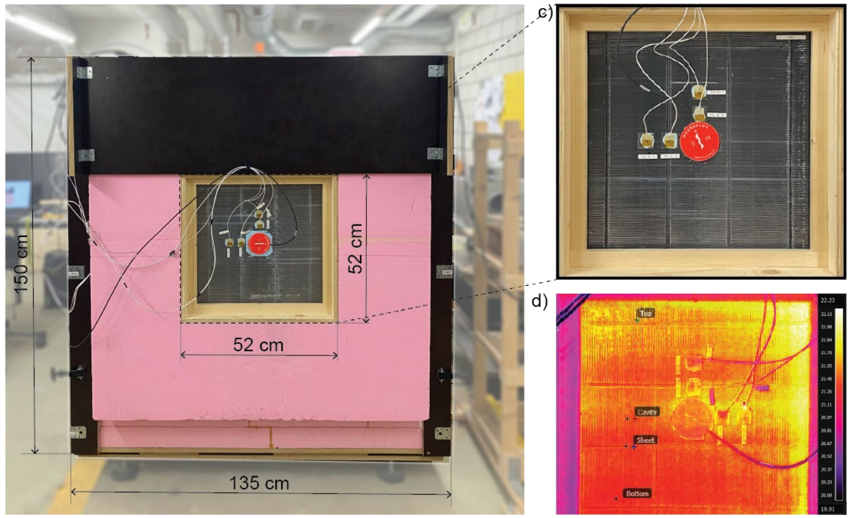
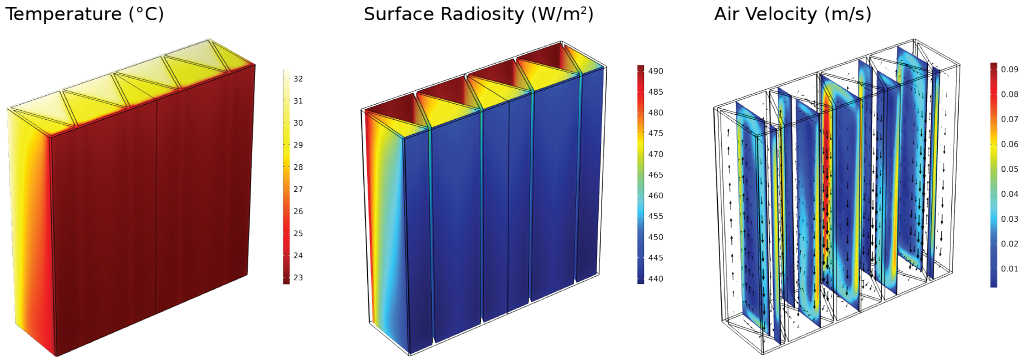
Component Scale

Thermal characterisation

- Complex geometries cannot be treated using ISO15099
- Measurement of u-value using the HB-HFM method
- Experimentally validated simulation model of heat transfer effects in 3DP components





Piccioni, Leschok et al., 2023. DOI 10.1088/1755-1315/1196/1/012063

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Component Scale

Thermal characterisation

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<!-- Created by: genBSDF +f +b +geom centimeter -c 5000 Infill_3DP.rad -->
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        <ThermalConductivity>0.27</ThermalConductivity>
