TU Delft

Enlightening cities: Design for natural rhythm

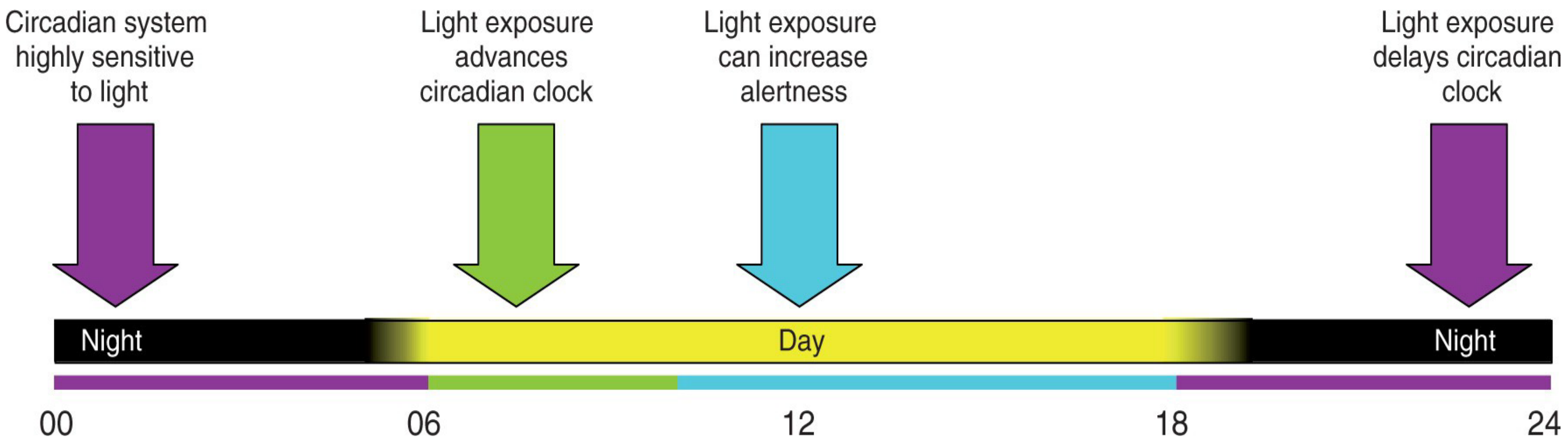
A framework for measuring the impact of facade- and city lighting design on circadian rhythm

Maartje Damen, 28-10-2024

Nima Forouzandeh Shahraki, Eleonora Brembilla, Giorgio Agugiaro

TUDelft

Circadian rhythm



Sensitivity to phase change in a 24-hour timeframe, Andersen et al. (2012)

Circadian rhythm: Impact of architectural design

Urban planning strategies significantly determine the possibility to receive solar irradiation in buildings

(Lopez et al., 2016)

Window size and availability has been proven to negatively affect sleep duration, sleep disturbances and sleep impairments

(Ghaeili Ardabili et al., 2023)

High levels of outdoor artificial light at night (ALAN) have been found to correlate with later weeknight bedtime and could be a serious contributor to some of the bigger health concerns of our times

(Paksarian et al., 2020, Gaston & Sánchez De Miguel, 2022)

Research questions

Research questions

What is the impact of façade design and lighting design on circadian health in urban context?

1. What factors are to be taken into consideration for modelling the impact of urban context on circadian light availability in existing buildings?
2. How can the impact of façade design and lighting design on circadian health in urban context be simulated?
3. What design recommendations can be derived from the assessment of the impact of façade design and lighting design on circadian health in urban context?

TUDelft

Goal

Enhancement of the accuracy and usability of the current 3D models for circadian lighting analysis, with the development of a method to enrich existing 3D data by incorporating precise information about window and floor levels.

The execution of a large-scale circadian lighting analysis that delivers results with a level of accuracy that closely approximates real-world conditions for individual homes and floor levels.

TU Delft

Content

- Introduction
- Research questions
- Methodology
  - **Phase 0:** Quantifying the impact of the built environment on circadian health
  - Geometrical preparation:

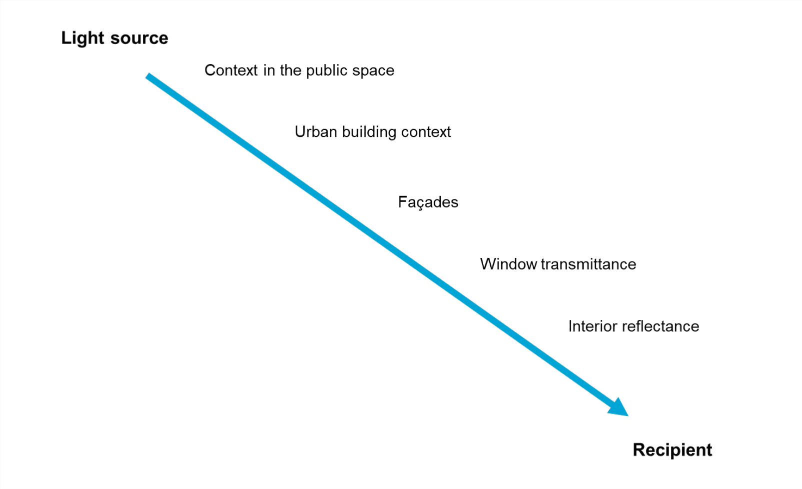
    Phase 1: Preparing urban geometrical and geographical information

    Phase 2: Extracting building window and floor level information from façade pictures

    Phase 3: Window boundary and floor level reconstruction in 3D environment
  - **Phase 4**: Circadian lighting modelling
- Key findings
- Discussion
- Conclusion

TU Delft

Methodology



Phase 0: Quantifying the impact of the built environment on circadian health

Scientific parameters

Intensity

Duration

Timing →

Contrast

Spectrum

	21.00-8.00	**8.00-18.00**	**18.00-21.00**
Reference value (mEDI)	<1 lx	>250 lx	<10 lx

Circadian lighting thresholds for measuring Melanopic equivalent daylight illuminance (Brown et al. 2022)

Scientific parameters

	21.00-8.00	8.00-18.00	18.00-21.00
Reference value (mEDI)	**< 1 lx**	**> 250 lx**	**< 10 lx**

Circadian lighting thresholds for measuring Melanopic equivalent daylight illuminance (based on Brown et al. 2022)

Intensity ***Timing*** ***Spectrum***

TU Delft

Intensity

3000 lx → 100 000 lx

Timing

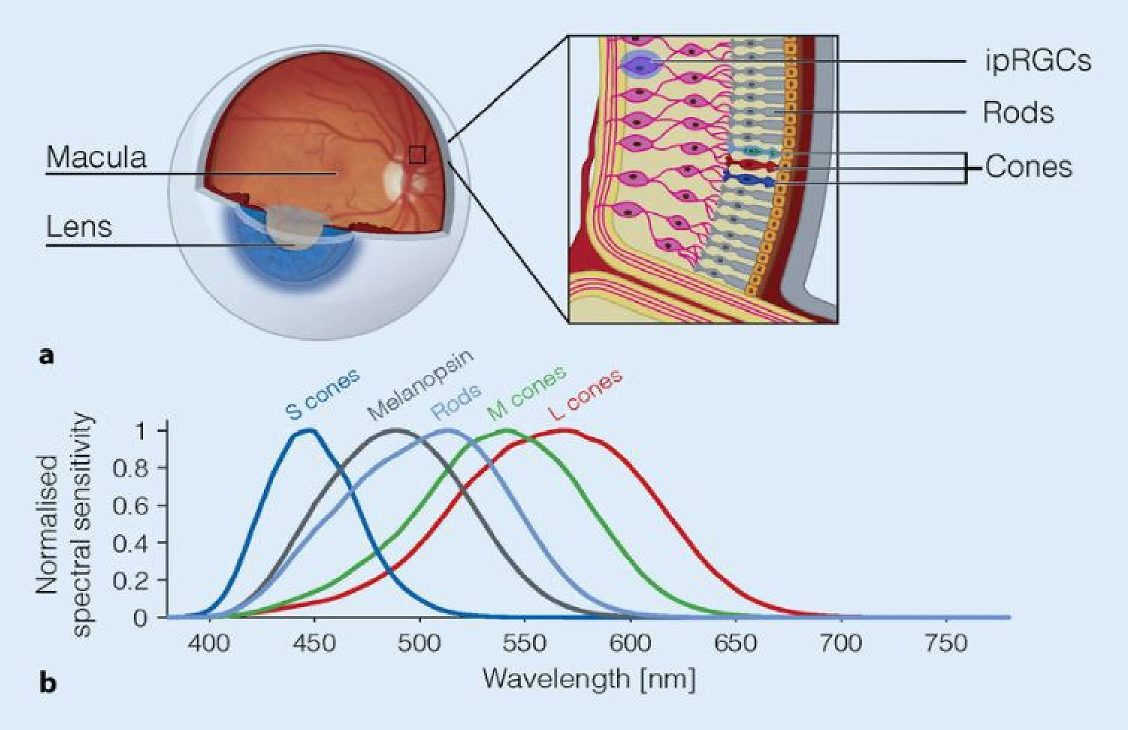
21.00 > ZZZ…. → 13.00 > !!!

Spectrum

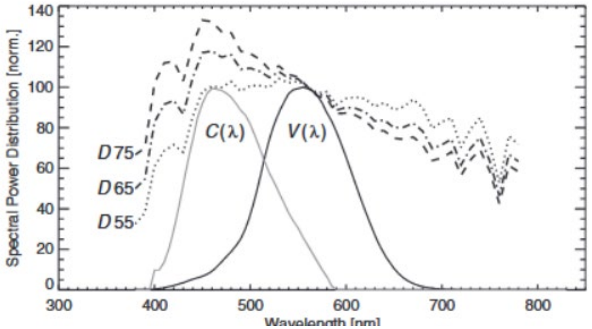
Purple/pink → Bright blue

TU Delft

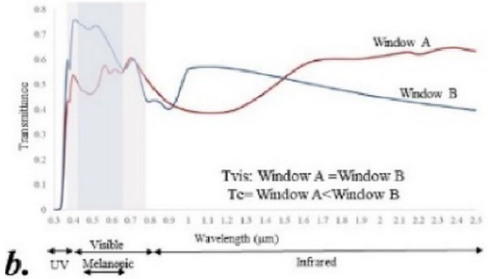
Spectrum



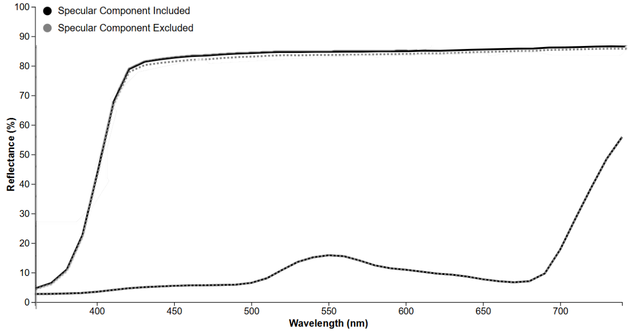
The sensitivity curves of the eye (Blume et al., 2019)



spectral power distribution for three CIE daylight illuminants, alongside photopic (V(λ)) and circadian (C (λ)) sensitivity curves (Andersen et al. 2012)



Variation in transmittance between two windows with similar Tvis (Ardabili et al., 2023)



Variation in reflectivity grass (bottom) and a white wall (top) (from spectralDB, 2024)

Quantifying the impact of the available circadian lighting

- Light source:
- **Watt:** unit of power (J/s)
- **Lumen, luminous flux:** unit of perceived power: total power Weighted by the sensitivity of the eye.
- **Lux, illuminance:** Visible light at the measurement point
- !! Visible light !!
- > to measure melanopic light:
- Circadian Stimulus (CS)
- Equivalent Melanopic Lux (EML)
- Melanopic equivalent daylight illuminance m-EDI (lx)
  - Fits within the international system of units!

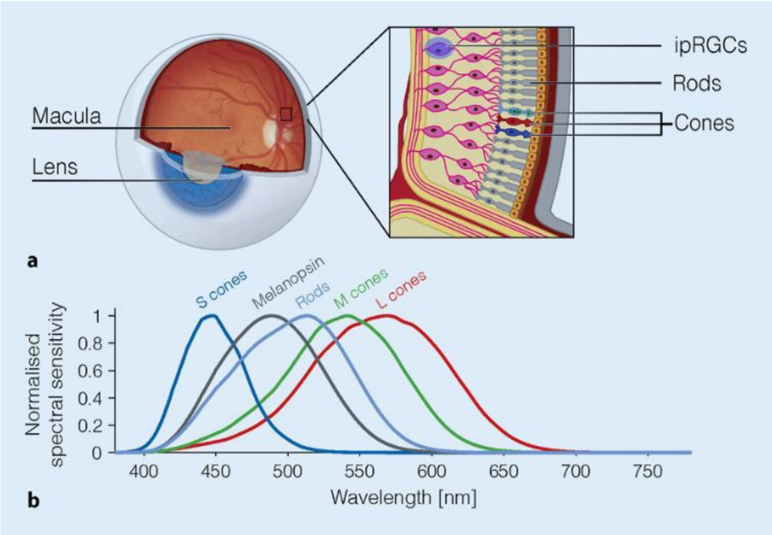


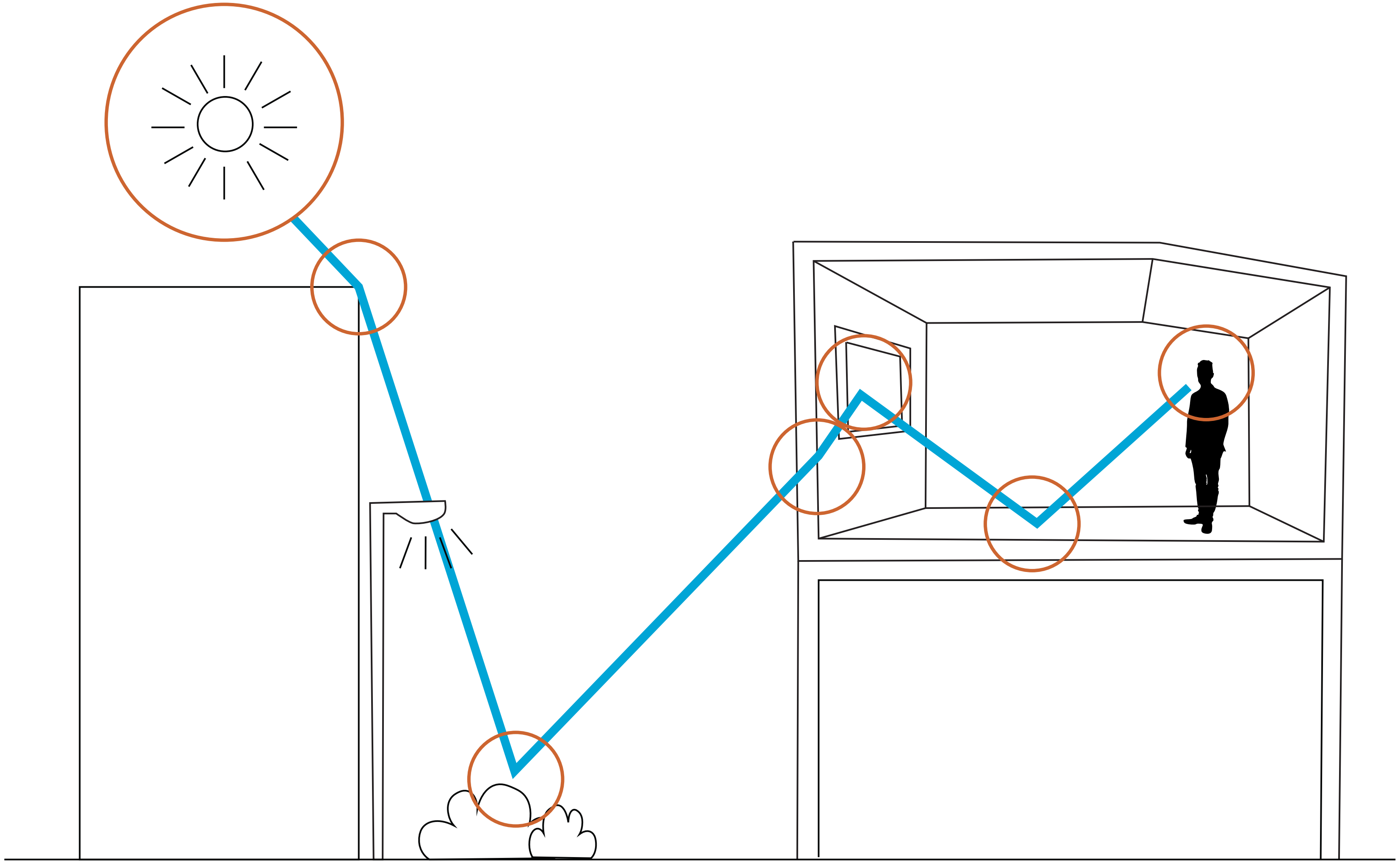
Figure 1-1 the sensitivity curves of the eye (Blume et al., 2019)

	21.00-8.00	8.00-18.00	18.00-21.00
Reference value (mEDI)	<1 lx	>250 lx	<10 lx

Circadian lighting thresholds for measuring Melanopic equivalent daylight illuminance (based on Brown et al. 2022)

