



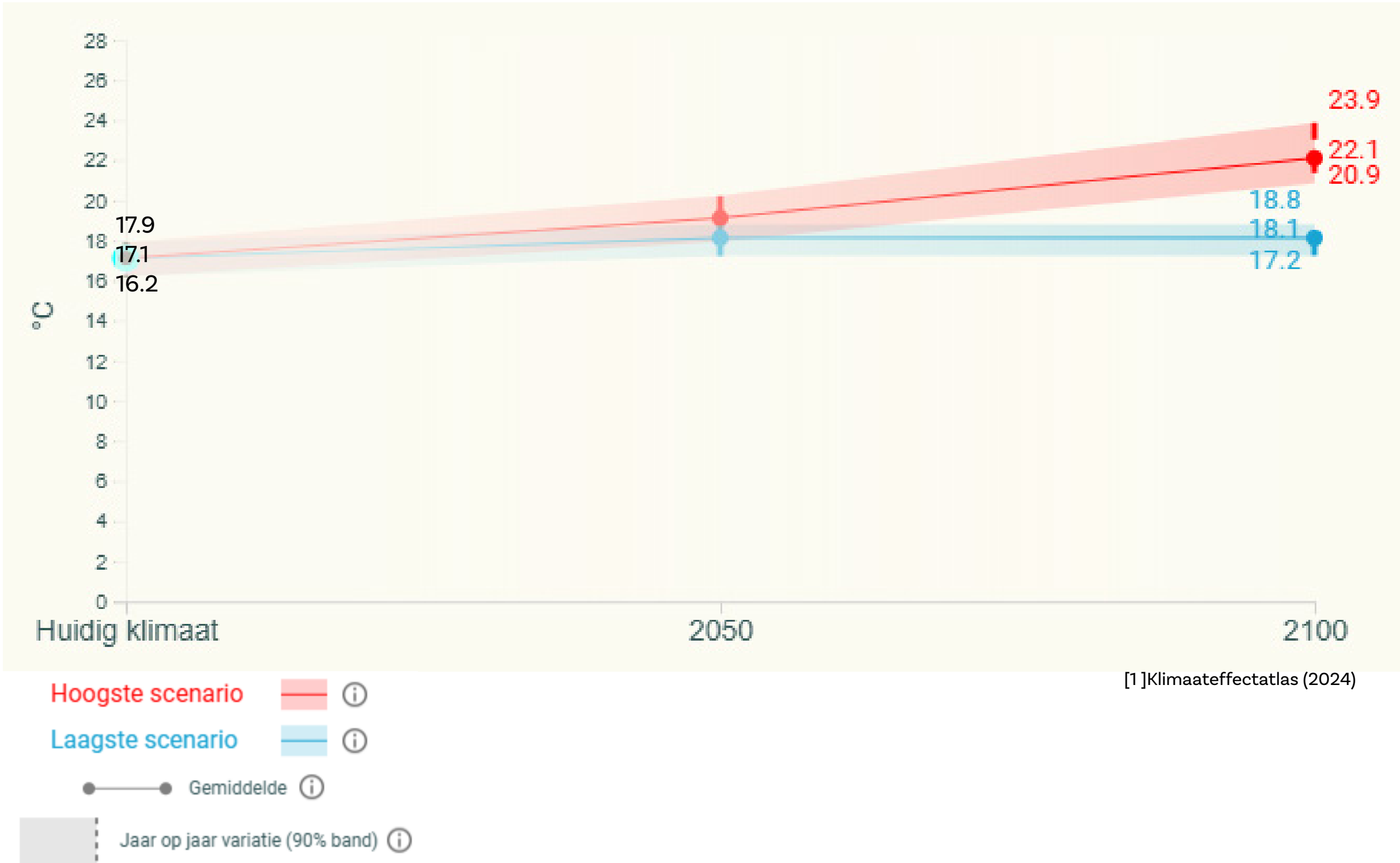
COOL BY DESIGN

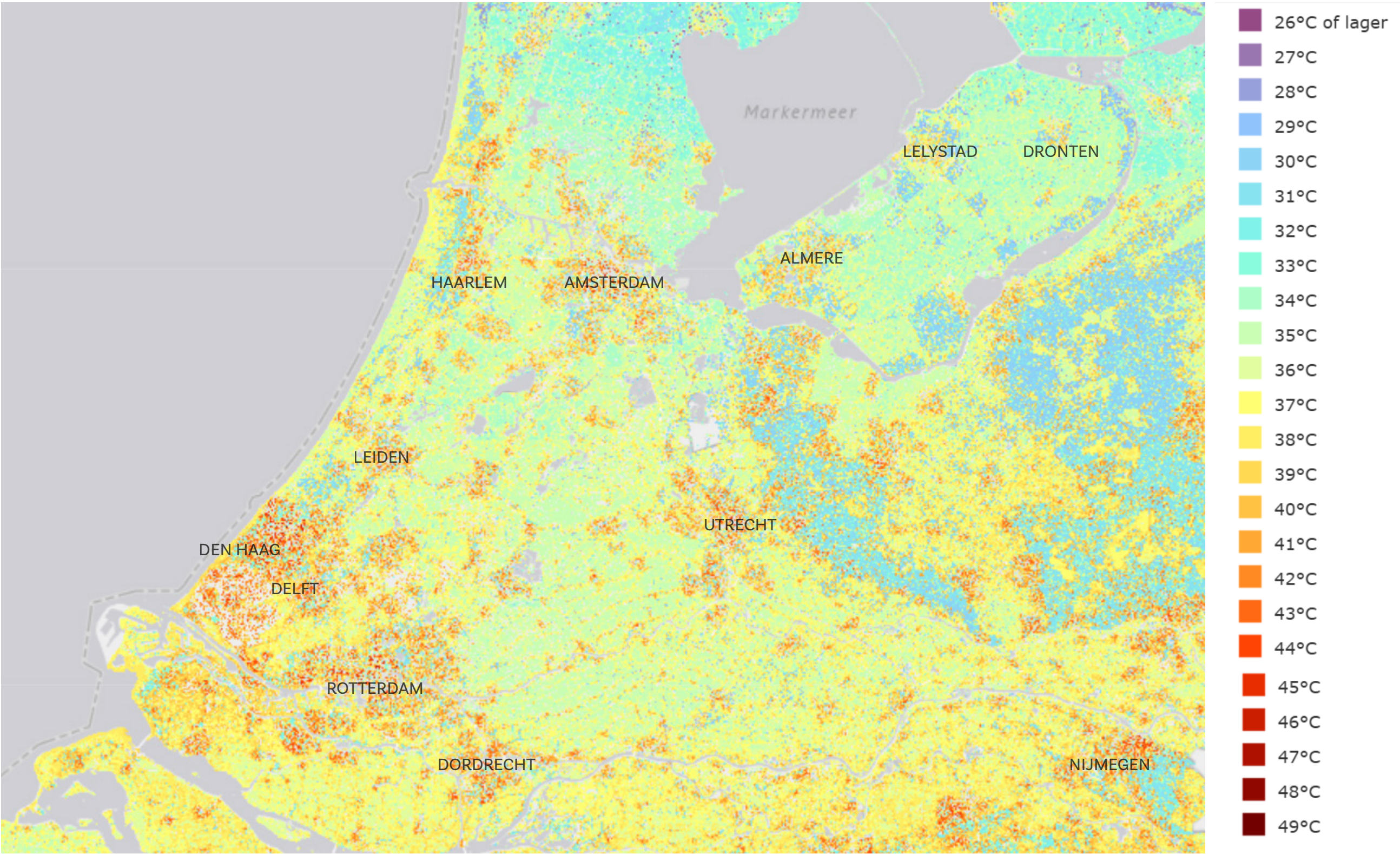
SOLFD: Extending SOLWEIG for Urban Design
Decision Making on Outdoor Thermal Comfort

Jessica Monahan
4994809
19/06/2025

1st Supervisor	Dr. C. García-Sánchez
2nd Supervisor	Dr. H. Ledoux
Delegate	Ir. E. Verbree