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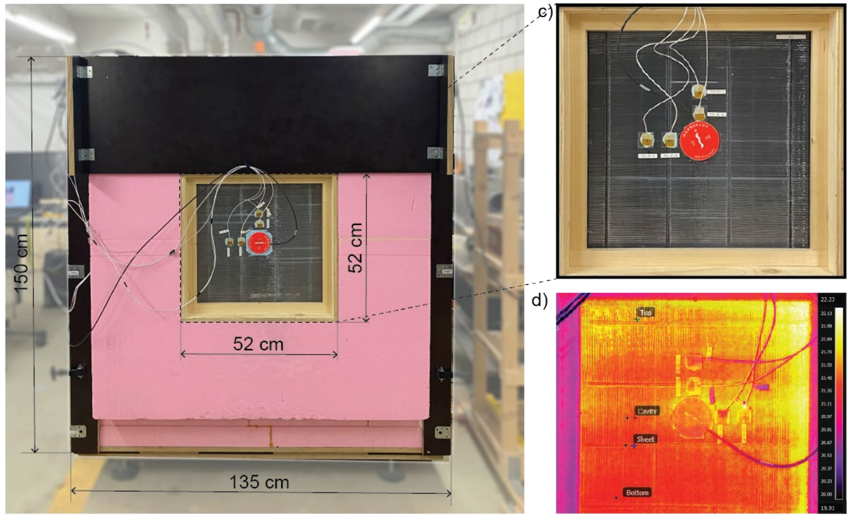
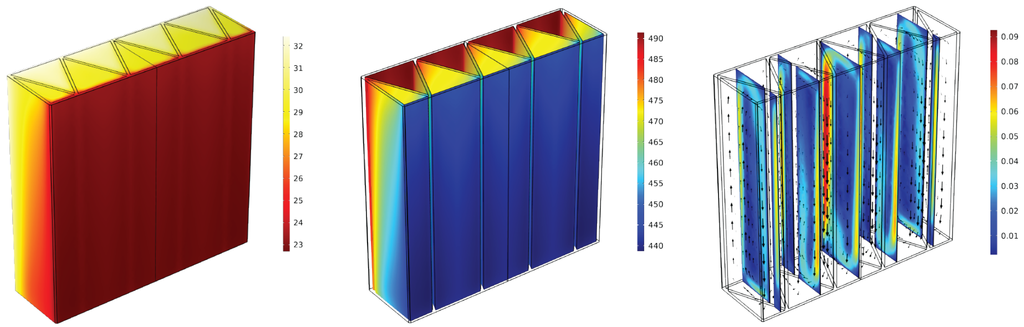
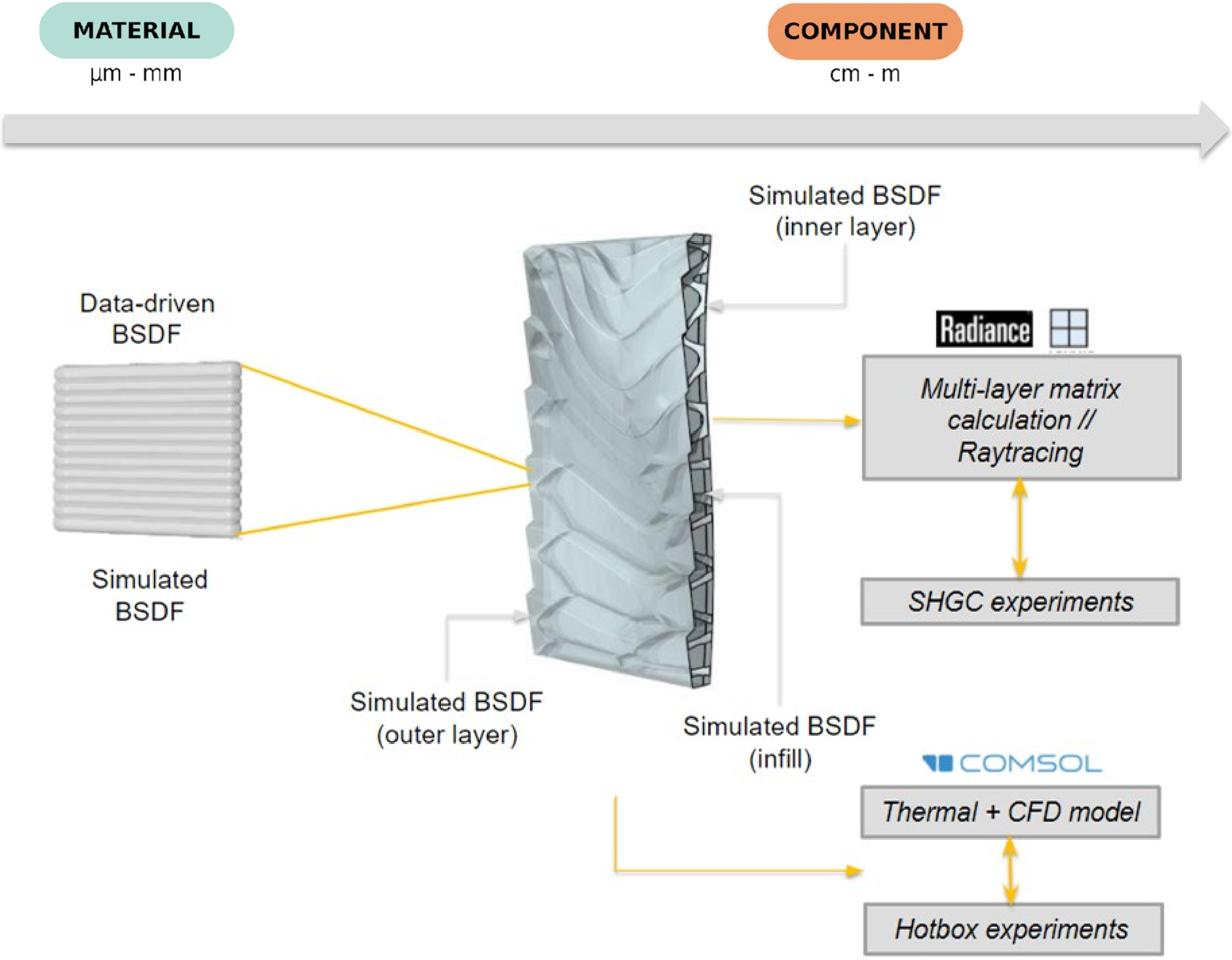
        <TIR>0</TIR>
        <PermeabilityFactor>0</PermeabilityFactor>
    </Material>
    <Geometry format="MGF"><MGFblock unit="centimeter">xf -t -50.178500 -50.100000 0
# The following was converted from RADIANCE scene input
```

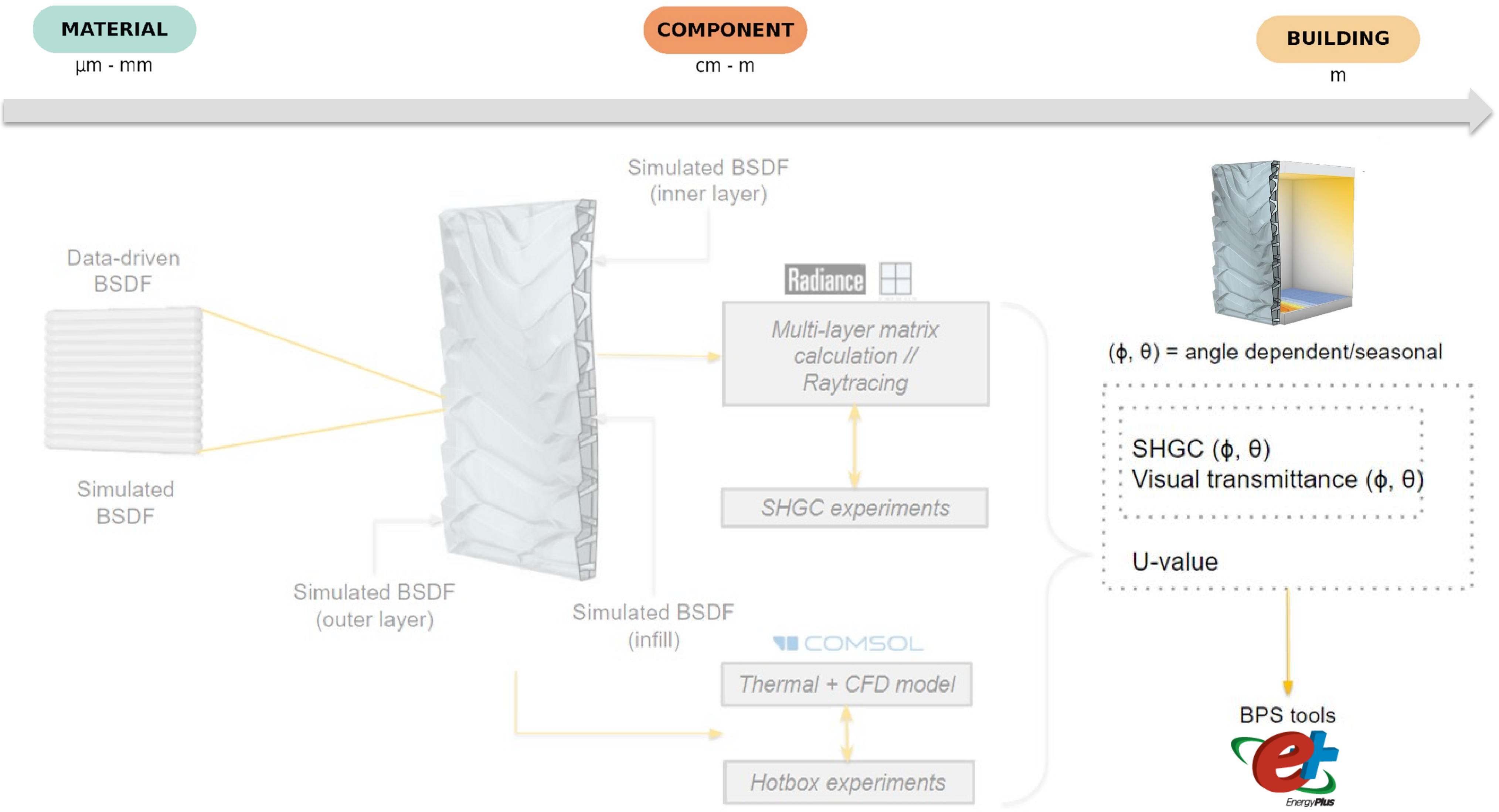
- Derive effective thermal conductivity for each layer (front, back, infill) and assign it to BSDF.xml
- WINDOW uses these to calculate U-value and the secondary heat flux of the component
- Treat cavities as solid and missing temperature-dependence of convective and radiative fluxes