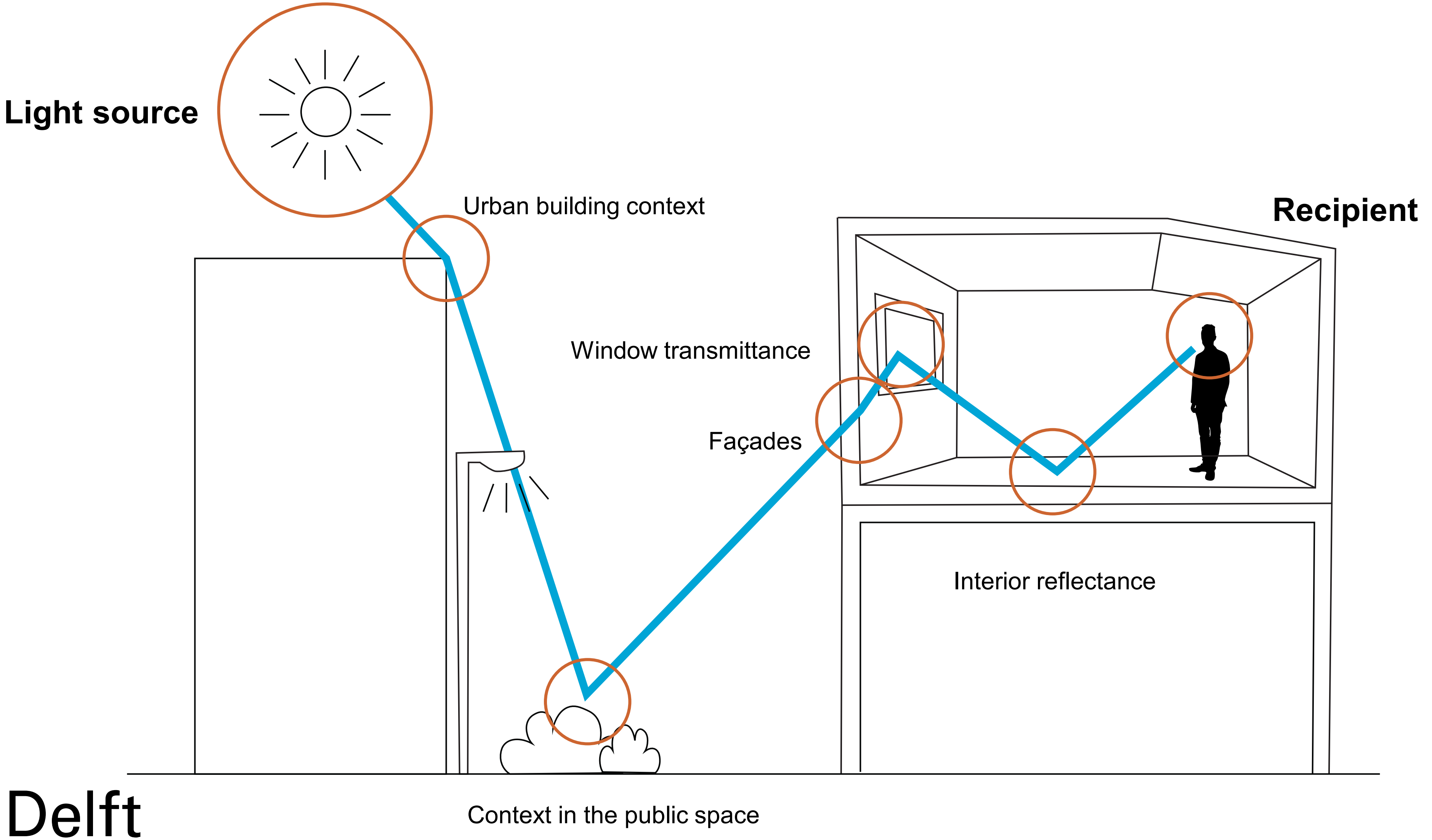
TU Delft

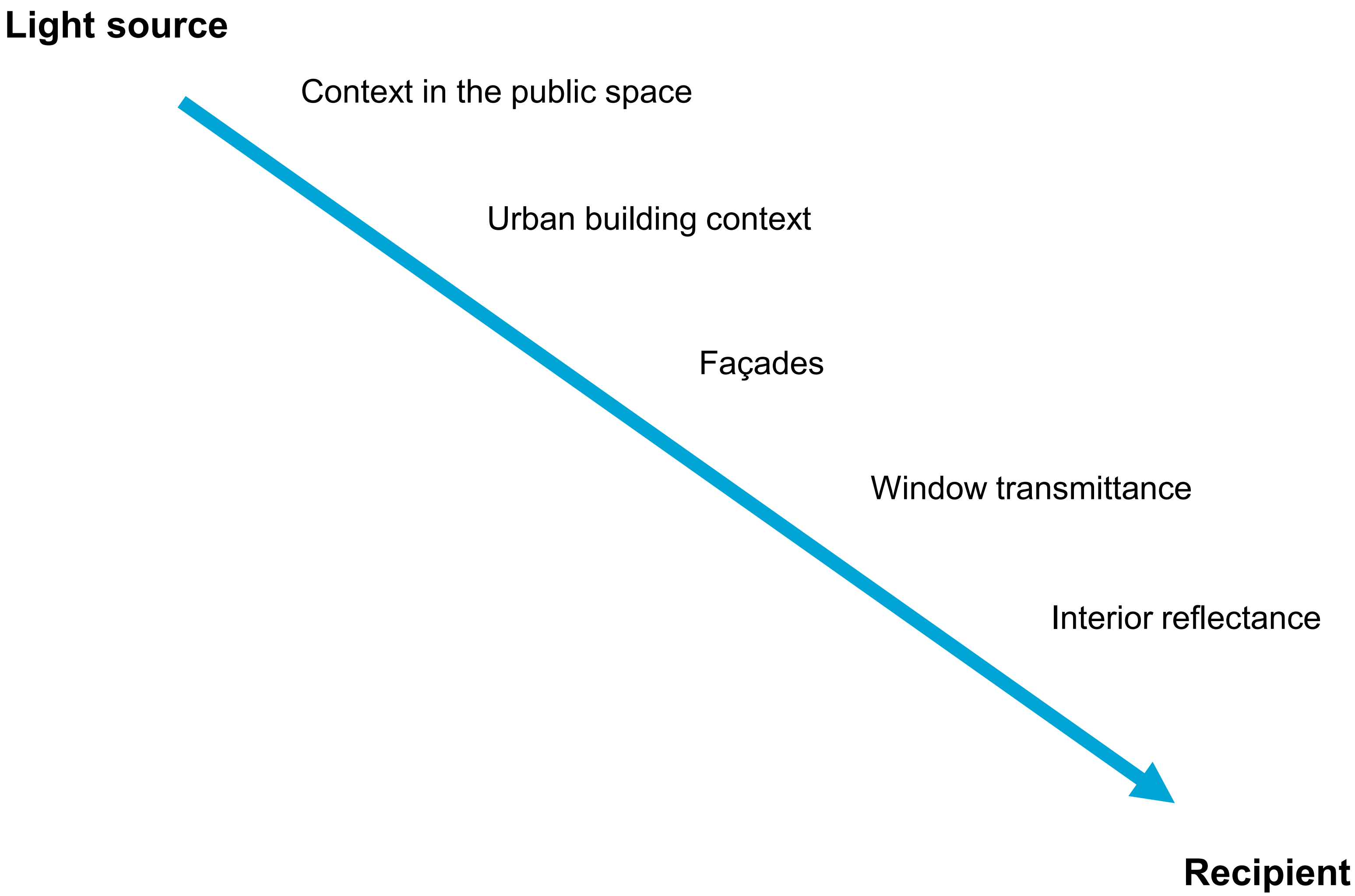
Factors affecting daylight availability



TU Delft

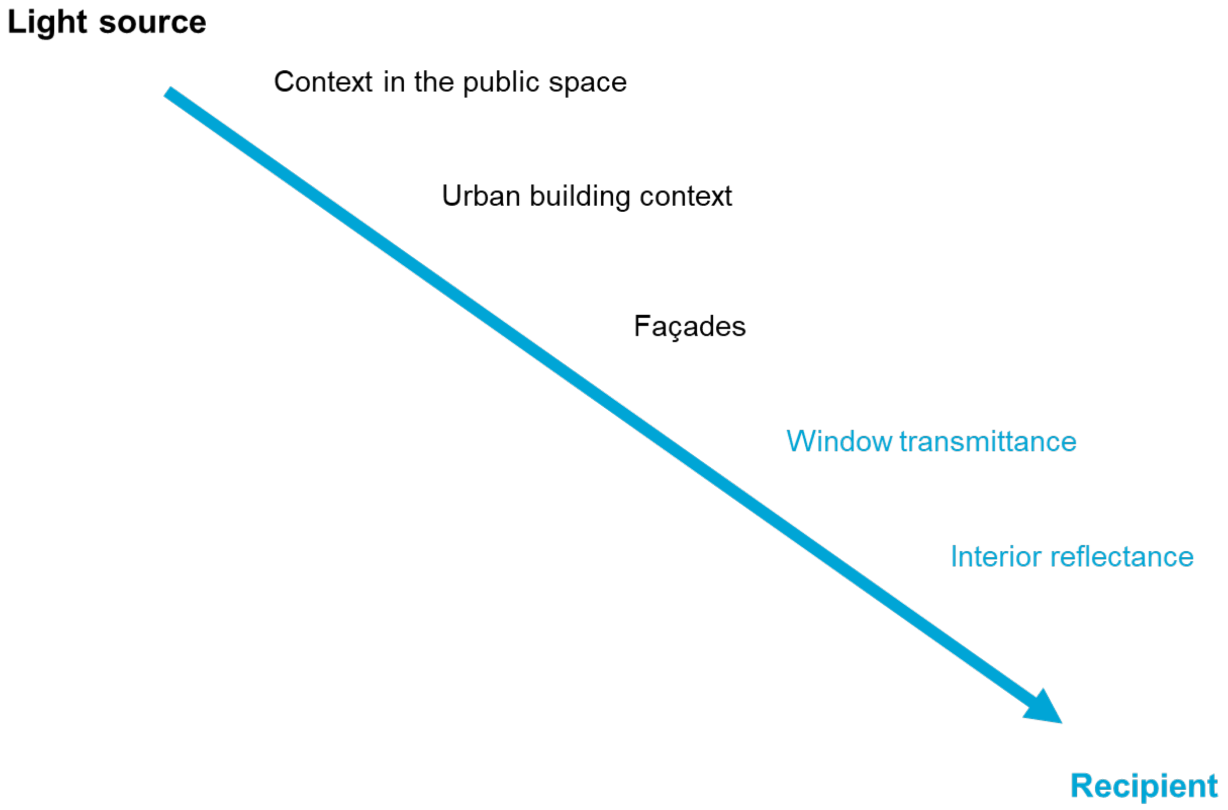
Factors affecting daylight availability



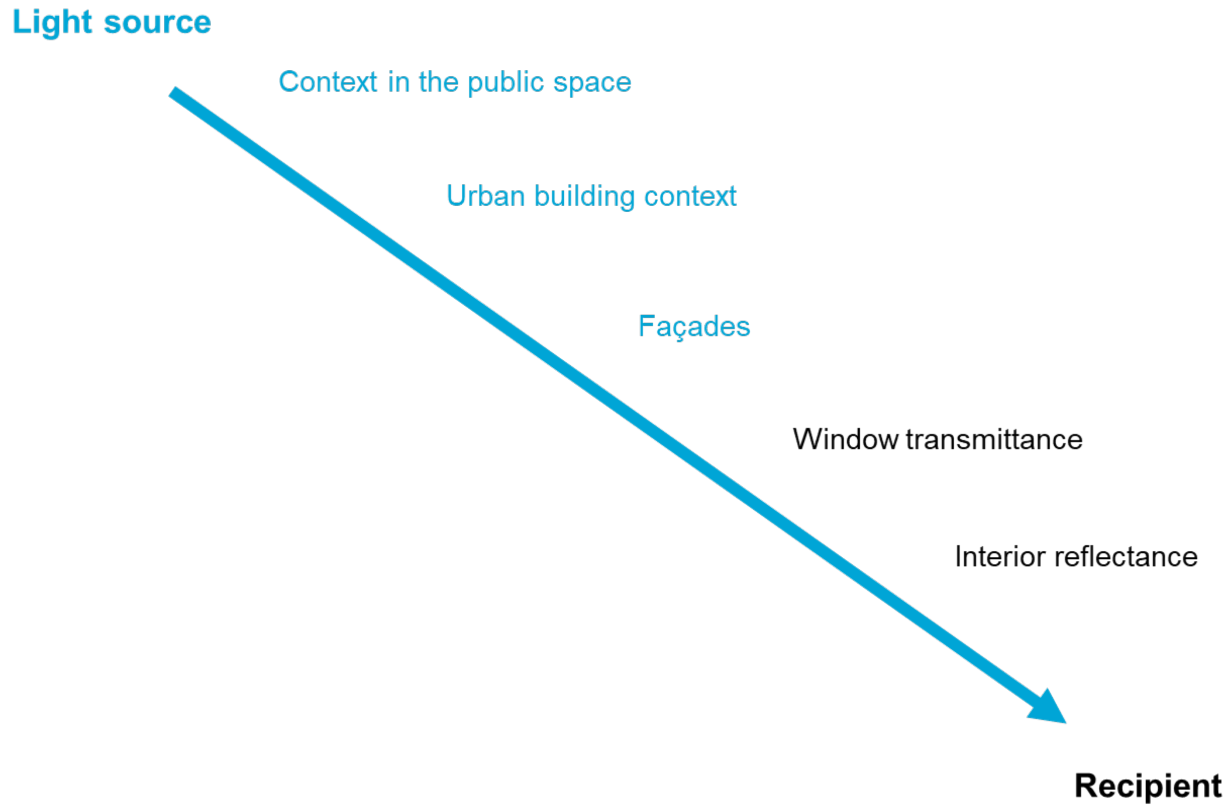

Light source
Context in the public space
Urban building context
Façades
Window transmittance
Interior reflectance
Recipient

TUDelft

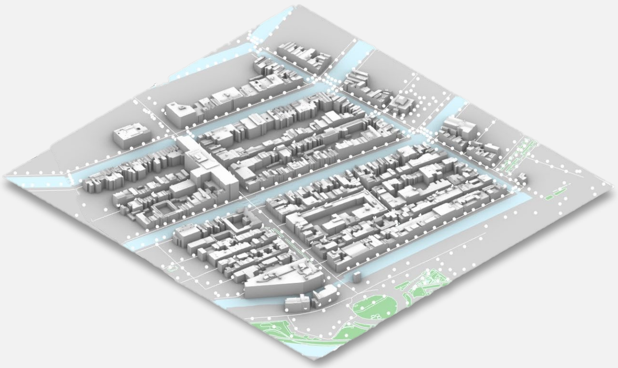
Factors considered consistent



Variable factors

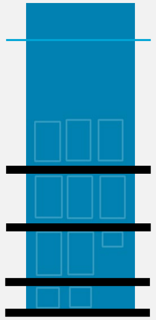


Phase 1



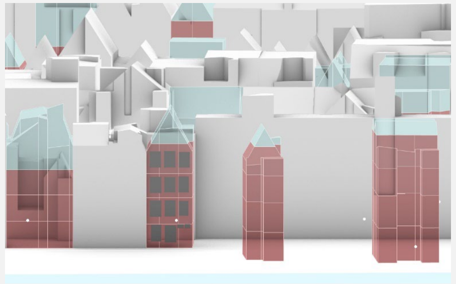
Preparing urban geometrical and geographical information

Phase 2



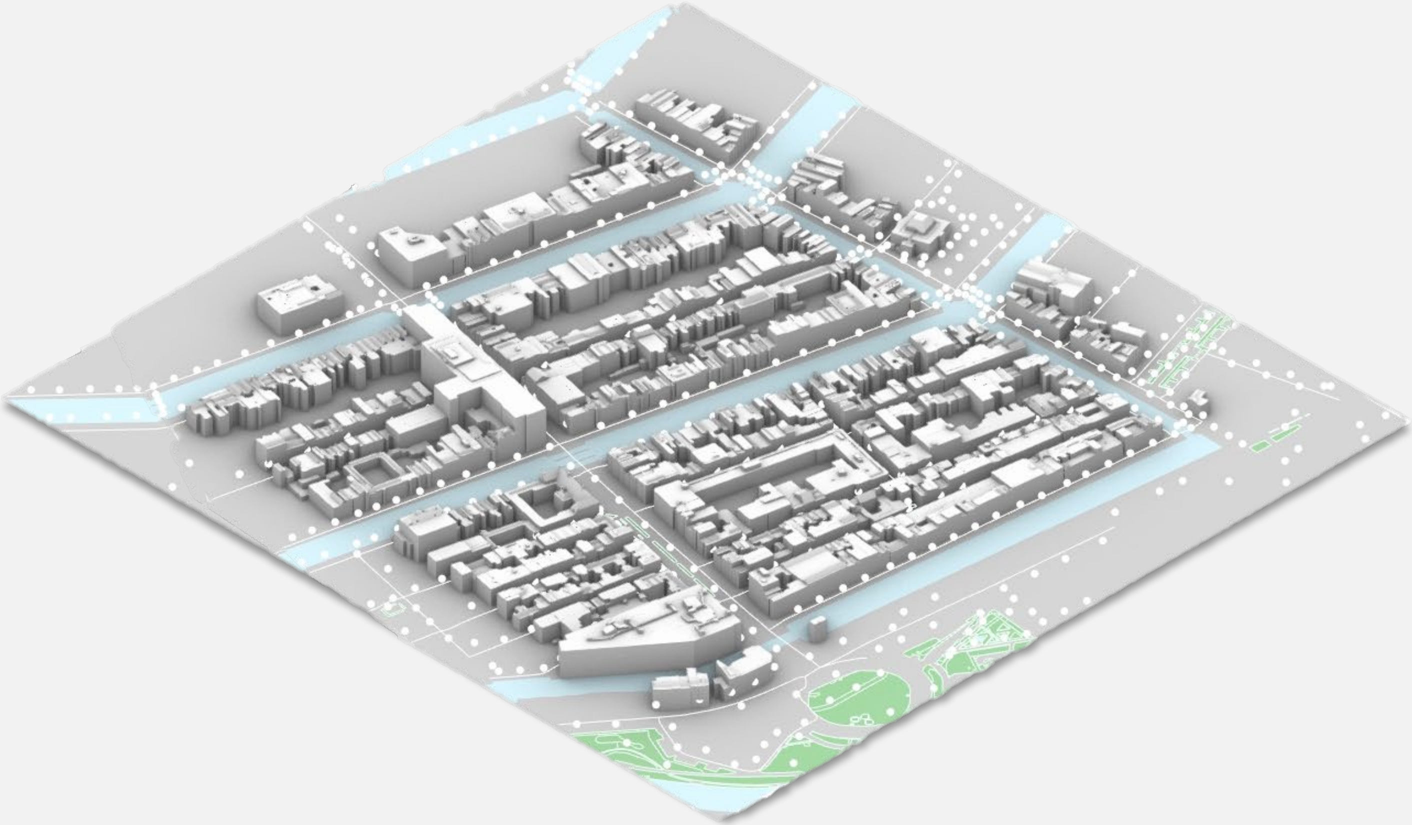
Extracting building window and floor level information from façade pictures

Phase 3



Window boundary and floor level reconstruction in 3D environment

Geometrical preparation



Geometrical preparation: Phase 1

Preparing urban geometrical and geographical information

Urban context implementation

Waterways & greenspaces

- BGT (basic registration large scale topography) (PDOK, 2024)

Urban building context

- 3DBAG Building information (Tudelft3d and 3DGI, 2024)

Street lanterns

- Data.Amsterdam (Gemeente Amsterdam, 2024)

Gathered in a Rhino Grasshopper environment

Basisregistratie Grootschalige Topografie (BGT) (PDOK, 2024)

Street lantern information (Gemeente Amsterdam, 2024)

3dBAG building information (Peters et al., 2022)

Rhinoceros 3D & rhino Grasshopper

Light source

Context in the public space

Urban building context

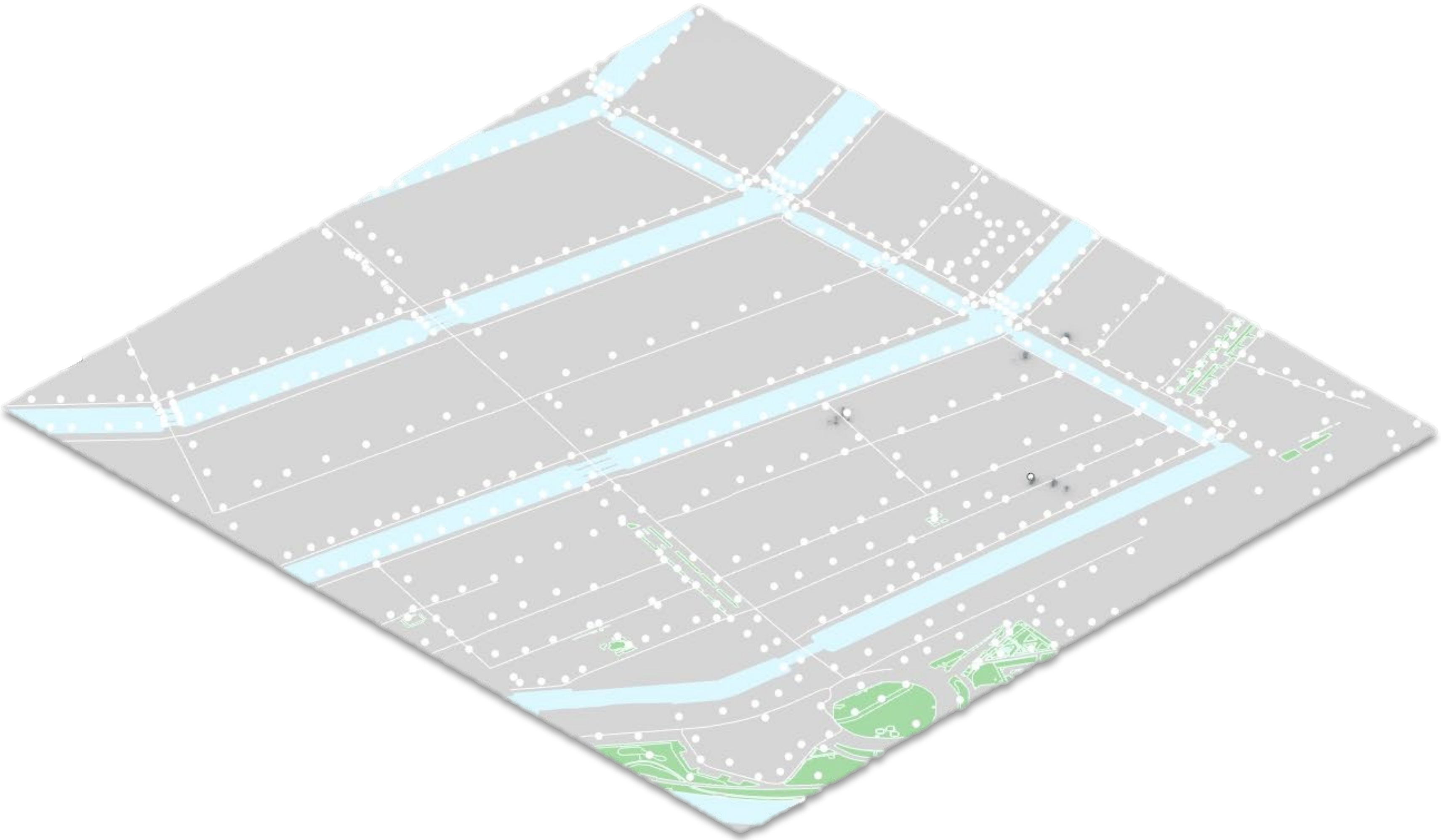
Facade

window transmittance

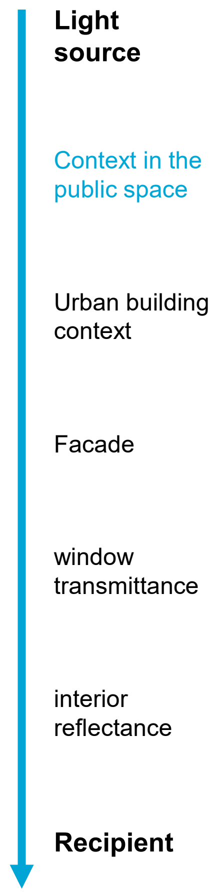
interior reflectance

Recipient

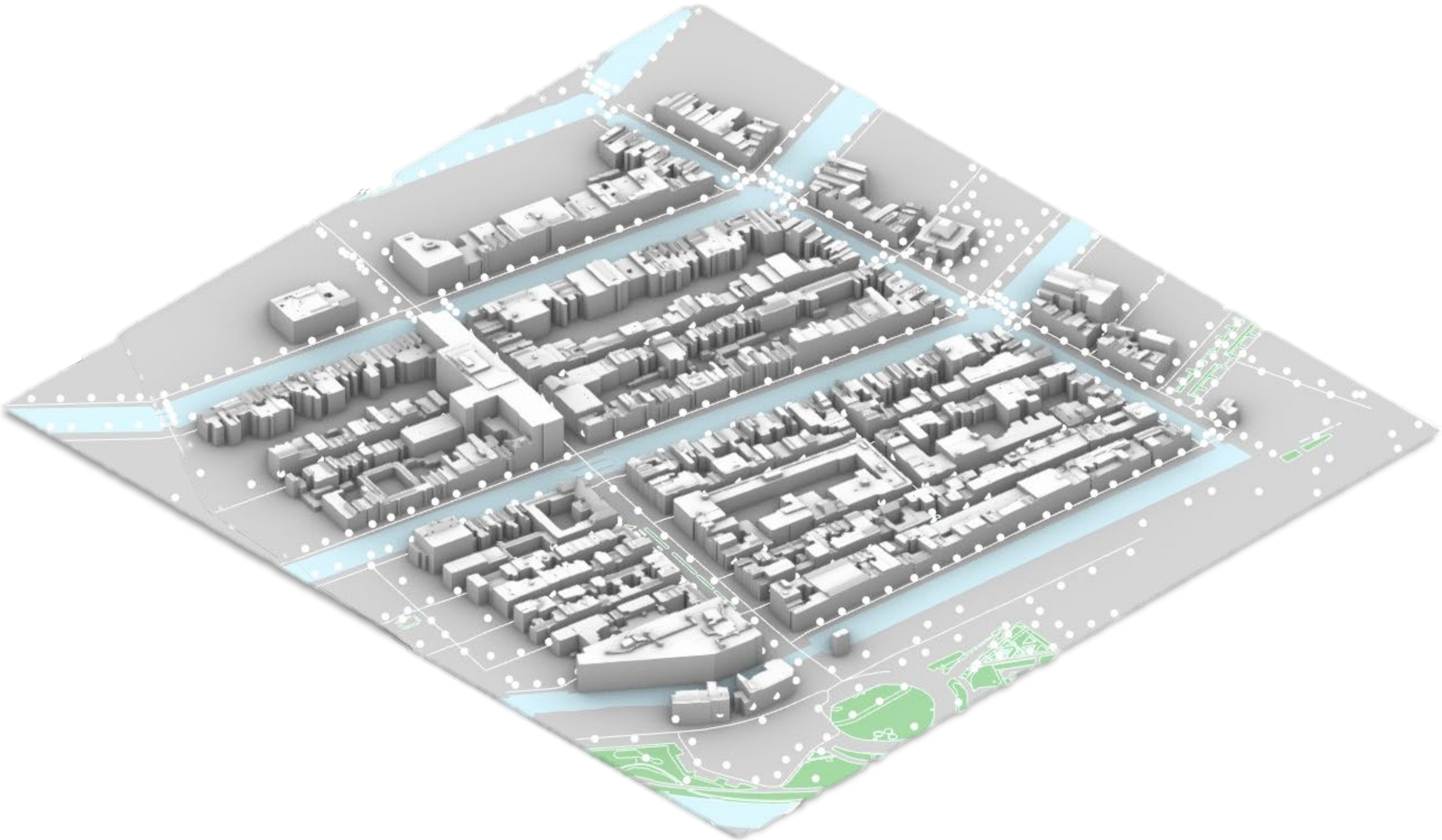
Surface water, green areas & street lighting positions