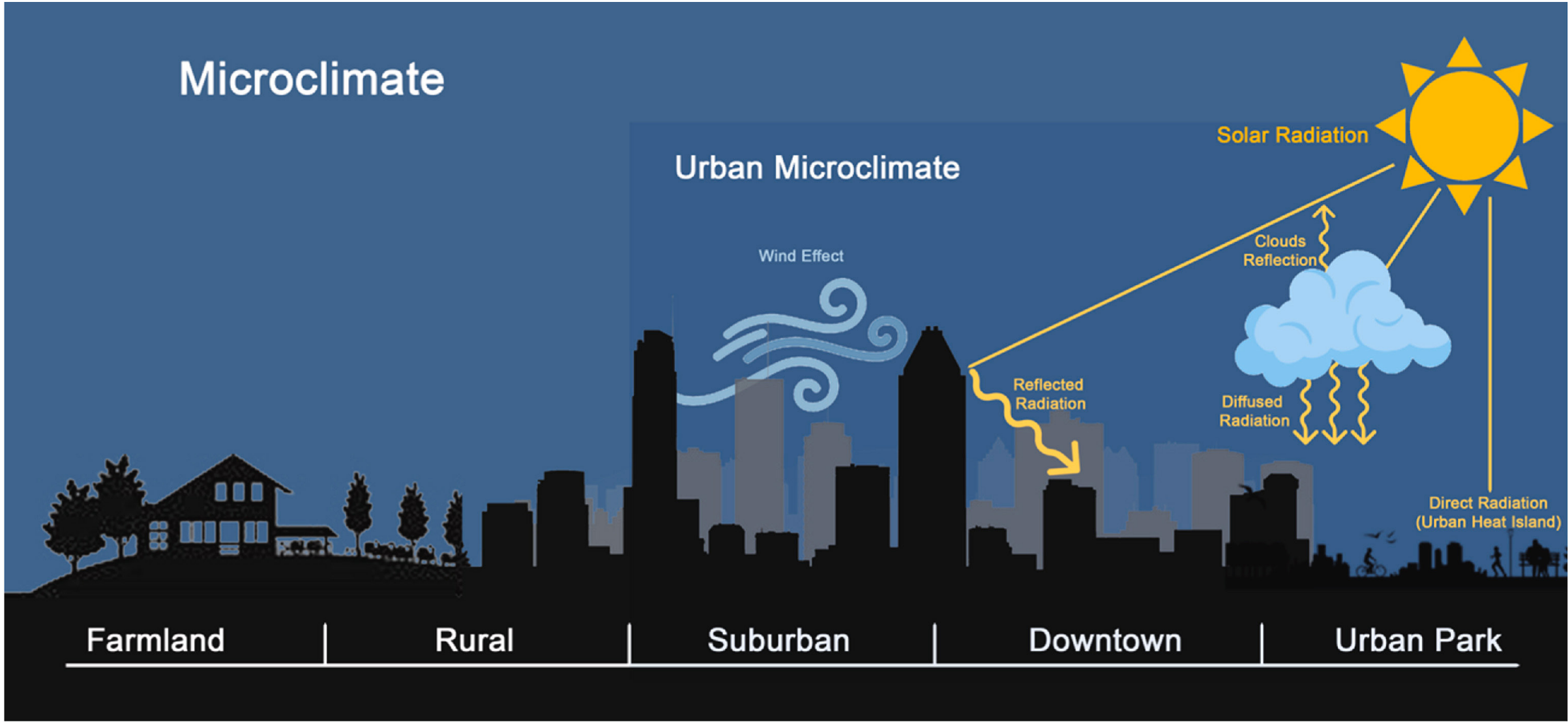
Average Summer Temperature in the Netherlands, Now and in The Future