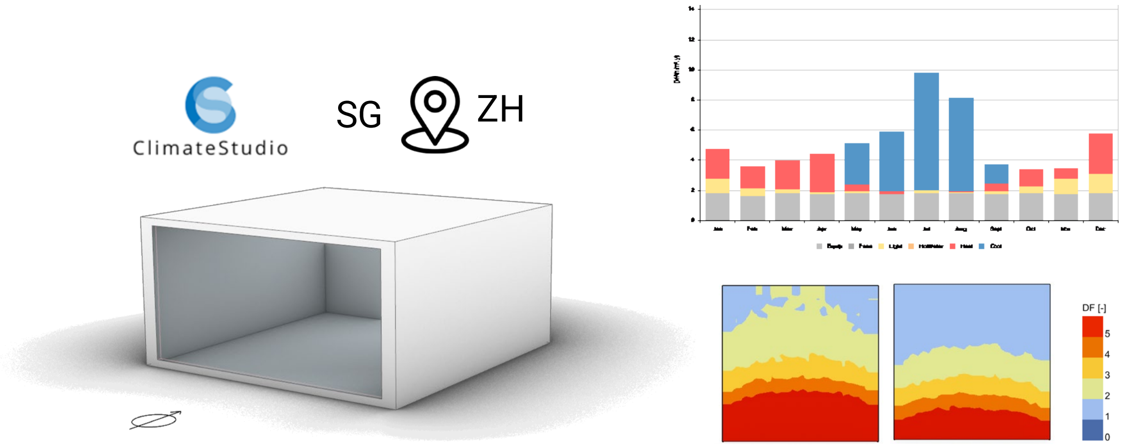
Piccioni, Leschok et al., 2023. DOI 10.1088/1755-1315/1196/1/012063


MATERIAL
µm - mm
COMPONENT
cm - m
Simulated BSDF
(inner layer)
Data-driven
BSDF
Radiance
Multi-layer matrix
calculation //
Raytracing
Simulated
BSDF
SHGC experiments
Simulated BSDF
(outer layer)
Simulated BSDF
(infill)
COMSOL
Thermal + CFD model
Hotbox experiments

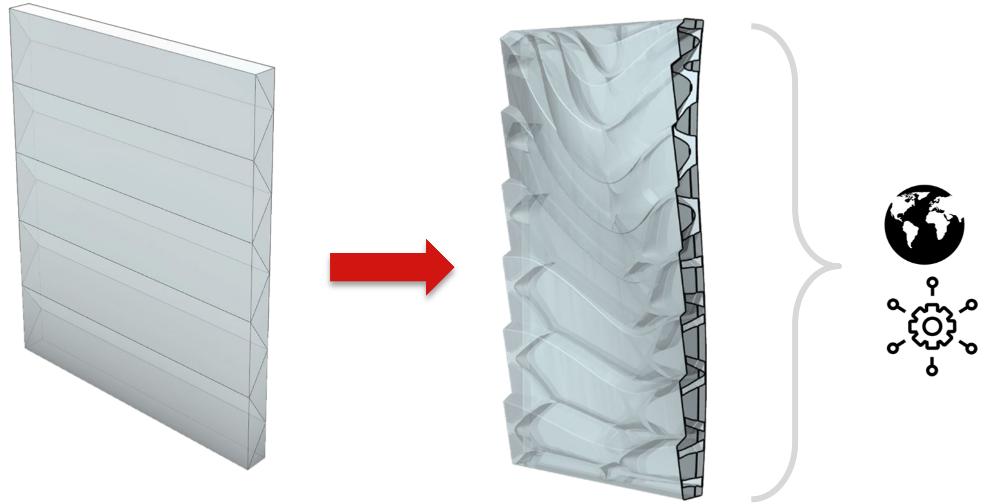

MATERIAL
µm - mm
COMPONENT
cm - m
BUILDING
m
Data-driven BSDF
Simulated BSDF
Simulated BSDF (inner layer)
Simulated BSDF (outer layer)
Simulated BSDF (infill)
Radiance
Multi-layer matrix calculation // Raytracing
SHGC experiments
COMSOL
Thermal + CFD model
Hotbox experiments
(ϕ, θ) = angle dependent/seasonal
SHGC (ϕ, θ)
Visual transmittance (ϕ, θ)
U-value
BPS tools
EnergyPlus

Outlook

Design for the building scale



- Validation and refinement of simulation approach for solar-thermal aspects
- Building-scale simulation of the performance of a 3DP façade in different climates
- Performance-informed design strategies for site-specific façade components



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NCCR Project 1C

Integrated 3D Printing Facade

Valeria Piccioni
Architecture and Building Systems

Matthias Leschok
Digital Building Technologies

Ina Cheibas
Architecture and Digital Fabrication

A/S Architecture and Building Systems

dbt Digital Building Technologies

GRAMAZIO KOHLER RESEARCH

National Centre of Competence in Research Digital Fabrication