Surface water, green areas & street lighting positions, translated from GIS to Rhino



Urban building context



Surface water, green areas & street lighting positions, translated from GIS to Rhino

Light source

Context in the public space

Urban building context

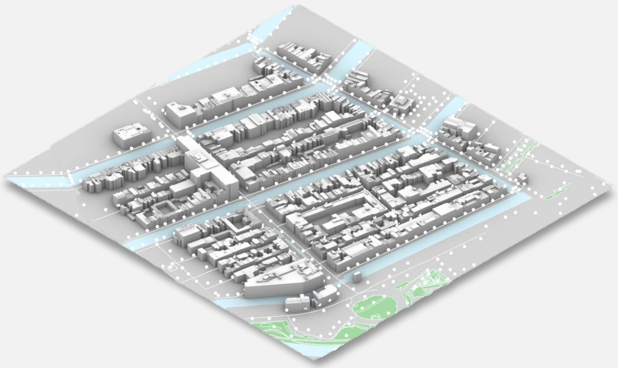
Facade

window transmittance

interior reflectance

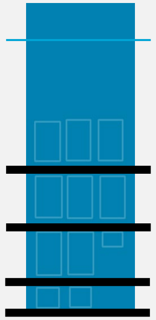
Recipient

Phase 1



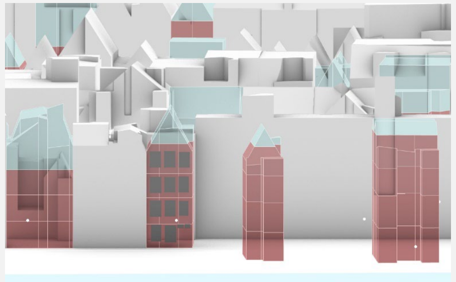
Preparing urban geometrical and geographical information

Phase 2



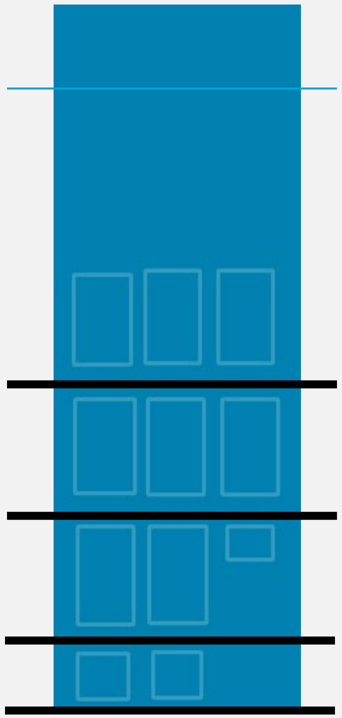
Extracting building window and floor level information from façade pictures

Phase 3



Window boundary and floor level reconstruction in 3D environment

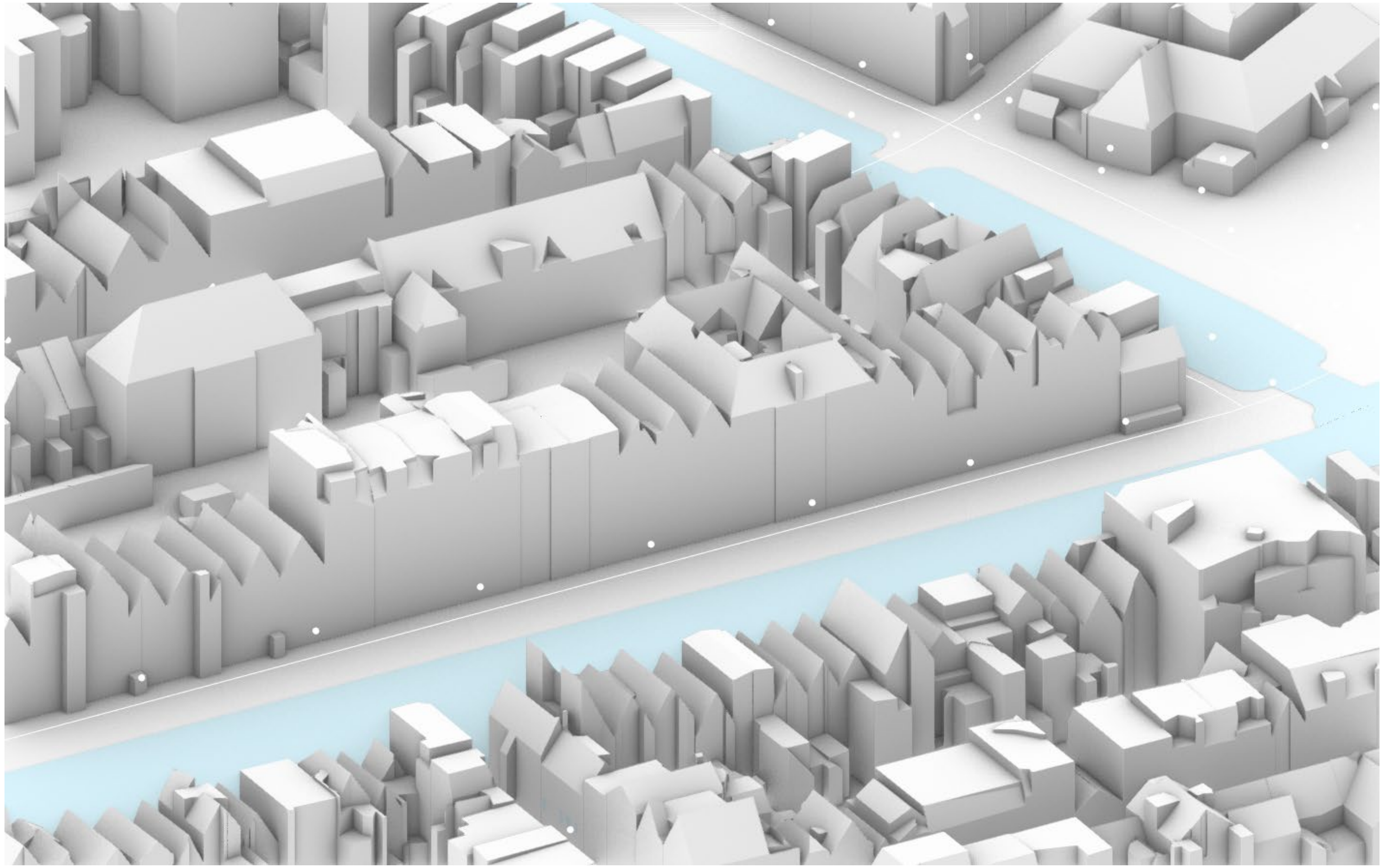
Geometrical preparation



Geometrical preparation: Phase 2

Extracting building window and floor level information from façade pictures

Current level of detail in 3D geometries



Light source

Context in the public space

Urban building context

Facade

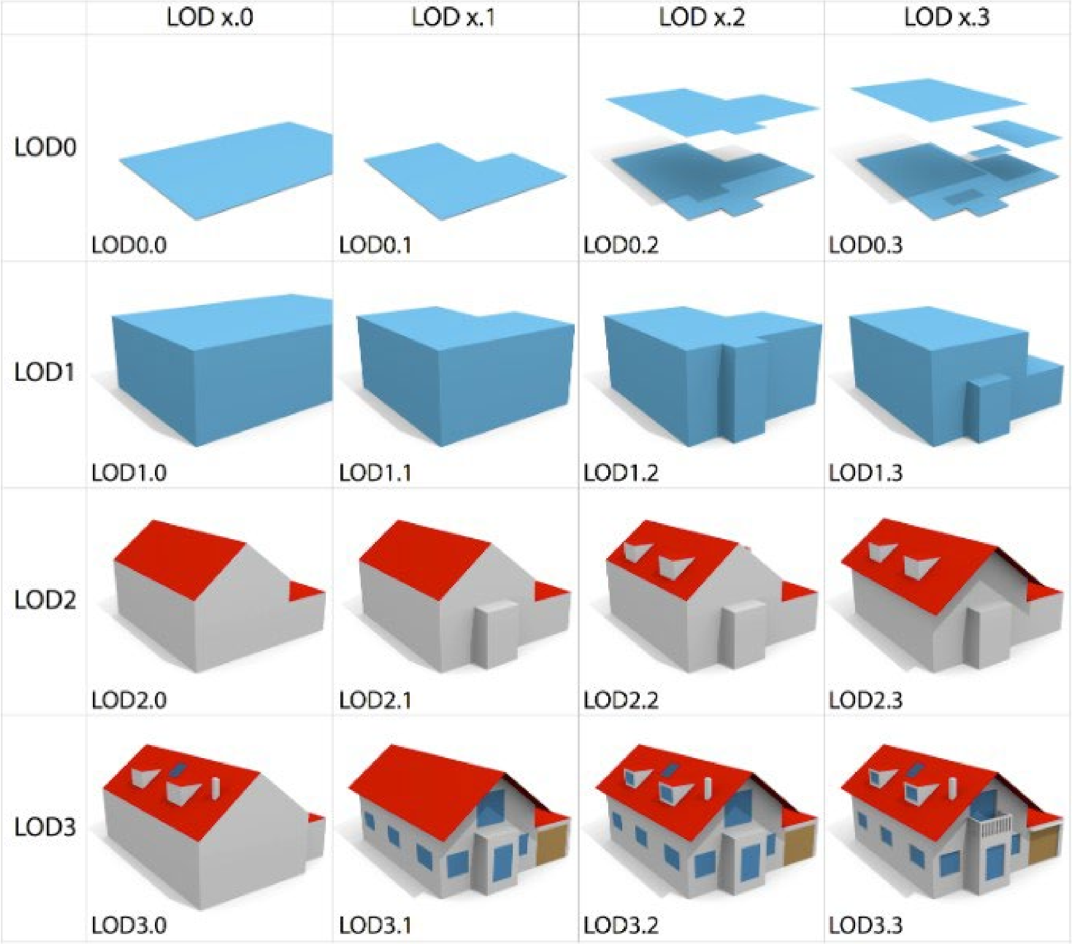
window transmittance

interior reflectance

Recipient

TU Delft

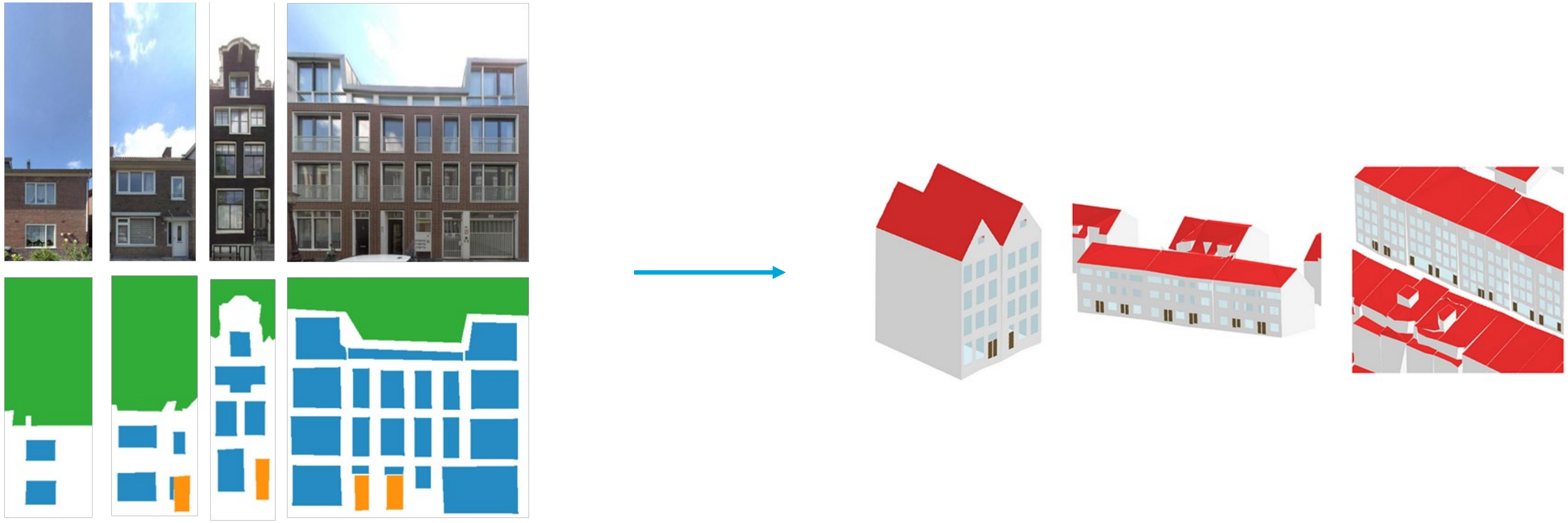
Urban building context



explanation Levels of Detail (LoD) (Biljecki et al., 2016)

Implementation of façade information:

- Eijgenstein (2020): 3D building enhancement with façade details by panoramic image sequencing

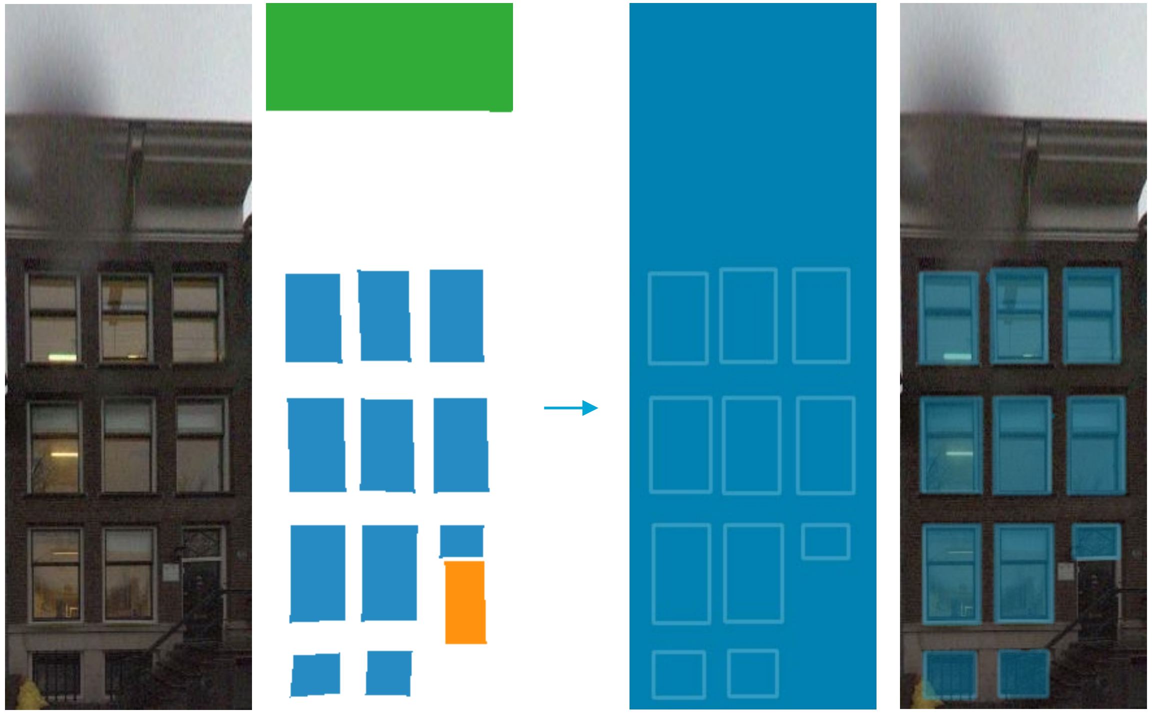


Facade steps from google streetview (top), façade masks (middle) to envisioned LoD 3.1 (Eijgenstein, 2020)

- Note: the visualisation is a demonstration of the potential enhancement. The geometries are placed over a wall surface and not properly integrated into the building.

Preparing for clustering algorithm

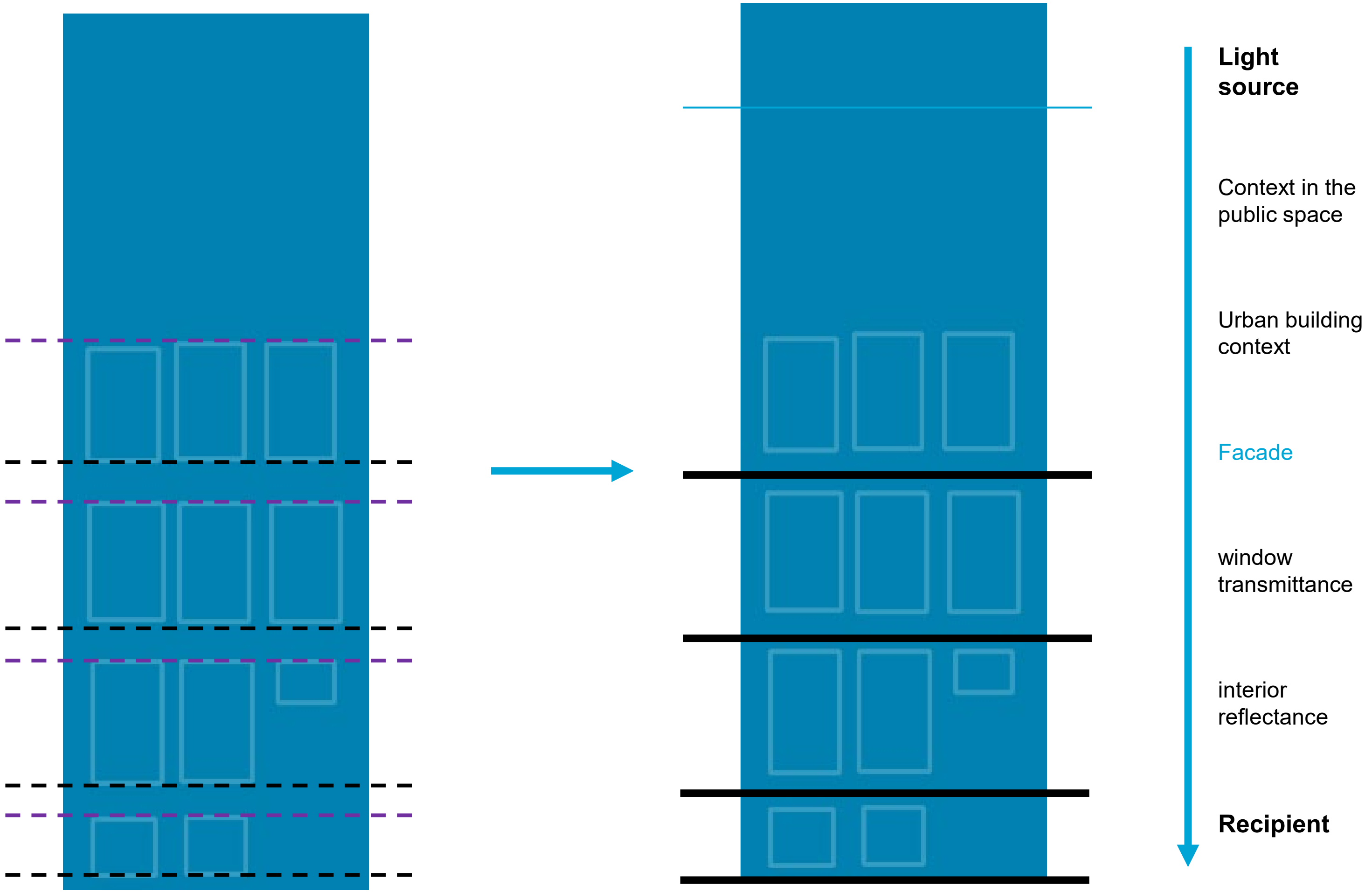
- Extract by colour
- Define orthogonal window boundaries



Left pictures: Façade database (Eijgenstein, 2020), right pictures, window shapes retrieved

Clustering algorithm

- For extracting floor levels
- For extracting Window-to-wall ratio per floor (WWR)

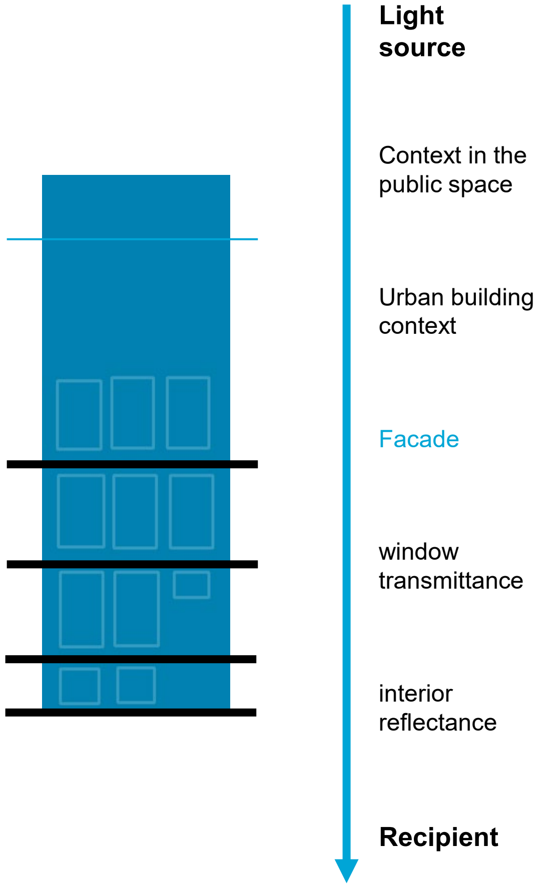


TU Delft

Clustering algorithm

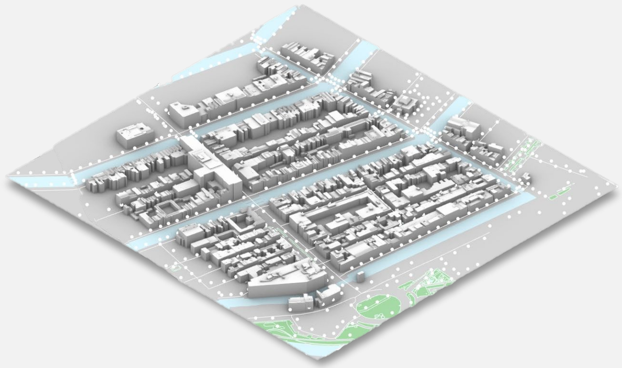
For each floor:

- Amount of window elements
- Relative window placement
- Floor level & ceiling height
  - Estimate at 2/3rd between top and bottom of window cluster boundaries
- WWR $\frac{\sum wall\ areas}{\sum window\ areas}$



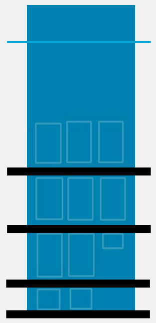
TU Delft

Phase 1



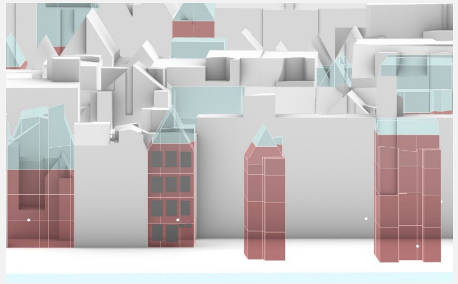
Preparing urban geometrical and geographical information

Phase 2



Extracting building window and floor level information from façade pictures

Phase 3



Window boundary and floor level reconstruction in 3D environment

Geometrical preparation

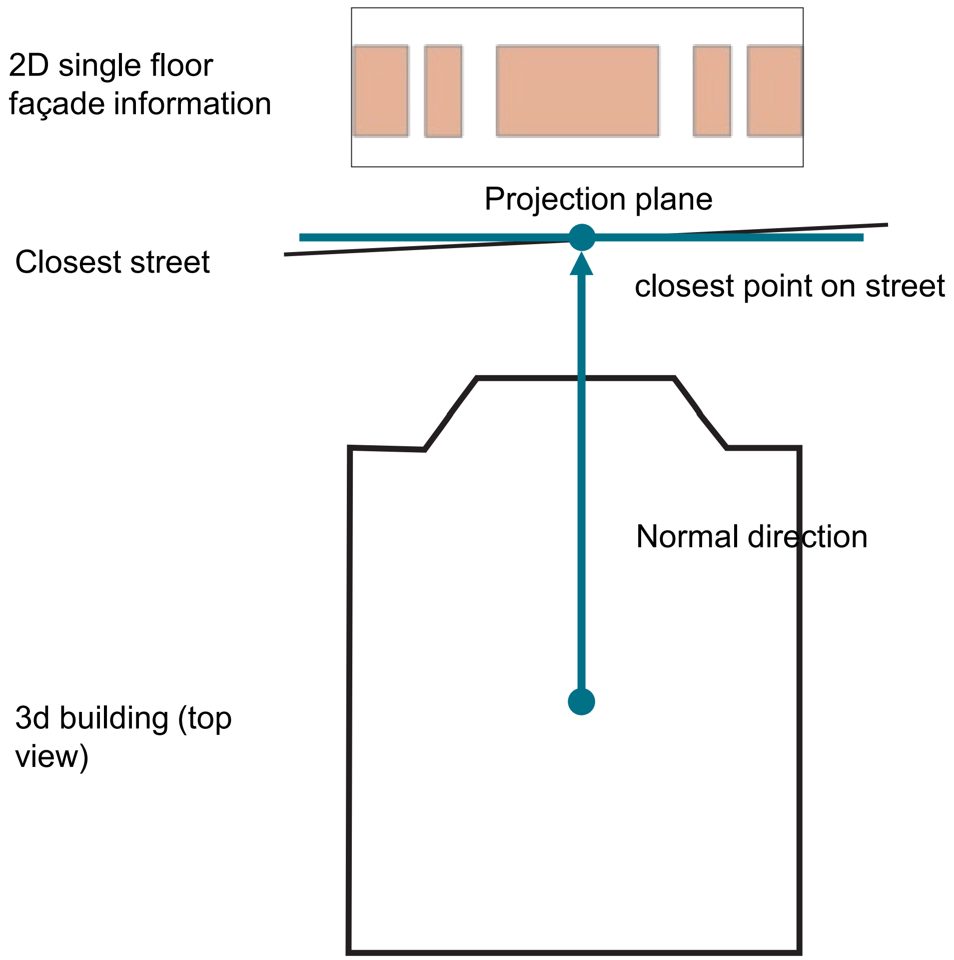
Geometrical preparation: Phase 3

Window boundary and floor level reconstruction in 3D environment

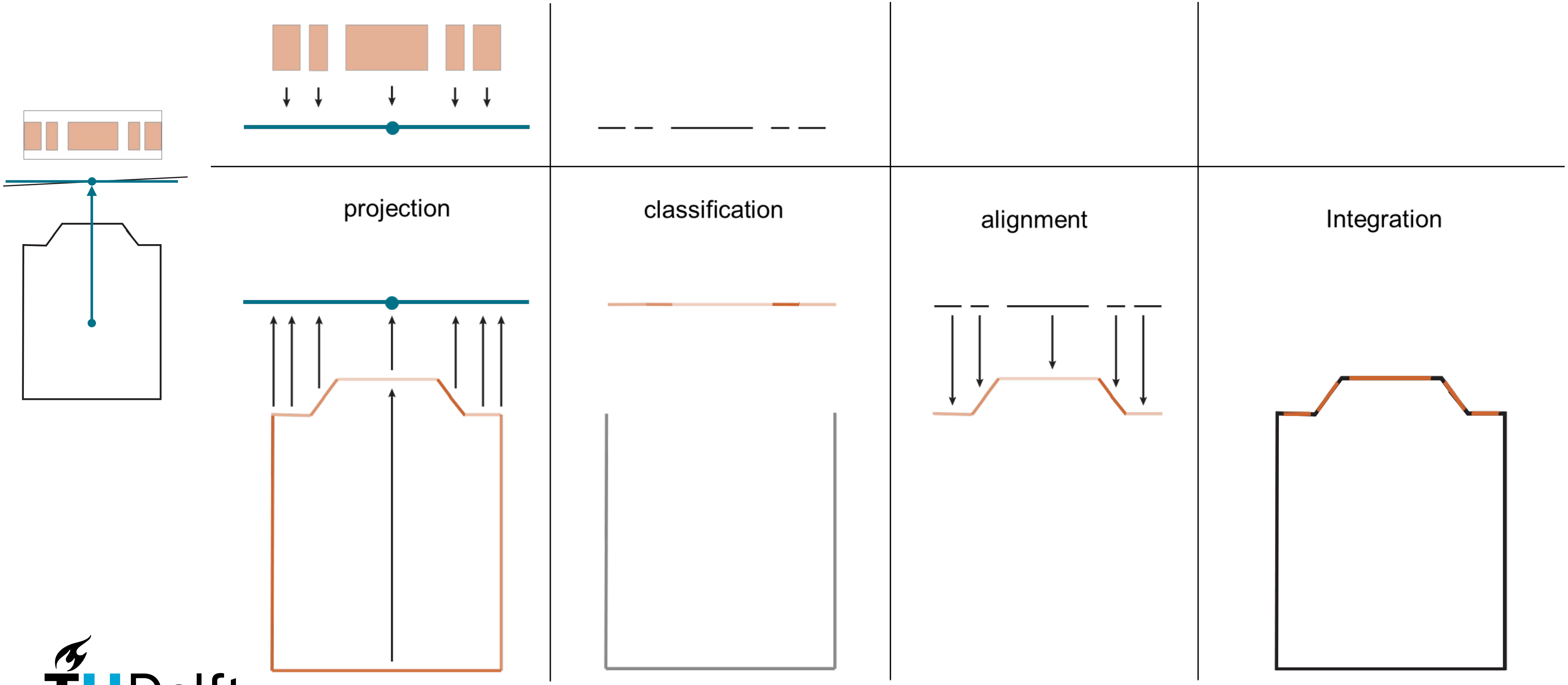
Window reconstruction by projection

Steps:

- Assign correct facade mask to the building (Building ID)
- Define mask projection plane
- Project 3D to 2D plane
- Shape & project 2D window information
- Project 2D window information to original geometries



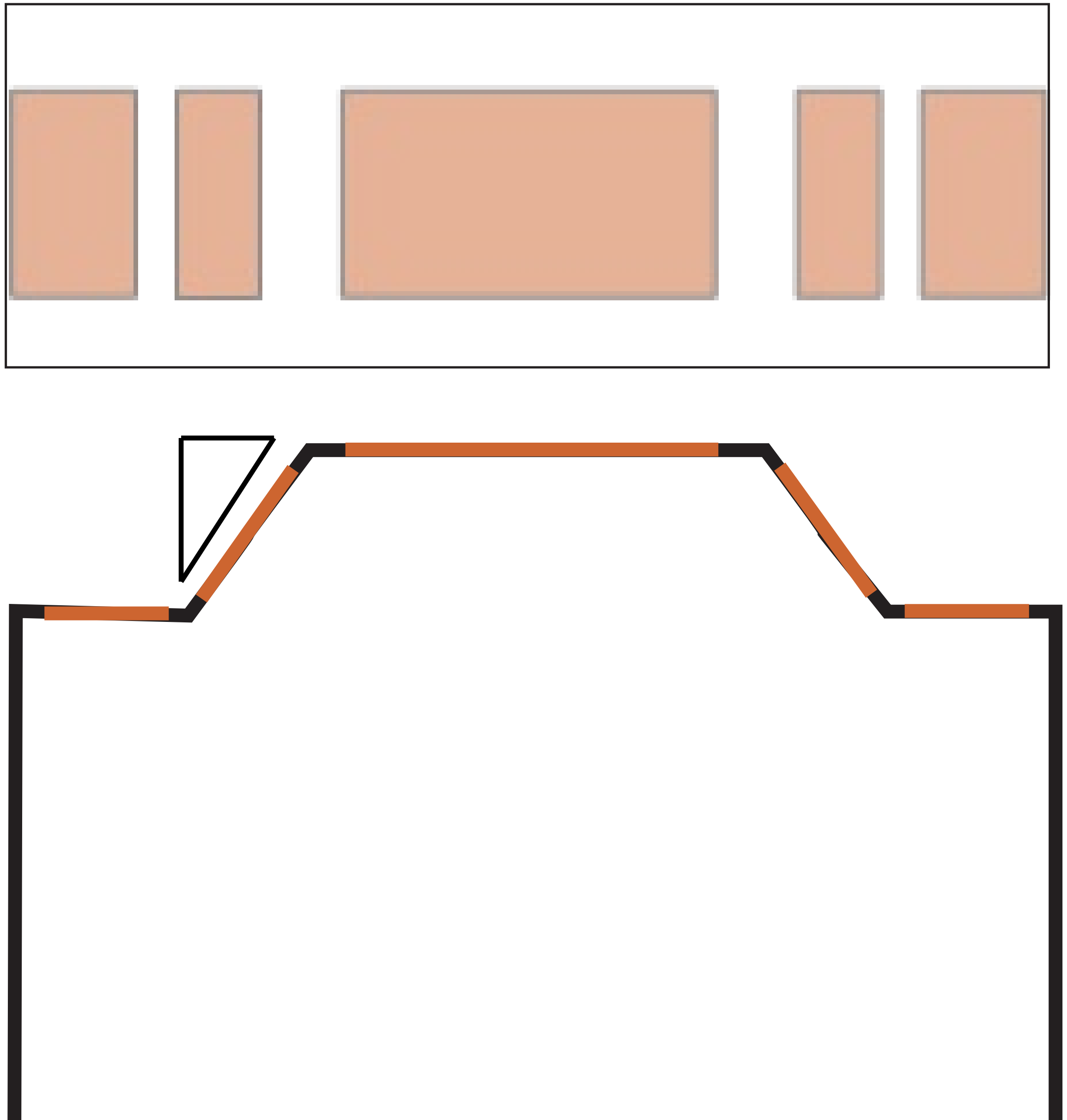
Window reconstruction by projection

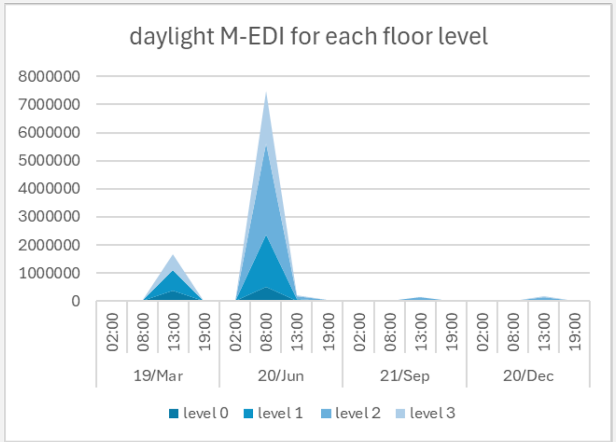


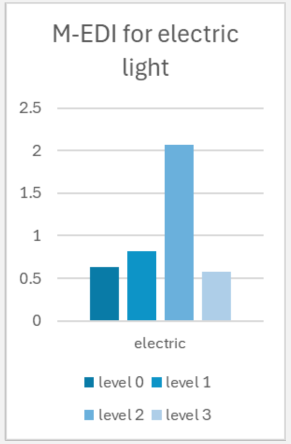
WWR correction

The original geometry's angles guide the projected shape:

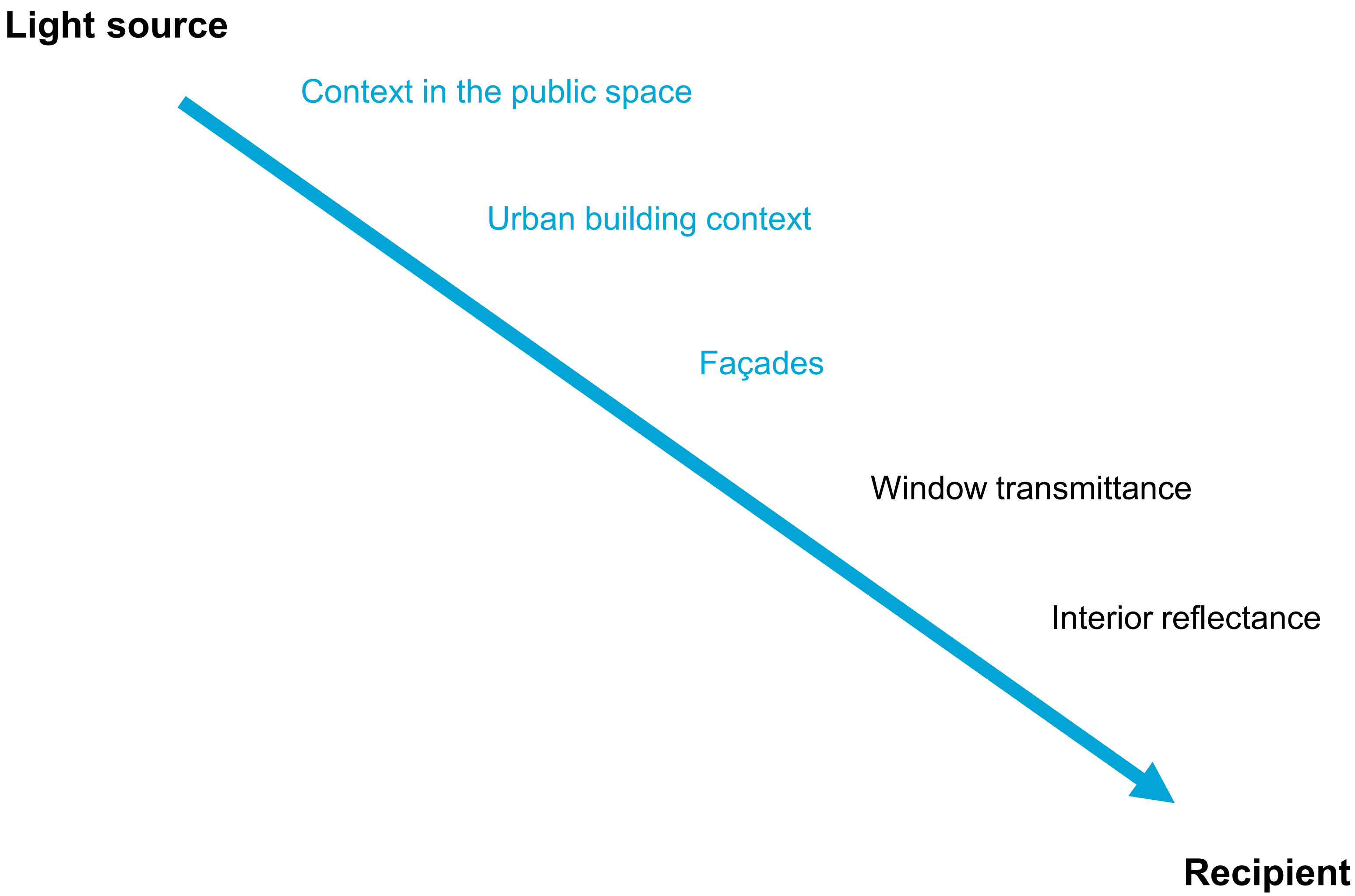
The information of the 3D building context allows for improved accuracy of window shapes and sizes







Phase 4: Circadian lighting modelling


Light source
Context in the public space
Urban building context
Façades
Window transmittance
Interior reflectance
Recipient

Light source

Context in the public space

Urban building context

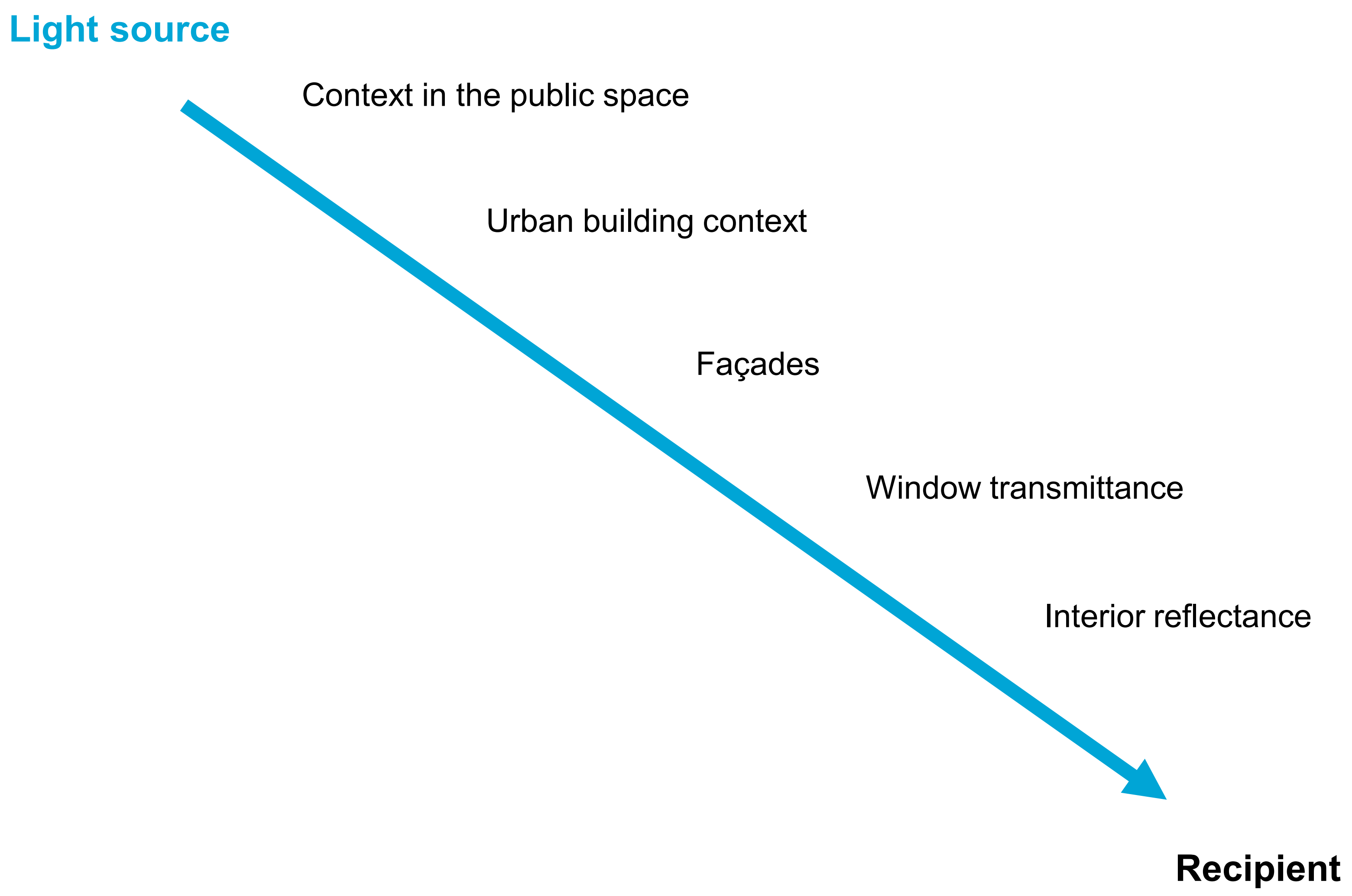
Façades

Window transmittance

Interior reflectance

Recipient

TU Delft


Light source
Context in the public space
Urban building context
Façades
Window transmittance
Interior reflectance
Recipient

TU Delft

Lighting inputs

Simulation of light:

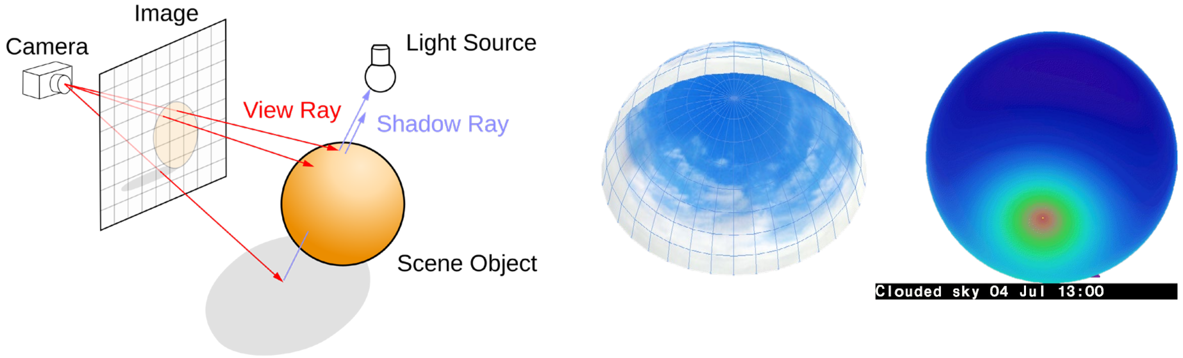
- Daylight:
  - **Spectrum**: SPD: Cie D65 for **diffuse** light & Cie ASTM for **direct** light (CIE, 2016)
  - **Intensity**: **Clear sky** simulation (TAU clear sky, 2009)
  - **Timing**: Time affects lighting position (direct sunlight)
- Artificial light: streetlight representation in Amsterdam (reference: Gemeente Amsterdam, 2024)
  - **Spectrum**: SPD: standard **LED** with correlated colour temperature: 3500K
  - **Intensity**: **3612 lm** (IES representation of lighting distribution)
  - **Timing**: Follows daylight: (when daylight = 0 lx)

TUDelft

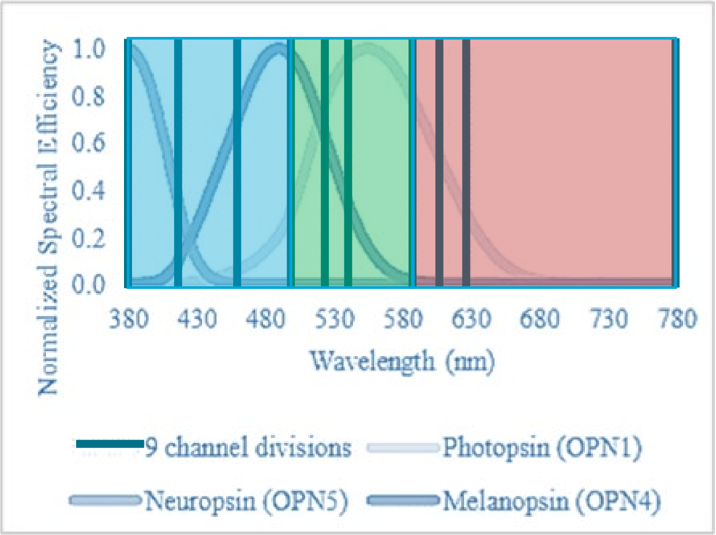
LARK circadian lighting simulation

- Ray tracing: Radiance
  - Settings: 2 ambient bounces
  - Sky simulation

- Simulation in 9 channels, based on melanopic and neuropic sensitivity:
  - Blue, green, red



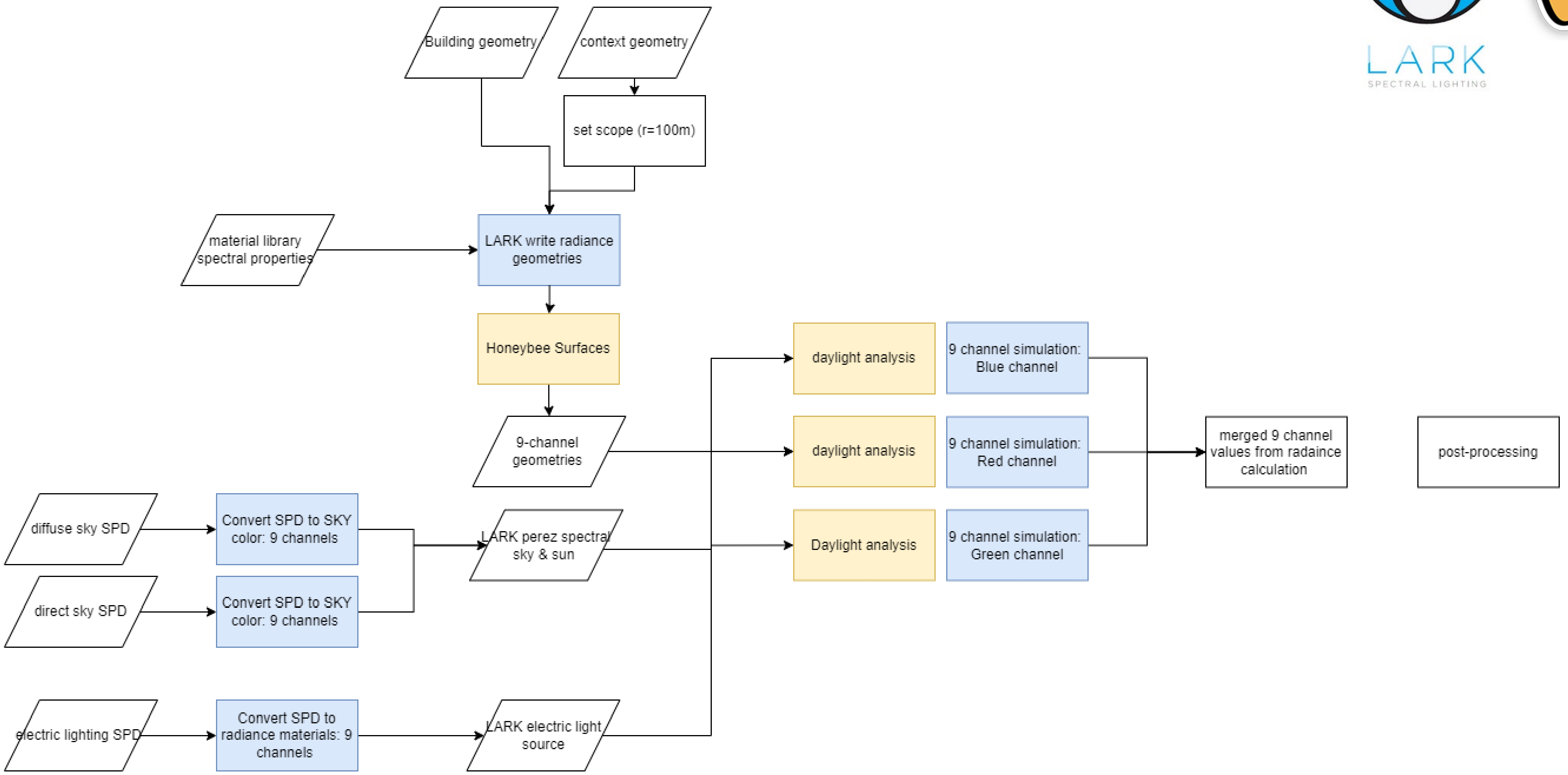
explanation raytracing and sky simulations (Wikipedia, 2024; own source)



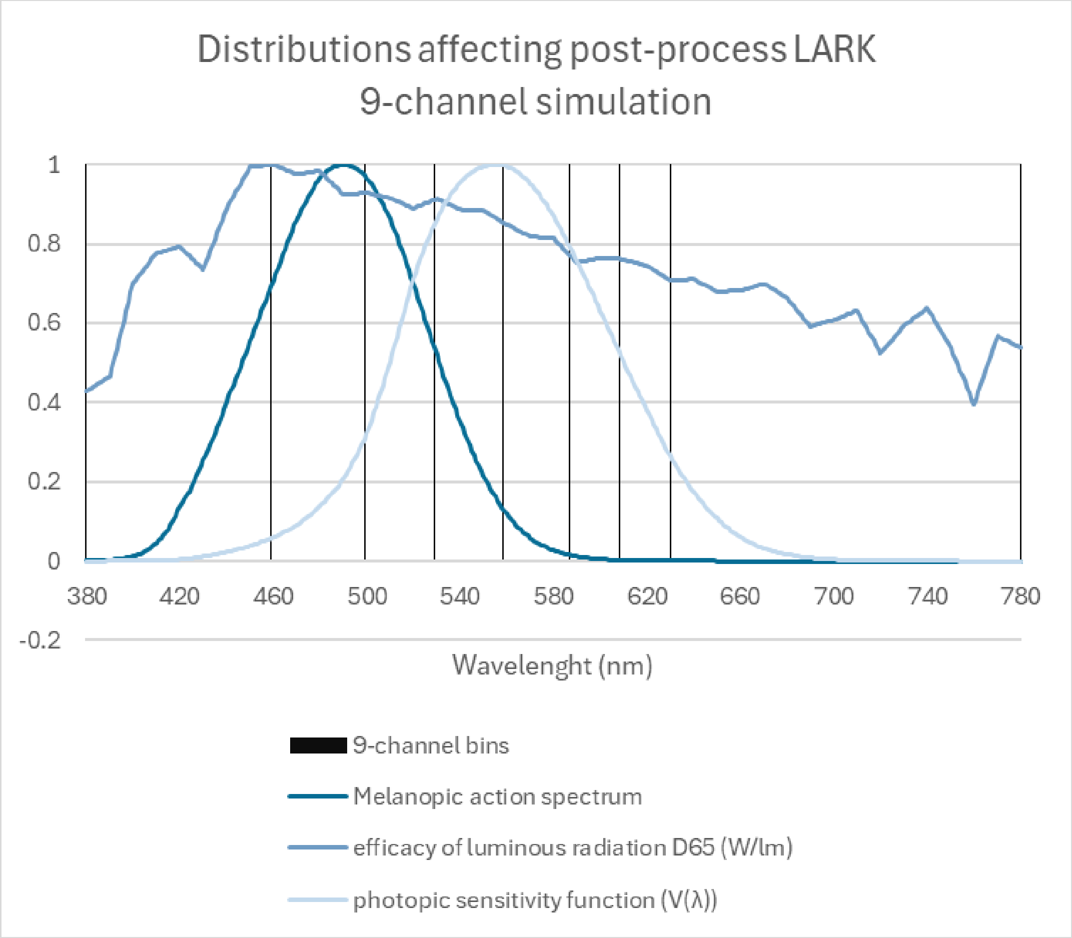
9-channel divisions (Jung et al., 2023 edited)

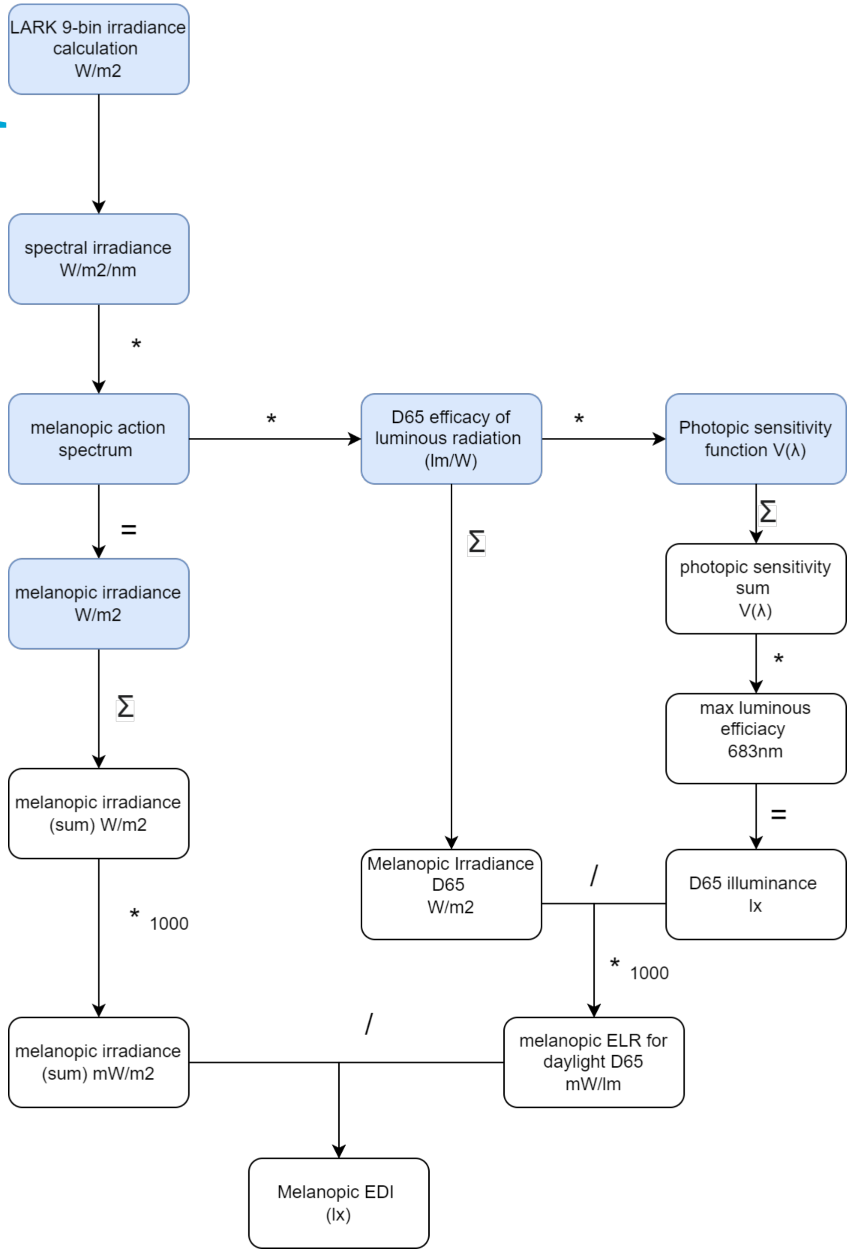
TU Delft

Flowchart Lark circadian lighting analysis



Processing the results: Spectrum





TU Delft

LARK 9 channel calculation

Result: for each building, for each floor level:

16 point-in-time measurements for Melanopic EDI (lx)

	21.00-8.00	8.00-18.00	18.00-21.00
Reference value (mEDI)	**< 1 lx**	**> 250 lx**	**< 10 lx**

→

	20-3	**21-6**	**22-9**	**21-12**
02.00				
8.00				
13.00				
19.00				

Light source

Context in the public space

Urban building context

Facade

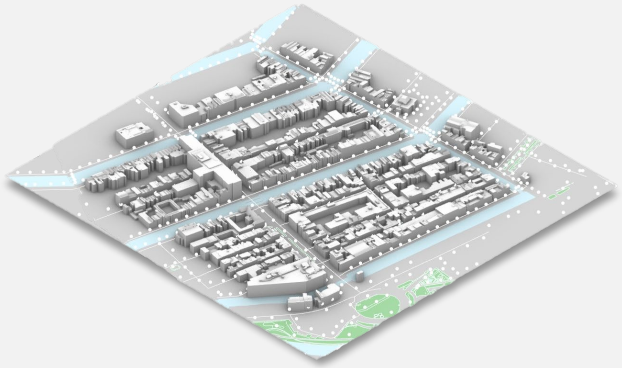
Window transmittance

Interior reflectance

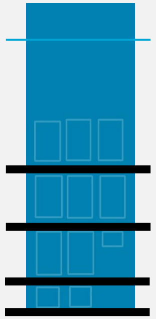
Recipient

TUDelft

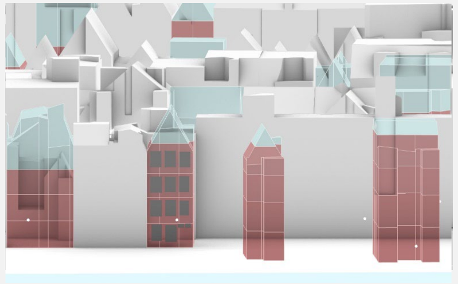
Phase 1



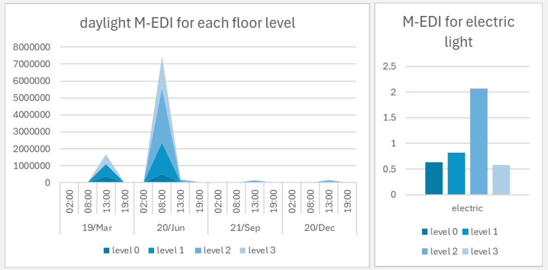
Phase 2



Phase 3



Phase 4



Key findings

Circadian lighting analysis on city-level

Light source

Context in the public space

Urban building context

Façades

Window transmittance

Interior reflectance

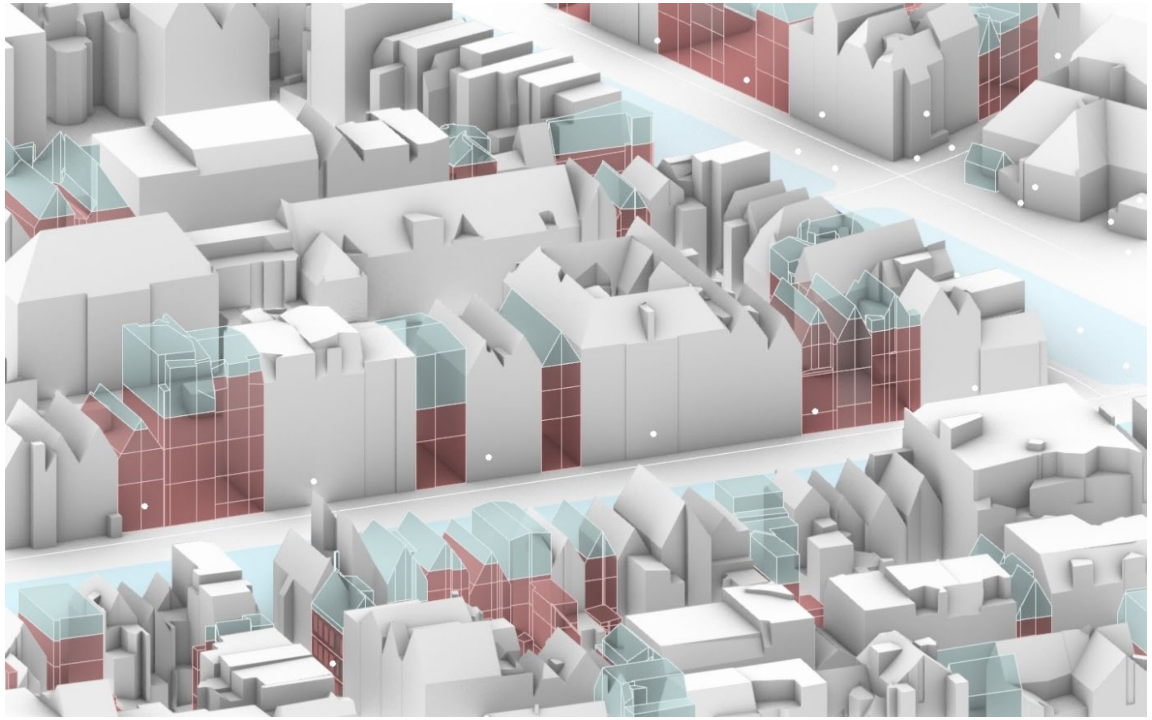
Recipient

TU Delft

Large-scale floor level iteration

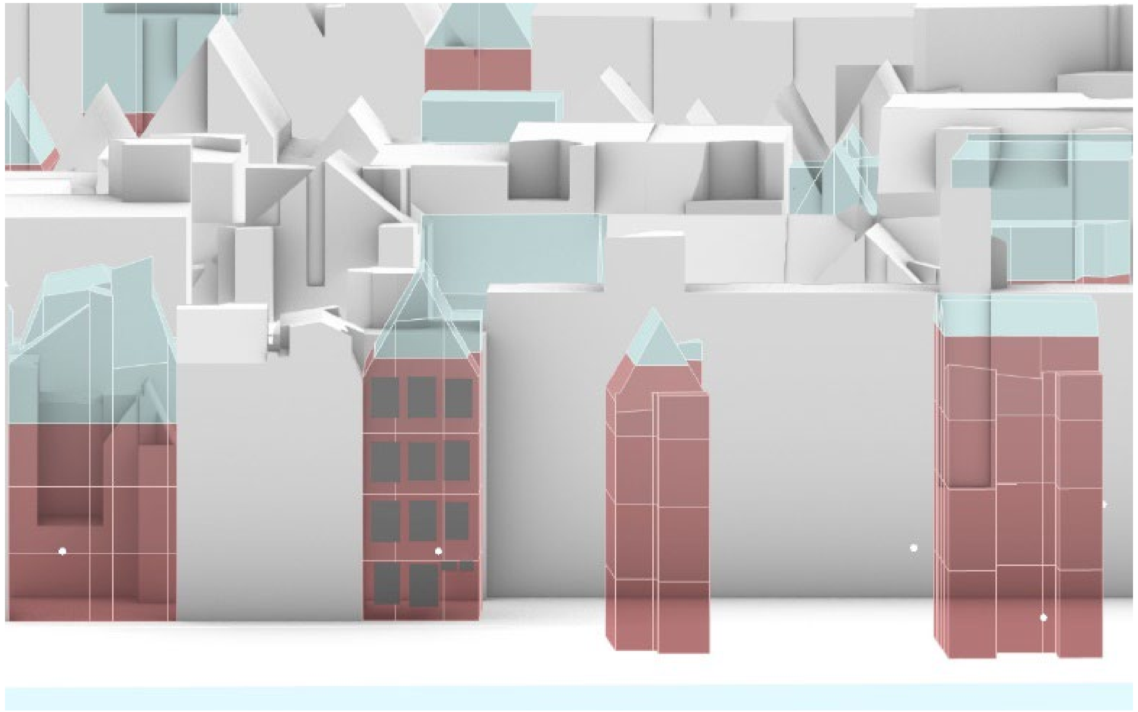
Figure 4.10 large-scale floor level splitting

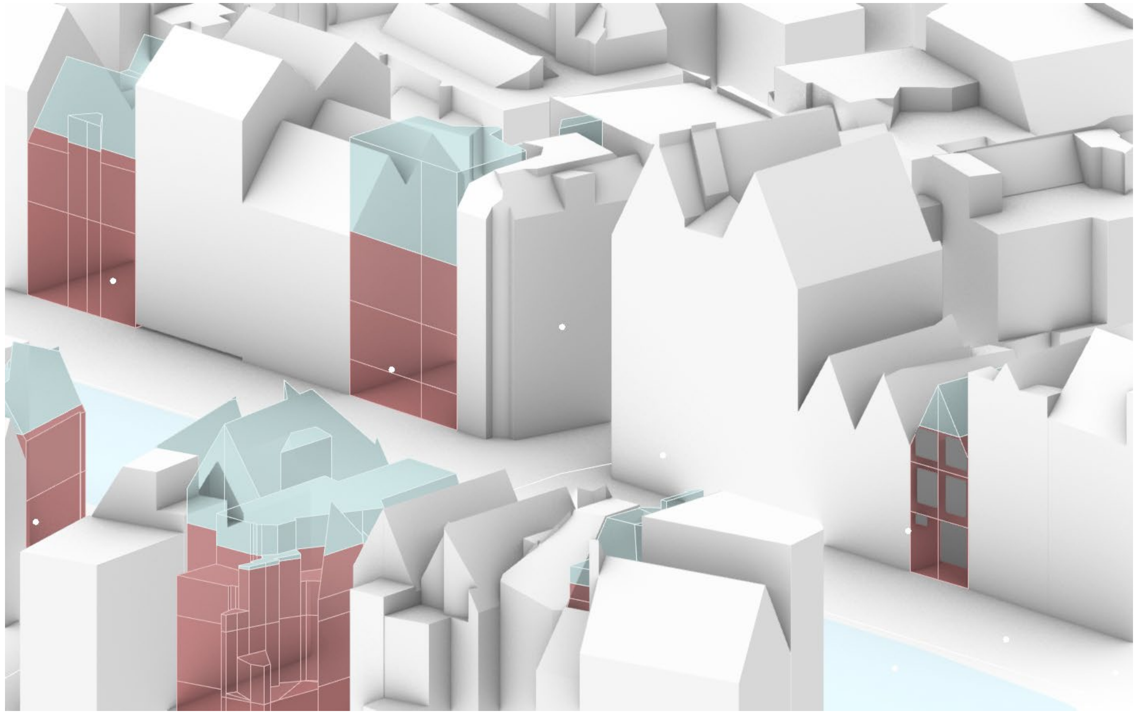
Large scale floor-level splitting



split level buildings, visualized side by side with google maps 3D image (google, 2024)

Large-scale floor level splitting & window placement samples





validation: floor level splitting returned similar results for the large-scale assessment as for the 5-building iteration

TU Delft

Result: 5 buildings with window placement

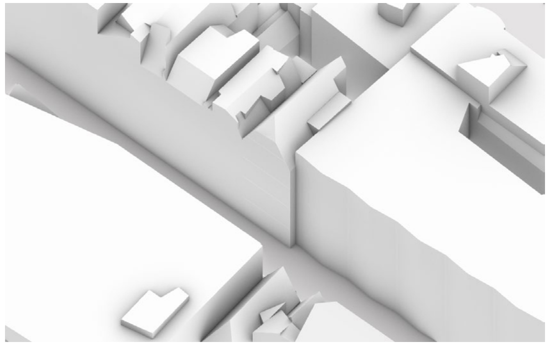
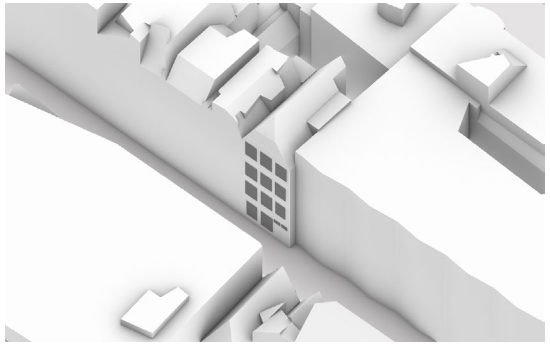
Building 1

Building ID: 363100012179151



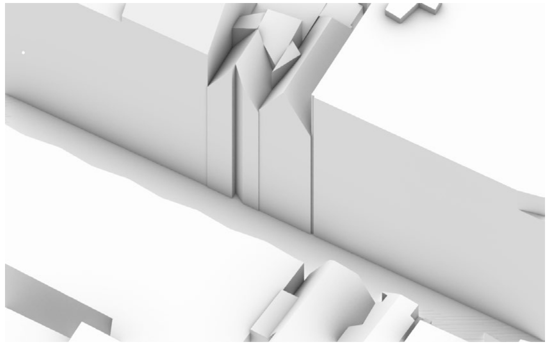
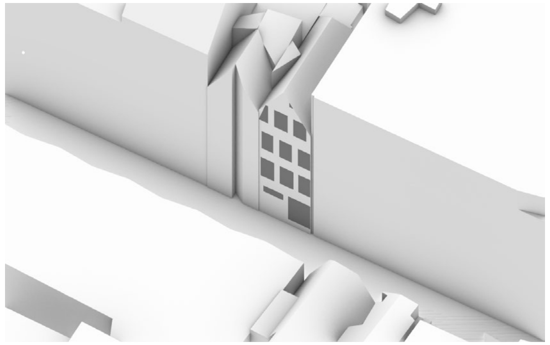
Building 2

Building ID: 363100012179524

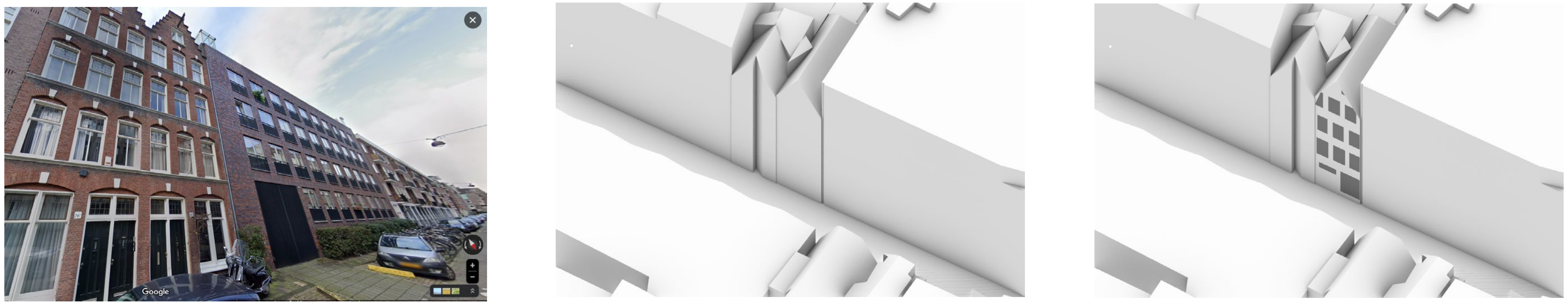
Building 3

Building ID: 363100012179516

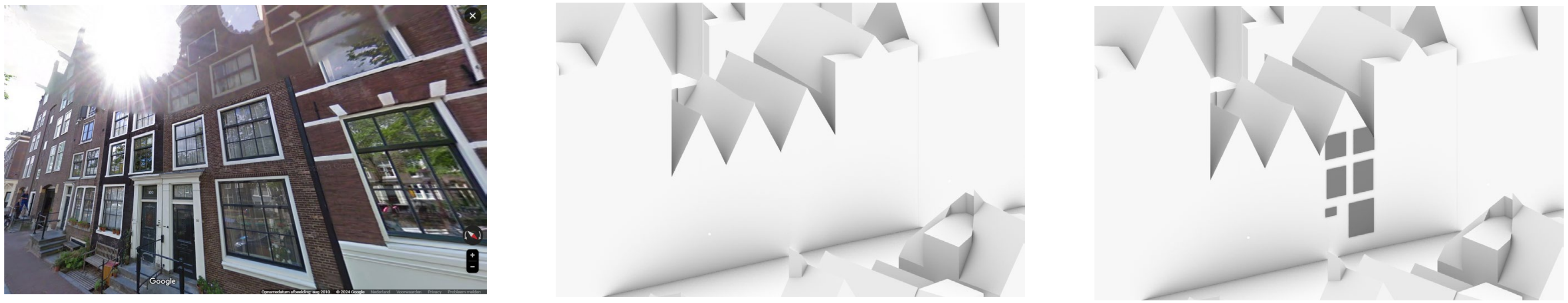
Building 3

Building ID: 363100012179516



Building 4

Building ID: 363100012180112



Building 5

Building ID: 363100012179197

building selection and window construction visualised (google maps, 2024 and own source)

9 channel simulation

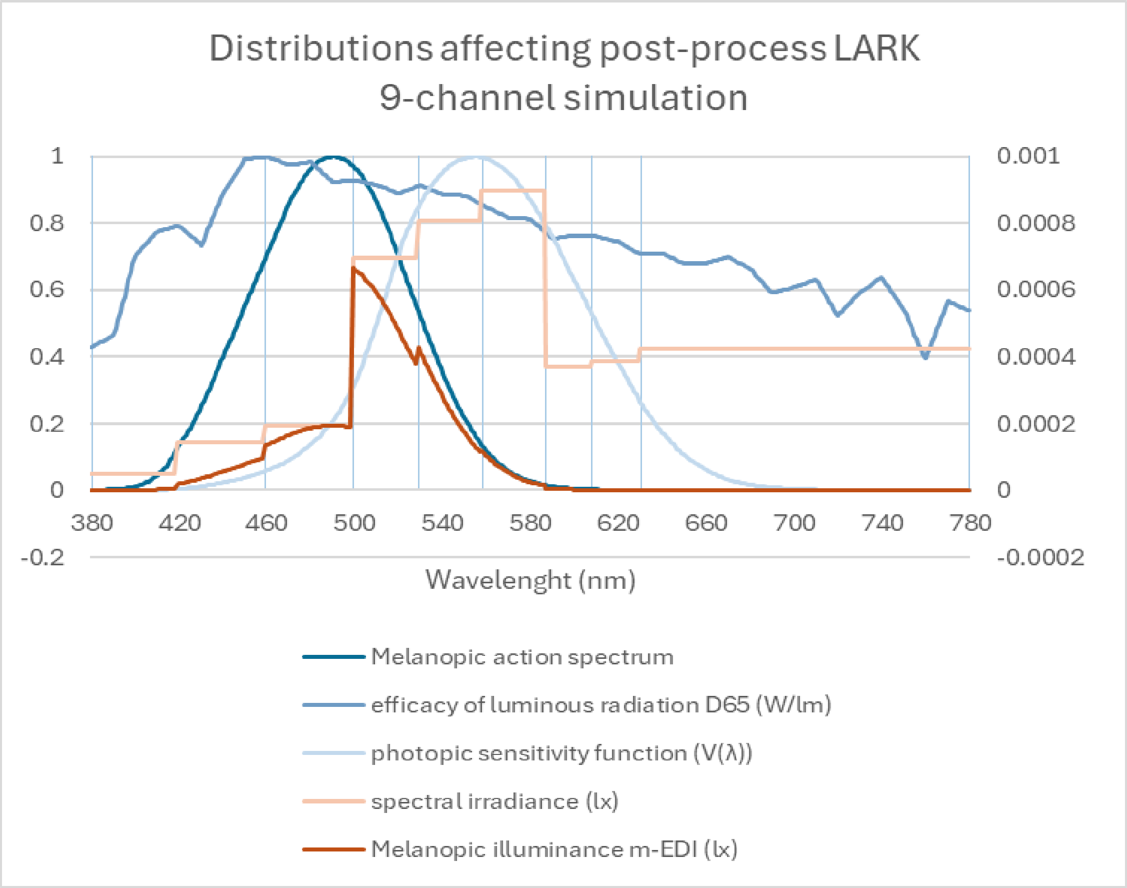
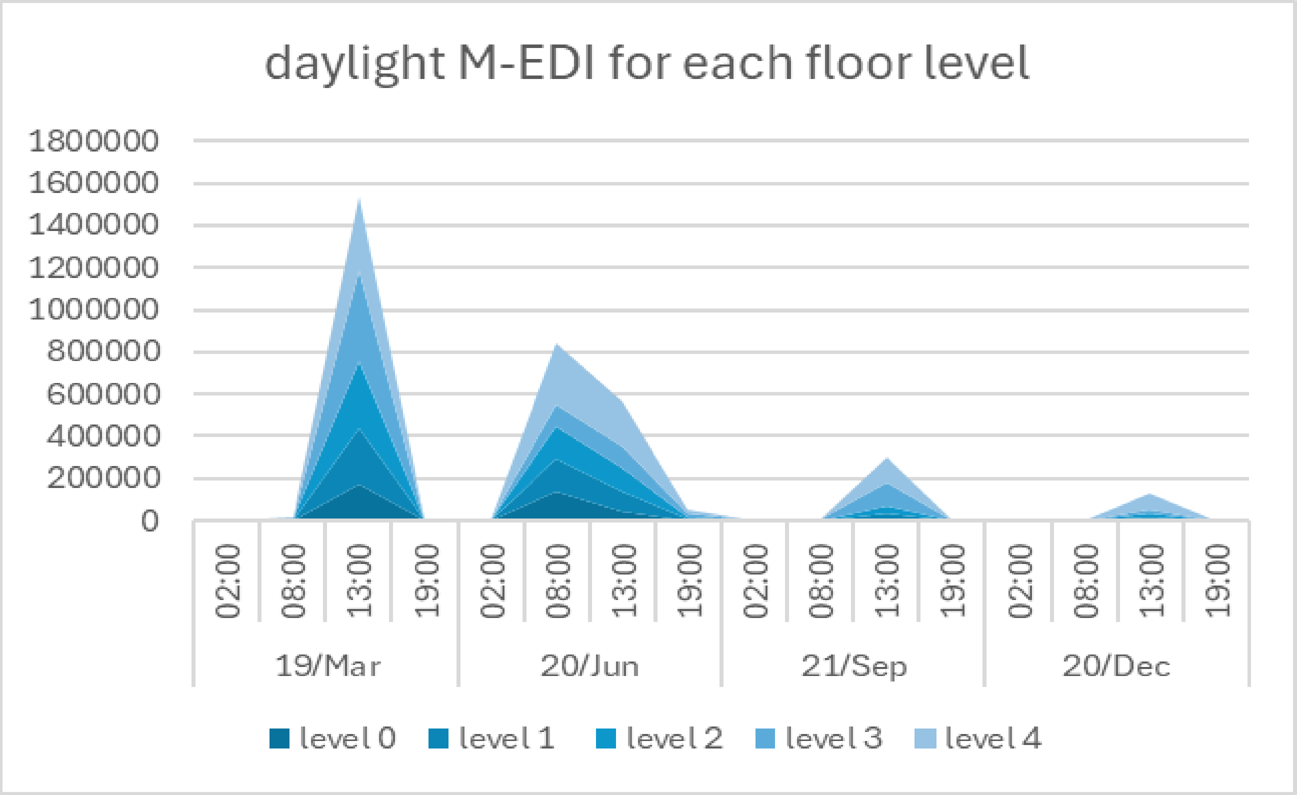
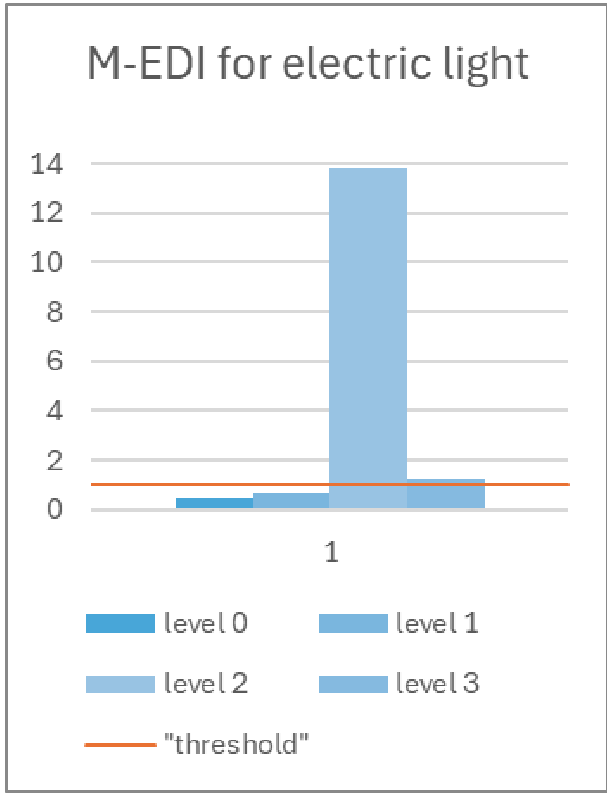


Figure 4-11 LARK post processing

TU Delft

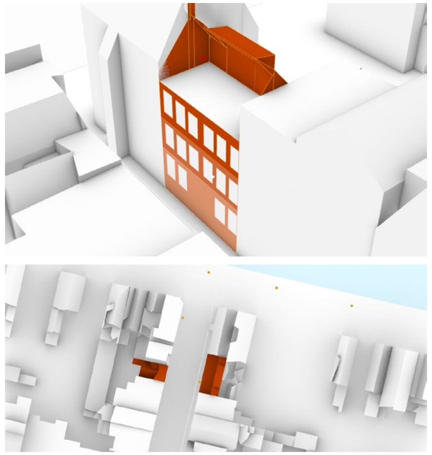


Building 2



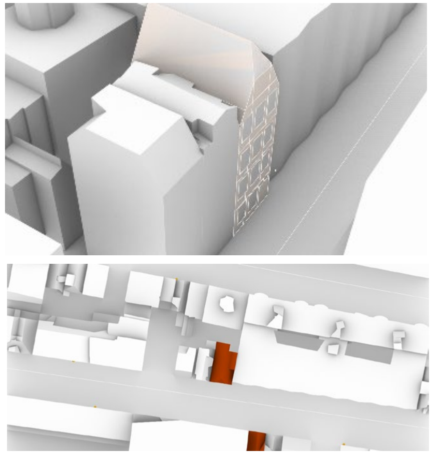
Building 5

Artificial lighting results



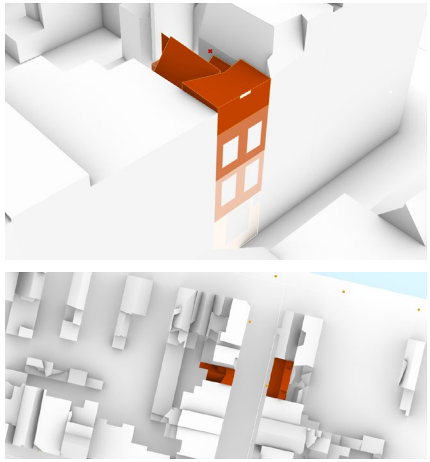
level 0	0.49
level 1	0.67
level 2	13.76
level 3	1.23

Building 1



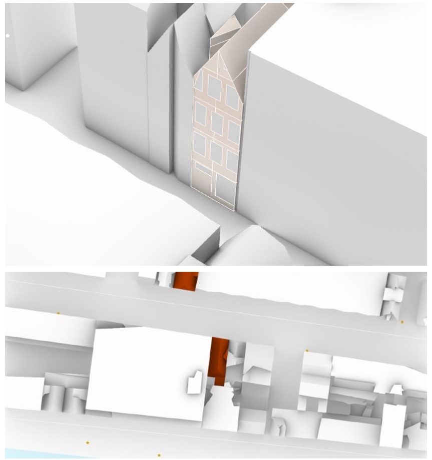
level 0	0
level 1	0.05
level 2	0.05
level 3	0.04
level 4	0.04

Building 3



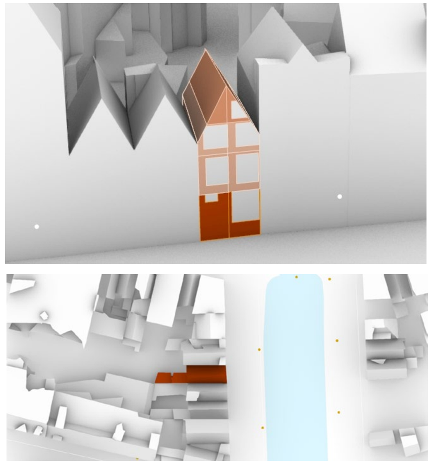
level 0	0
level 1	0.26
level 2	0.6
level 3	2.37

Building 5



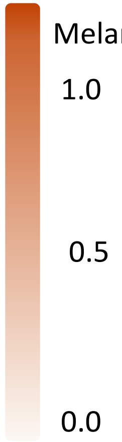
level 0	0
level 1	0.04
level 2	0.06
level 3	0.08
level 4	0.05

Building 2



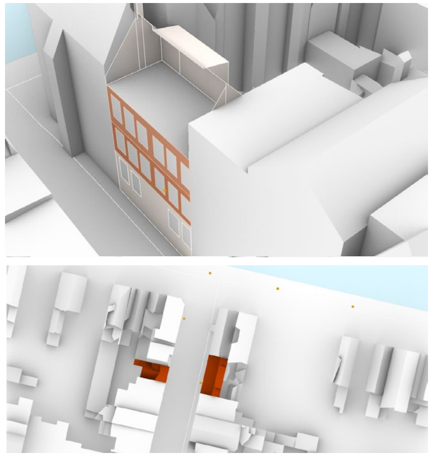
level 0	1.07
level 1	0.34
level 2	0.32
level 3	0.49

Building 4



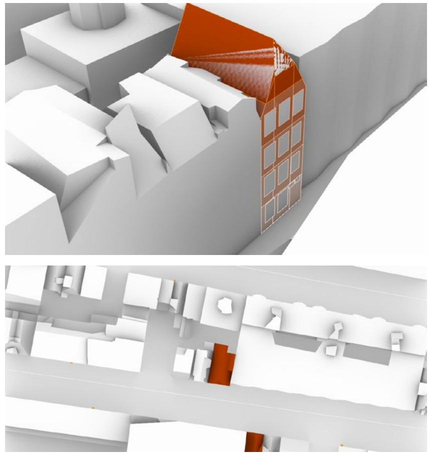
Brown (2022):
m-EDI <1.0 lx

Natural lighting results: mid-winter (21-12, 13.00)



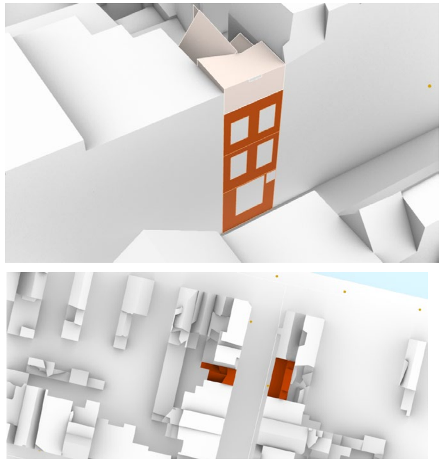
level 0	29.3
level 1	515.4
level 2	453.7
level 3	x

Building 1



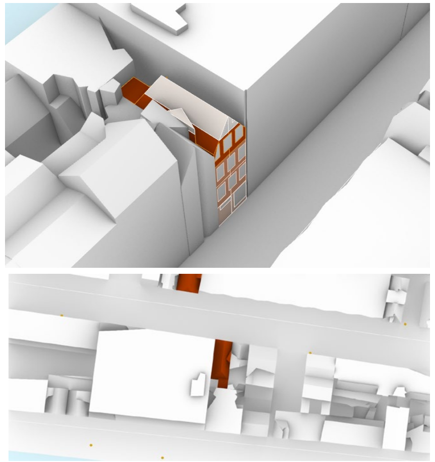
level 0	184.0
level 1	422.6
level 2	475.4
level 3	1125.1
level 4	29.2

Building 3



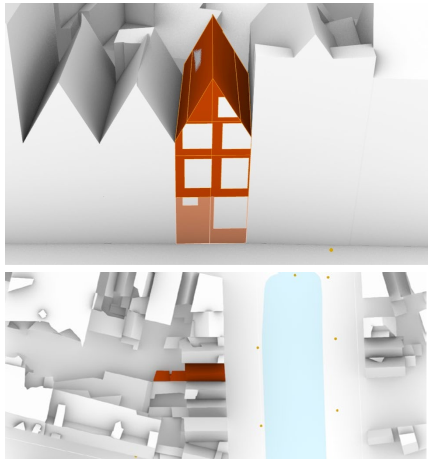
level 0	691.5
level 1	761.5
level 2	780.5
level 3	66.2

Building 5



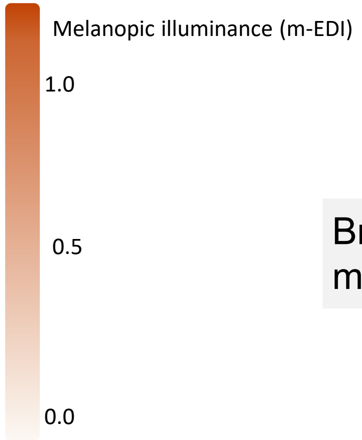
level 0	165.4
level 1	324.1
level 2	457.6
level 3	609.7
level 4	2283.8

Building 2



level 0	515.7
level 1	1202.7
level 2	2232.9
level 3	965.4

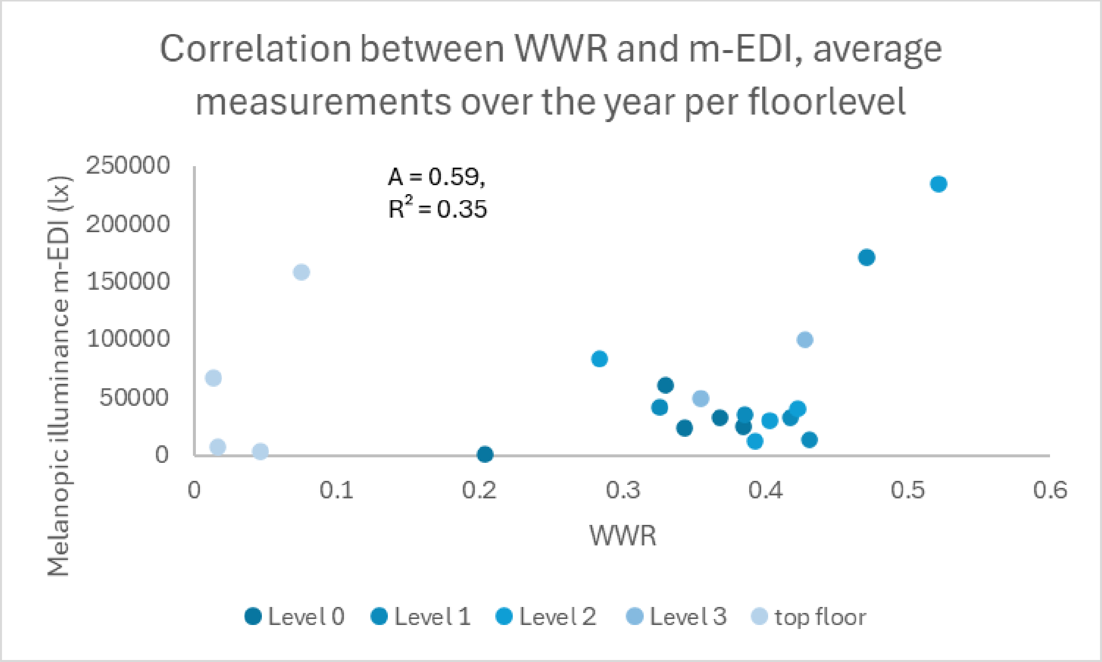
Building 4

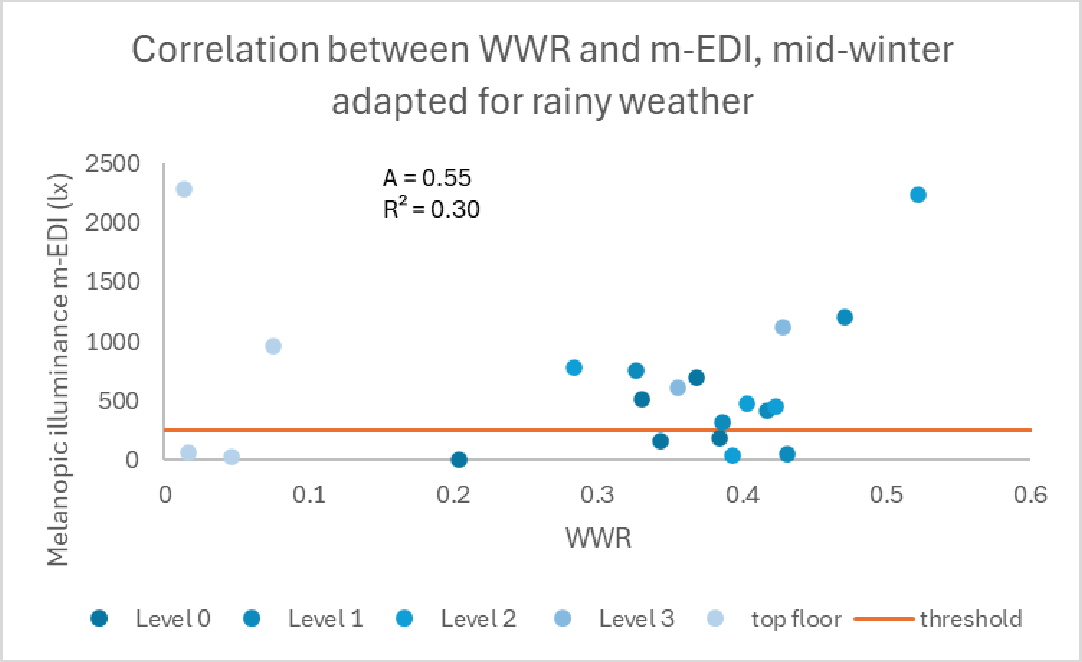


Brown (2022):
m-EDI > 250 lx

TUDelft

Results, visualised.



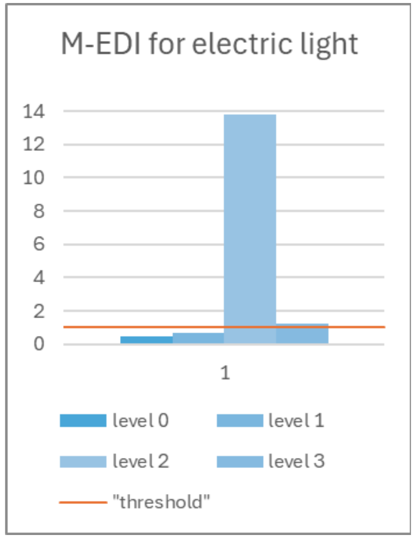


TU Delft

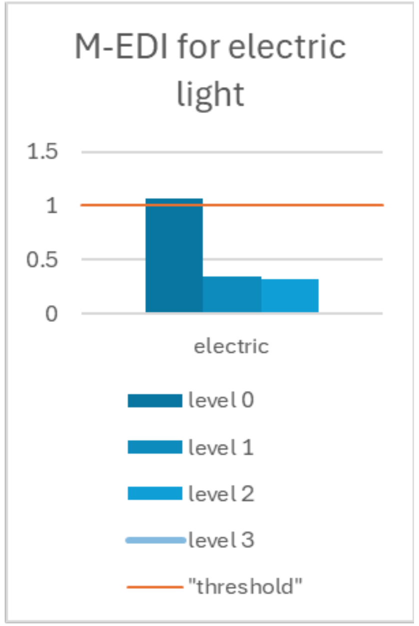
Results:

- Impact of streetlight on circadian light (at night)
  - With lighting placement near buildings, as shown in the case of Building 1, the artificial lighting values well exceed appropriate levels for m-EDI by night, and even the levels for evening exposure are surpassed in this situation.

- Impact of cities on circadian lighting availability
  - Consistently sufficient daylight for mid-day
  - Surplus in summer evenings, lack in winter evenings
  - High variation between floor levels for small streets



Building 1



Building 4

TU Delft

Discussion

Research question & goals

What is the impact of façade design and lighting design on circadian health in urban context?

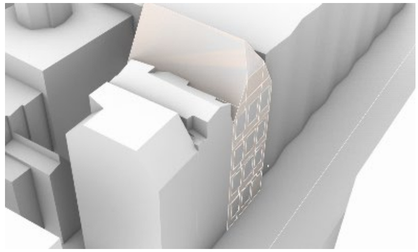
Enhancement of the accuracy and usability of the current 3D models for circadian lighting analysis, with the development of a method to enrich existing 3D data by incorporating precise information about window and floor levels.

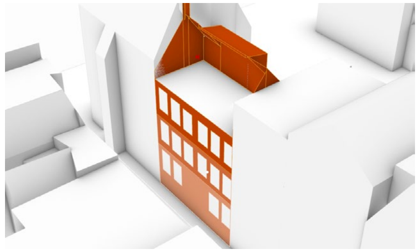
The execution of a large-scale circadian lighting analysis that delivers results with a level of accuracy that closely approximates real-world conditions for individual homes and floor levels.

TU Delft

Enhancement of current 3D models

- A workflow of implementing picture-based façade information in large-scale datasets is feasible:
- Merging of 3DBAG, (based on satellite-imaging: 2D within the horizontal plane) with street-level imaging (2D within the vertical plane) brings a new Level of Detail that has not been found feasible with a single data source.
- Improving the accuracy of window information, including complex façade geometries
- Implementing building-specific floor-level information in the 3D geometries



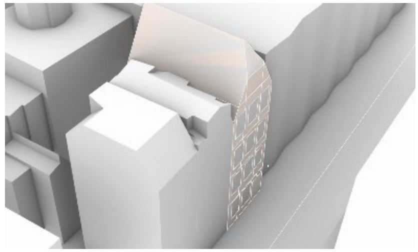


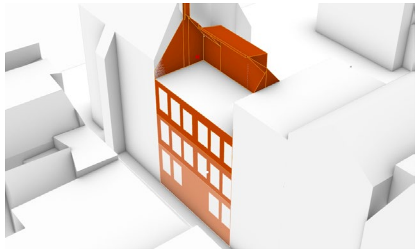
TU Delft

Enhancement of current 3D models

Discussion:

- The level of accuracy of both sources is not high enough to derive accurate top-floor window placements, especially for buildings with complex façade shapes
- some inconsistencies appear with façade splitting, resulting in non-watertight geometries

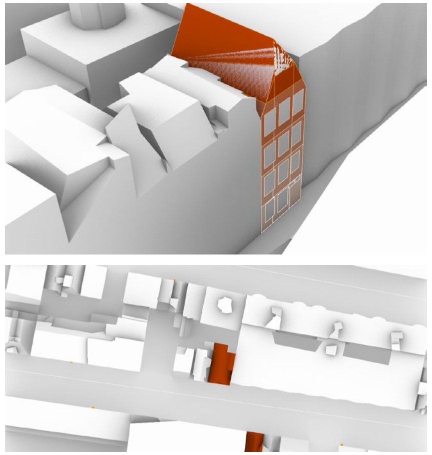




TU Delft

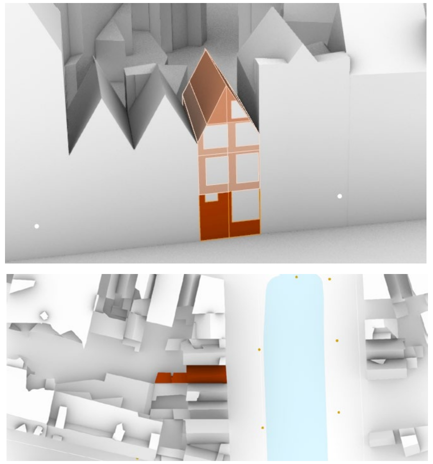
Large-scale circadian lighting analysis

- Surplus of artificial light & shortage of natural light in winter caused by urban context: buildings and street lighting
- Circadian lighting availability is heavily affected by daylight availability, and thus by seasonal variations: All buildings tested retrieve sufficient mid-day incident circadian light over the seasons.
  - Summer evenings encounter a surplus
  - Winter mornings and evenings encounter a shortage.
- **High variations are found for different building levels: the addition of floor level information for large-scale circadian lighting assessment is shown highly relevant.**



level 0	184.0
level 1	422.6
level 2	475.4
level 3	1125.1
level 4	29.2

Building 3



level 0	1.07
level 1	0.34
level 2	0.32
level 3	0.49

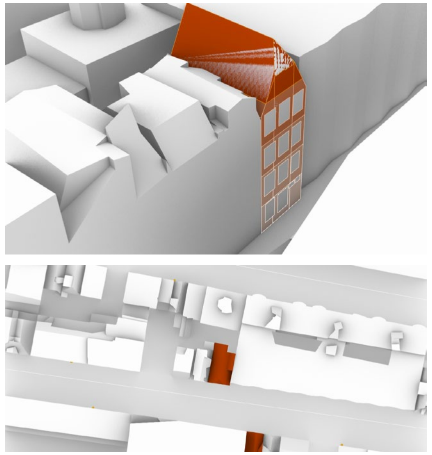
Building 4

TU Delft

Large-scale circadian lighting analysis

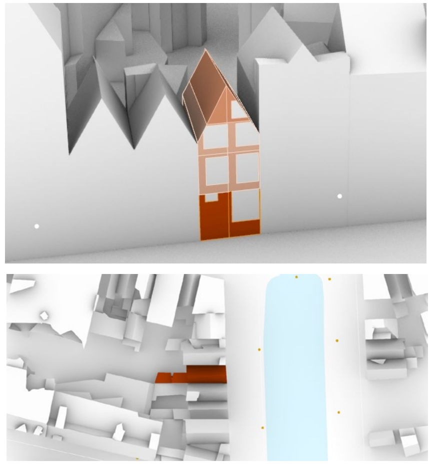
Discussion:

- Representative urban context: Trees, lights, moving objects, surface reflectance
- Representative lighting conditions
- Top-floor accuracy: geometrical complications lead to inaccurate lighting results



level 0	184.0
level 1	422.6
level 2	475.4
level 3	1125.1
level 4	29.2

Building 3



level 0	1.07
level 1	0.34
level 2	0.32
level 3	0.49

Building 4

TU Delft

Design recommendations

Light source

Context in the public space

Urban building context

Facade

window transmittance

interior reflectance

Recipient

Light source:

- Spectrum: spectral tuning for minimizing the circadian receptivity of light
- Intensity: light-source design optimisation for small streets (orientation, placement)

Context:

- Regulations: development of regulations of incident circadian light

Façade:

- Optimise façade design per floor level to help counteract urban context light blocking

Further development for large-scale analysis would allow for a multi-factor analysis and more specific design suggestions can be derived.

Further recommendations

- Translation of the concept from Grasshopper to a Python environment for large-scale assessment
  - window integration
  - Circadian lighting analysis
- Enlarging the information basis of façade information
- Lighting analysis:
  - Implementation of more accurate electric light sources (municipality)
  - Implementation of representative daylight SPD variations

Light source

Context in the public space

Urban building context

Façades

Window transmittance

Interior reflectance

Recipient

Thank you

Impact of façades

- What design recommendations can be derived from the assessment of the impact of façade design and lighting design on circadian health in urban context?

Orientation & WWR

TU Delft

Impact of urban context elements

- What factors are to be taken into consideration for modelling the impact of urban context on circadian light availability in existing buildings?

Constant factors

- Artificial light is steady, always negative. Can be filtered with a constant factor: window transmittance, window placement or root solution: spectral tuning.

- Intensity
- Spectrum
- Timing

Reactive factors:

Mitigating seasonal effects

Daylight is highly variable, and thus there must be designed with this variation in mind: in summer, a surplus of daylight is eminent in evenings:

TU Delft

- Dense building environments can have a negative impact of daylight availability, which is especially eminent on lower levels in small streets.
  - With the proof of this workflow, an estimate can be done of which buildings and which floor levels suffer most from lack of natural circadian light, based on their urban context and their façade design. This information could motivate urban planners to design more consciously, could help interior designers and architects to allocate living functions within a home,
- Next to that, this helps bring the relevance of architectural design for circadian health under attention, encouraging policy-makers to develop regulations for general urban health.

- Intensity;
- Spectrum;
- ~~Duration;~~
- Timing;
- ~~Contrast.~~

	21.00-8.00	8.00-18.00	18.00-21.00
Reference value (mEDI)	<1 lx	>250 lx	<10 lx

Circadian lighting thresholds for measuring Melanopic equivalent daylight illuminance (based on Brown et al. 2022)

Discussion

- Phase 1: Representative urban context:
  - Trees
  - Other obstruction elements
  - Moving objects & additional artificial lighting
  - Lighting & reflection values from windows in urban context
- Phase 2: Assumptions in extracting façade & floor level information:
  - Orthogonal windows
  - Simplification of roof shapes for WWR (inaccurate top level WWR calculation)
  - Relative floor positioning
- Phase 3: scalability
- Phase 4:
  - Representative lighting conditions:

    Lack of accurate street lighting information

    Variation of daylight SPD through the day
  - High daylight values;

    Representative window transmittance

    Interior reflectance

    orientation of the recipient

    > impact on incident artificial light

TU Delft

Methodological limitations:

Grasshopper environment: Complexity for elaborate data structures:

- error propagation
- tool limitations
- lack of debugging tools
- data misalignment

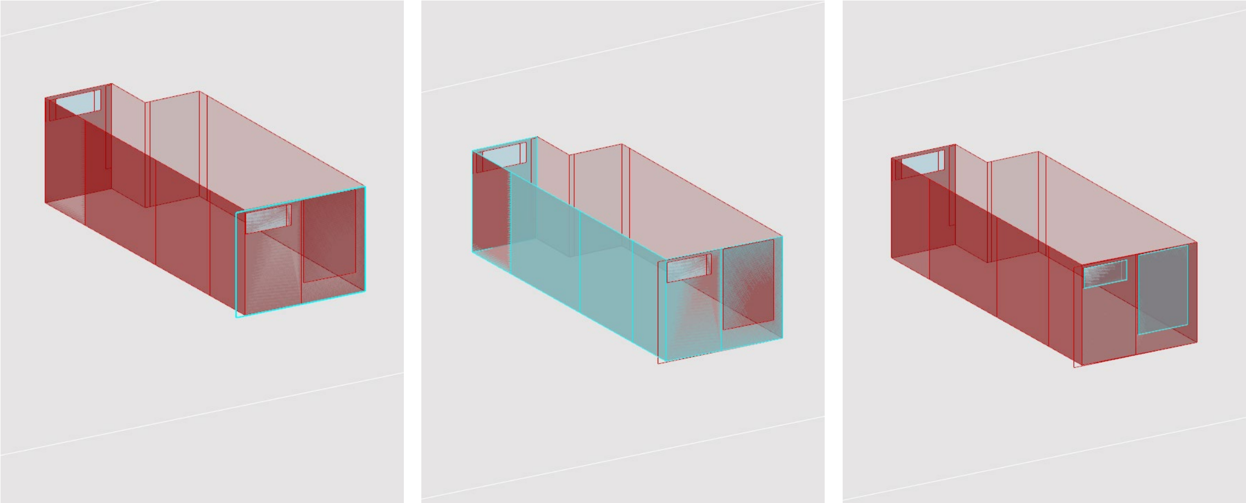
Little timestamps were measured for:

- tracing the scale of impact daylight has on consistency in rhythm over extended periods of time
- How these nuances affect design choices

Methodological limitations

Window boundary reconstruction & projection

- Grouping façade 3D façade elements based on normal direction and closeness to the street:
  - **limit**: non-parallel façade elements visible from the picture are excluded
- Selection of visible facades with the Grasshopper Make2D algorithm, returning visible elements
  - **limit**: Tool designed for flattening in view, aimed for visualisations
  - **limit**: high calculation time

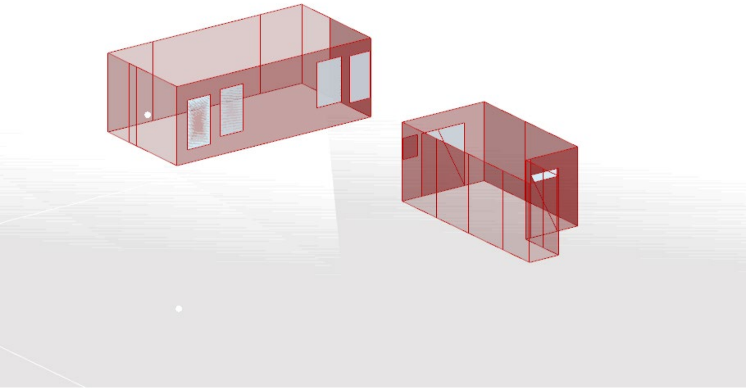


Example: limit when using the make2D algorithm takes a façade edge into account

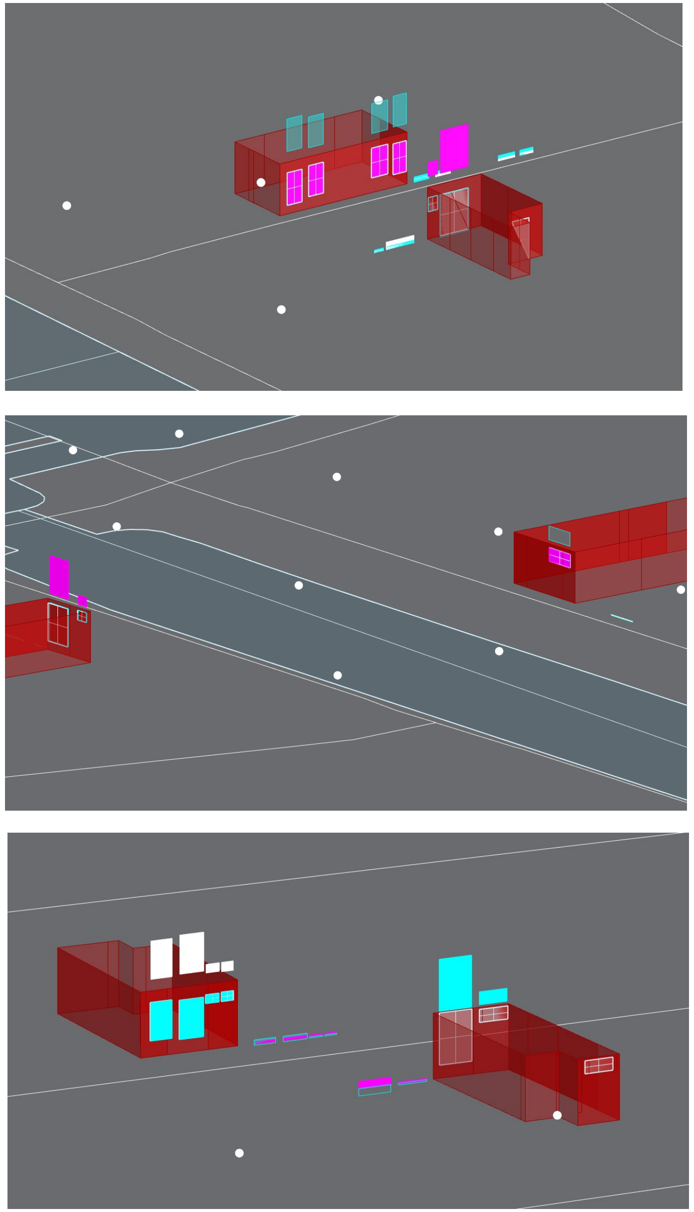
THRASH

Methodological limitations

- Relative window position
  - Four different window plane projection methods are needed to cover the variation in orientation and thus relative vector multiplication
  - For extracting the window boundaries, this is no issue as all window planes are outside of each other's range and thus no extraction of duplicate windows is done.



Extracting window boundaries shows good results



Four versions of boundary reconstruction are needed to find correct window placement for different façade orientations

TU Delft

Fun idea about design recommendation:

- Visualise the use of the tool in illustrator in different manners!!
- Light source placement could be easily tested with this model
- Urban canyon
- Sketch design of a building that includes:
  - Orientation
  - Wwr differences per floor
  - Window transmittance

Check why march and September are so strongly different?????

Design impact

Write about different target groups:
How can who affect which design impact factors? Who is the strongest stakeholder in affecting circadian health?

LARK 9 channel calculation

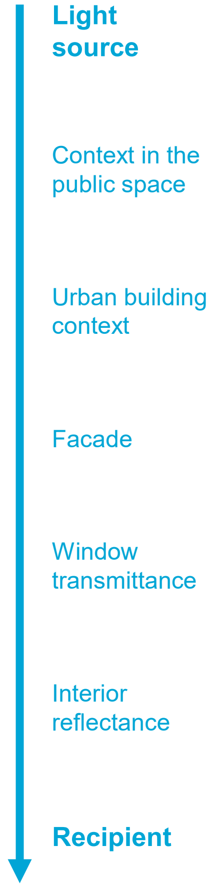
Lighting calculations done with LARK spectral lighting tool (RADIANCE-based simulation)

For each colour channel:

- HB grid-based simulation analysis recipe:
  - climate-based sky
  - 0 lx sky for electric lighting simulation
- Clear sky situation: Tau Clear sky
- HB Daylight analysis, grid-based simulation (single sensor per floor, single direction)
- run LARK radiance files
- Merge channel output

	20-3	21-6	22-9	21-12
02.00				
8.00				
13.00				
19.00				

Result: for each building, for each floor level, 16 point-in-time measurements for Melanopic EDI (lx)



TU Delft

How to measure circadian lighting?

- Circadian Stimulus (CS) (Rea et al. 2021)
  - > 0.3 CS during daytime and < 0.1 CS during evening hours (Li et al., 2022)
- Equivalent Melanopic Lux (EML) (lucas et al., 2014)
  - > 4 hours with > 275 EML before noon (IWBI, 2022)
- Melanopic equivalent daylight D65 illuminance (mEDI) (CIE, 2018)
  - **> 250 lx during daytime;**
  - **> 10 lx from 18:00 to 21:00;**
  - **> 1 lx from 21:00 to 08:00 (Brown et al., 2022)**

	21.00-8.00	8.00-18.00	18.00-21.00
Reference value (mEDI)	<1 lx	>250 lx	<10 lx

Circadian lighting thresholds for dimeasuring Melanopic equivalent daylight illuminance (based on Brown et al. 2022)

- Measurement in a digital environment:
  - LARK (version 3.0: Jung et al., 2023) > open, **mEDI** measurements
  - ALFA (version 1.9: Solemna,, 2024) > licenced, EML measurements

TUDelft

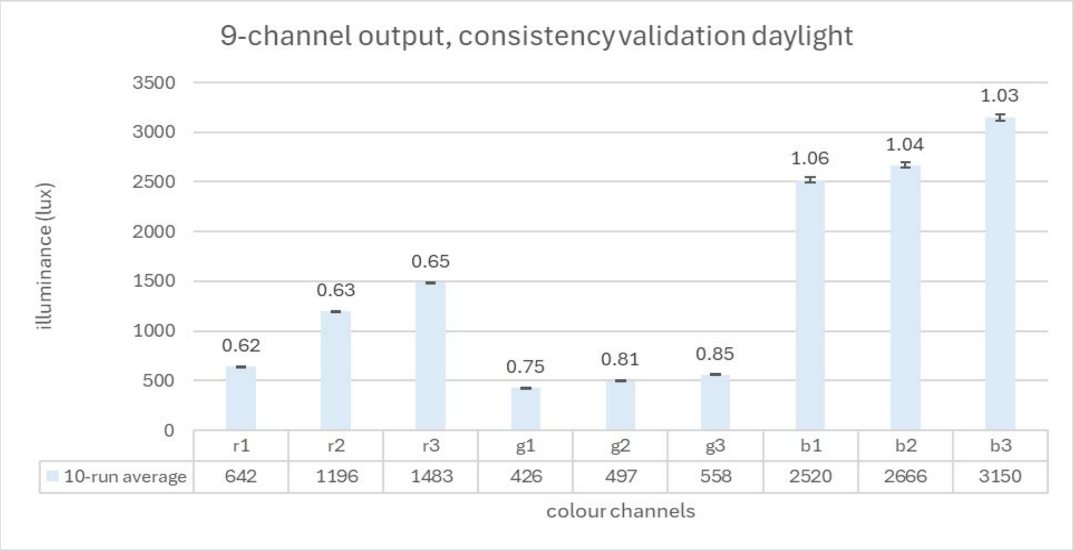
Radiance settings

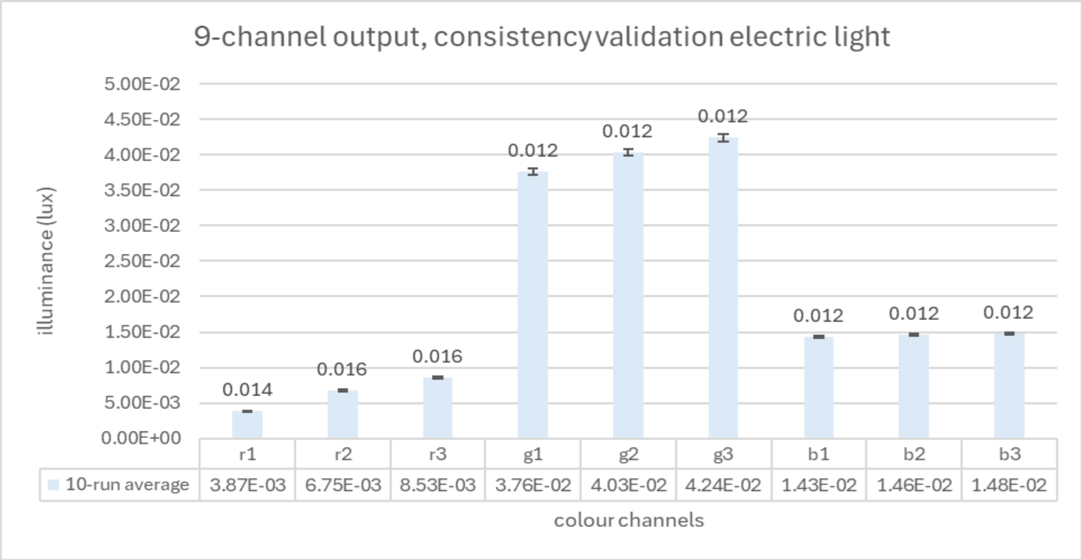
- LARK calculation template
- quality 0
- -ab 2
- -ad 512
- -as 256
- -ar 128
- -aa 0.100
- -lw 0.0001

- the settings as described by Jung et al. (2023)
- -ab 6
- -ad 102
- -as 500
- -ar 100
- -aa 0.1
- - lw 0.0001

- The final settings derived from these two metrics:
  - quality 2
  - -ab 2
  - -ad 1024
  - -as 256
  - -ar 128
  - -aa 0.1
  - -lw 0.0001

Consistency validation 9-channel simulation

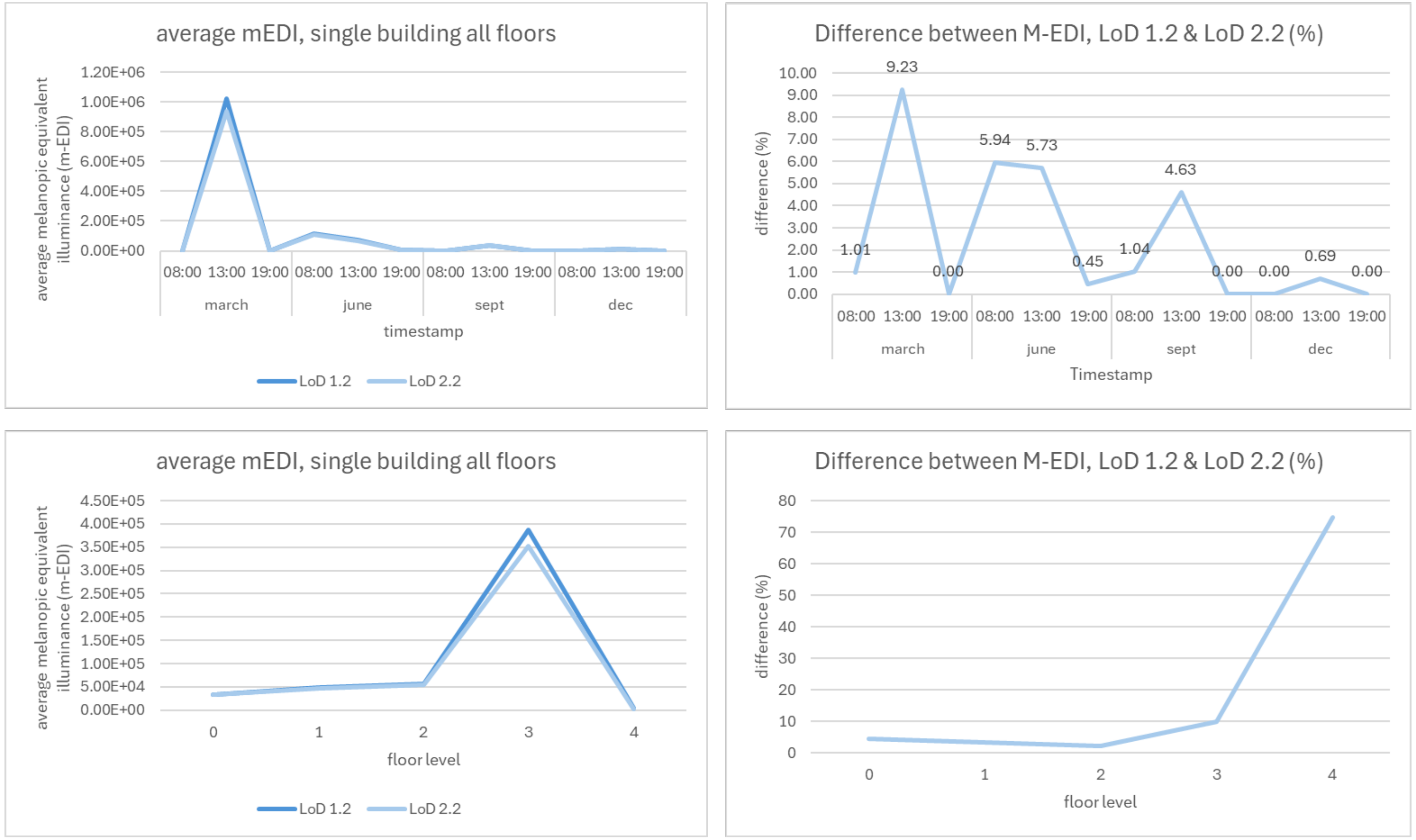




consistency validation of radiance 9-channel calculation

TU Delft

Comparison in daylight availability measurements for two contextual levels of detail (loD1.2, LoD2.2)



Comparison in daylight availability measurements for two contextual levels of detail (loD1.2, LoD2.2)

Material library

Property	Value	Value	Value	Value	Value	Value	Value
V(λ) Reflectance	12.84%	18.38%	62.96%	88.42%	35.91%	11.96%	10.39%
M(λ) Reflectance	10.53%	17.03%	54.37%	87.47%	25.72%	7.47%	22.14%
M/P Ratio	0.82	0.93	0.86	0.99	0.72	0.62	2.13
Specularity	0.00%	0.27%	0.31%	1.04%	0.00%	0.00%	0.00%
Roughness	0.30	0.20	0.20	0.20	0.00	0.20	0.00
	01137, Dirty brick	01100, Concrete Grey Exterior Floor Tiles	00704, Beige Plaster Wall	00583, White painted ceiling	00434, Wood Maple	01110, Grass	00496, Purplish Blue

TU Delft

Lighting measurements

Reference values: Brown et al. (2022)

Measurement positioning:

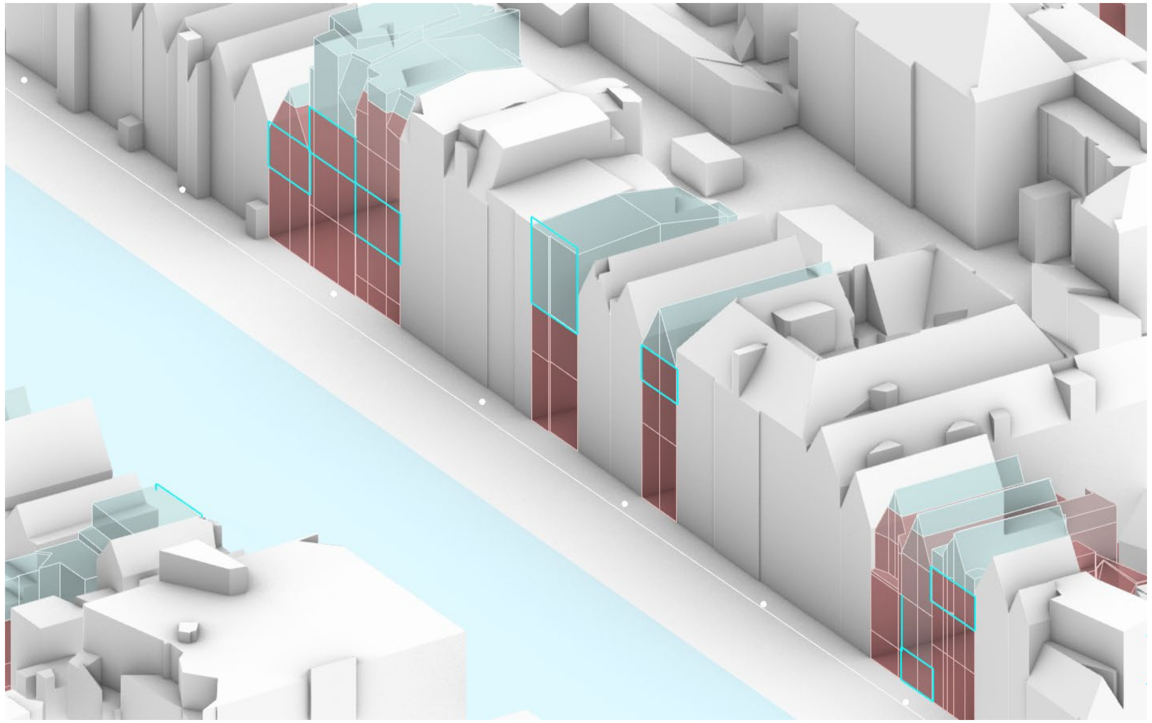
- Recipient: Brown et al. (2022) centre of the room at seating hight (1.1m), oriented towards the window

21.00-8.00	8.00-18.00	18.00-21.00
1 mEDI	250 mEDI	10 mEDI

Circadian lighting thresholds for different measurement metrics (based on Brown et al. 2022)

TUDelft

Large-scale window plane per floor



selection of window plane, per floorlevel (level 3 selected)

TU Delft

Single building tests

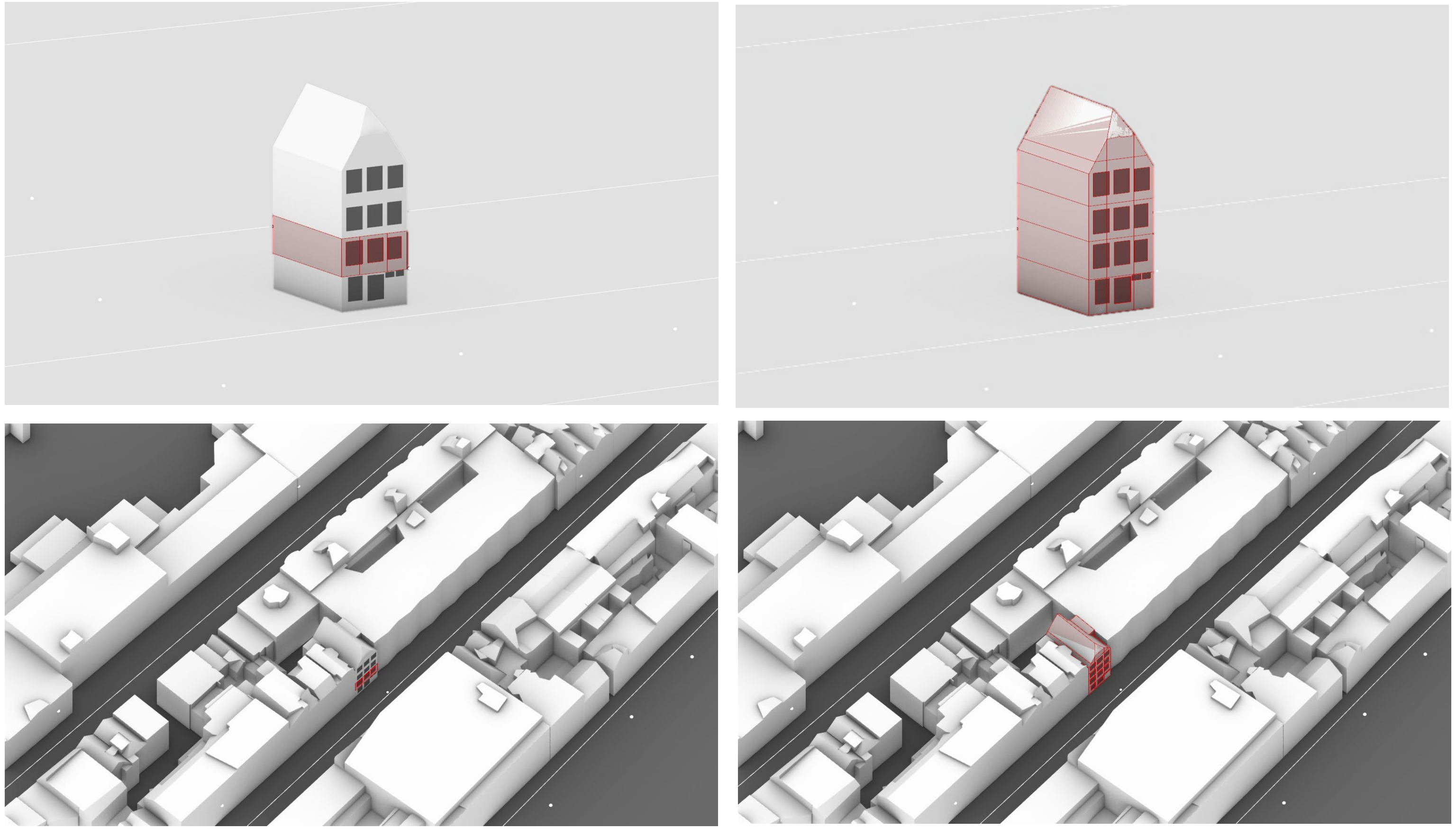


Figure 4-14 Single floor test (left) single building test (right)

Building-level scope (intensity, spectrum)

- Window transmittance
  - Influential, affecting distribution and intensity (0-1)

    double glass HR++ 0,7-0,8

    solar controlled glass 0,1 (joostdevree.nl, 2024)
- Interior reflectance
  - Influential: Within the bounds of EN 17037 (regulatory values): variations of 50% (Koster, 2022)
- Recipient
  - Positioning, behaviour, individual variation for circadian lighting sensitivity

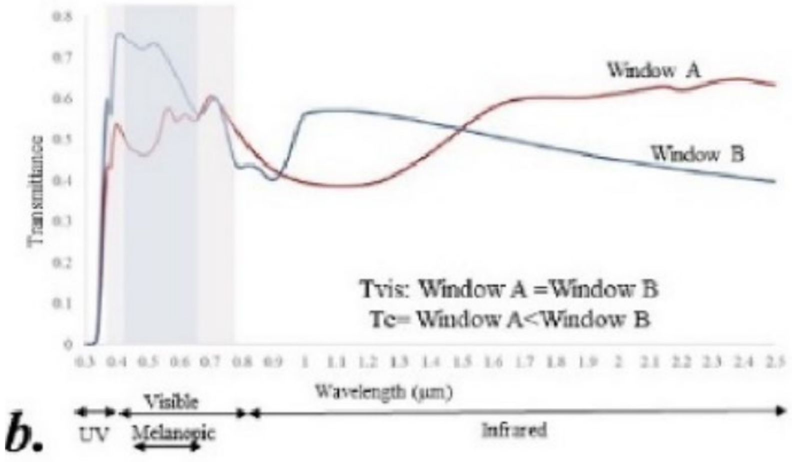


Figure 2-4 variation in transmittance between two windows with similar Tvis (Ardabili et al., 2023)

Light source

Context in the public space

Urban building context

Façades

Window transmittance

Interior reflectance

Recipient

TU Delft