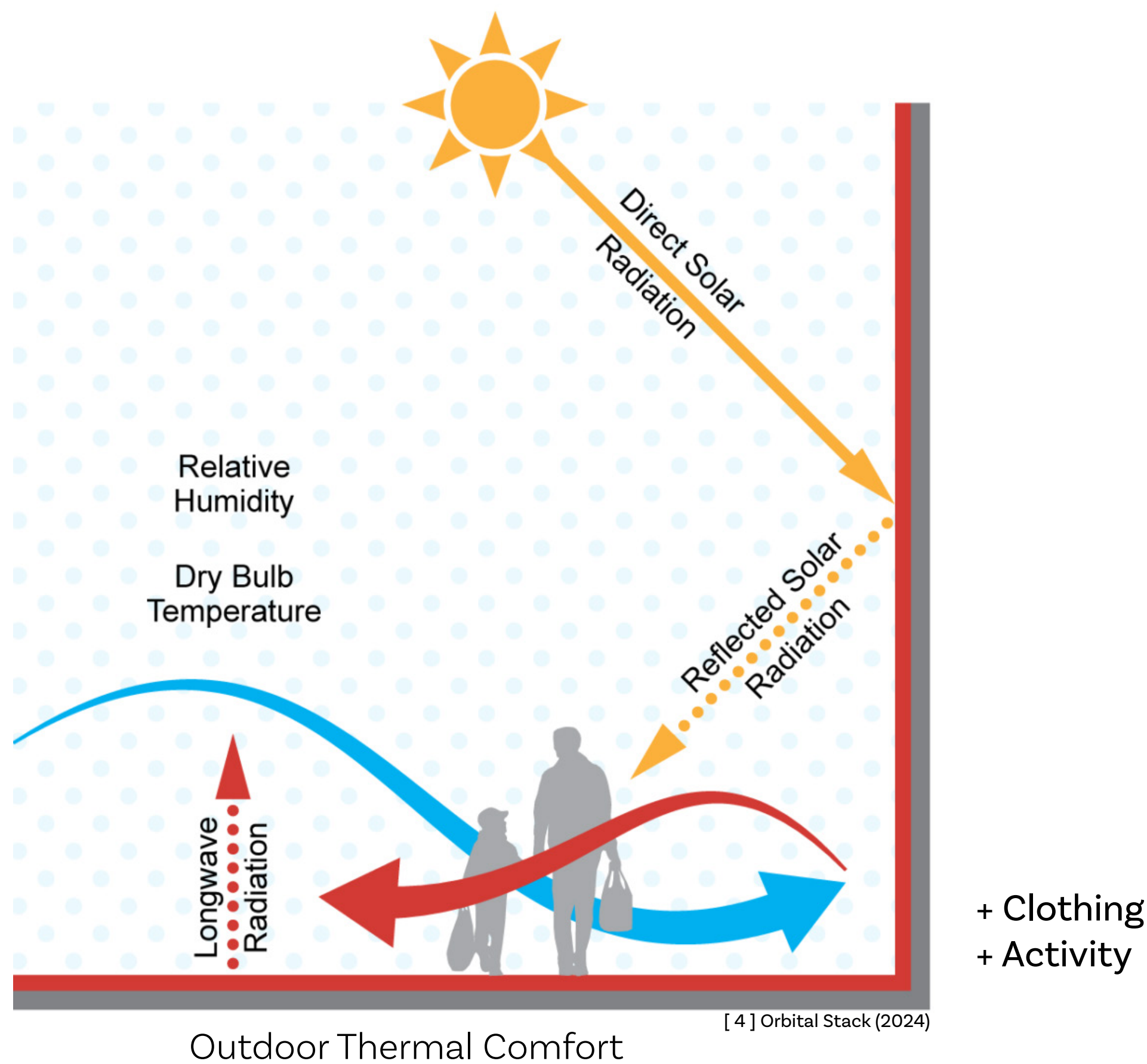
[2] Nationale Hittestresskaart (2020)

Perceived temperature across the Netherlands on a hot summer day



Urban Microclimate

[3] Yang et al. (2024)





Dry bulb (air) temperature



Humidity



Air speed



Mean radiant temperature

Outdoor Thermal Comfort



Dry bulb (air) temperature



Humidity



Air speed

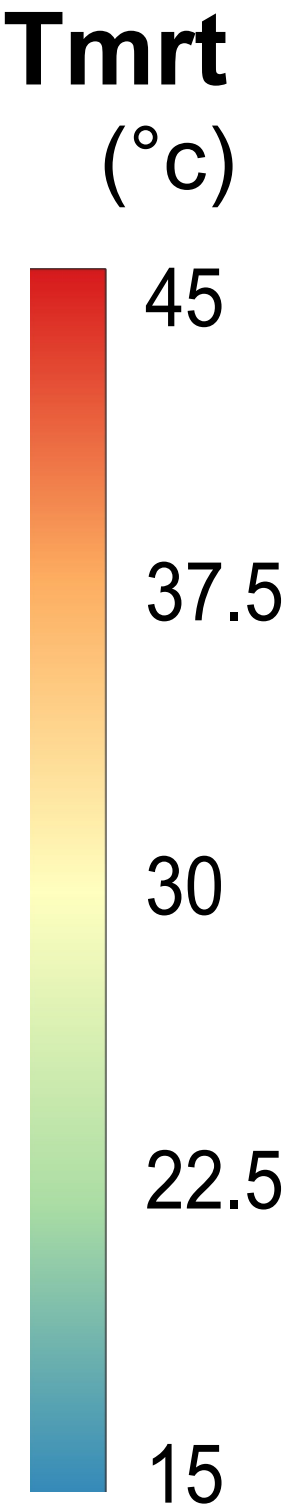
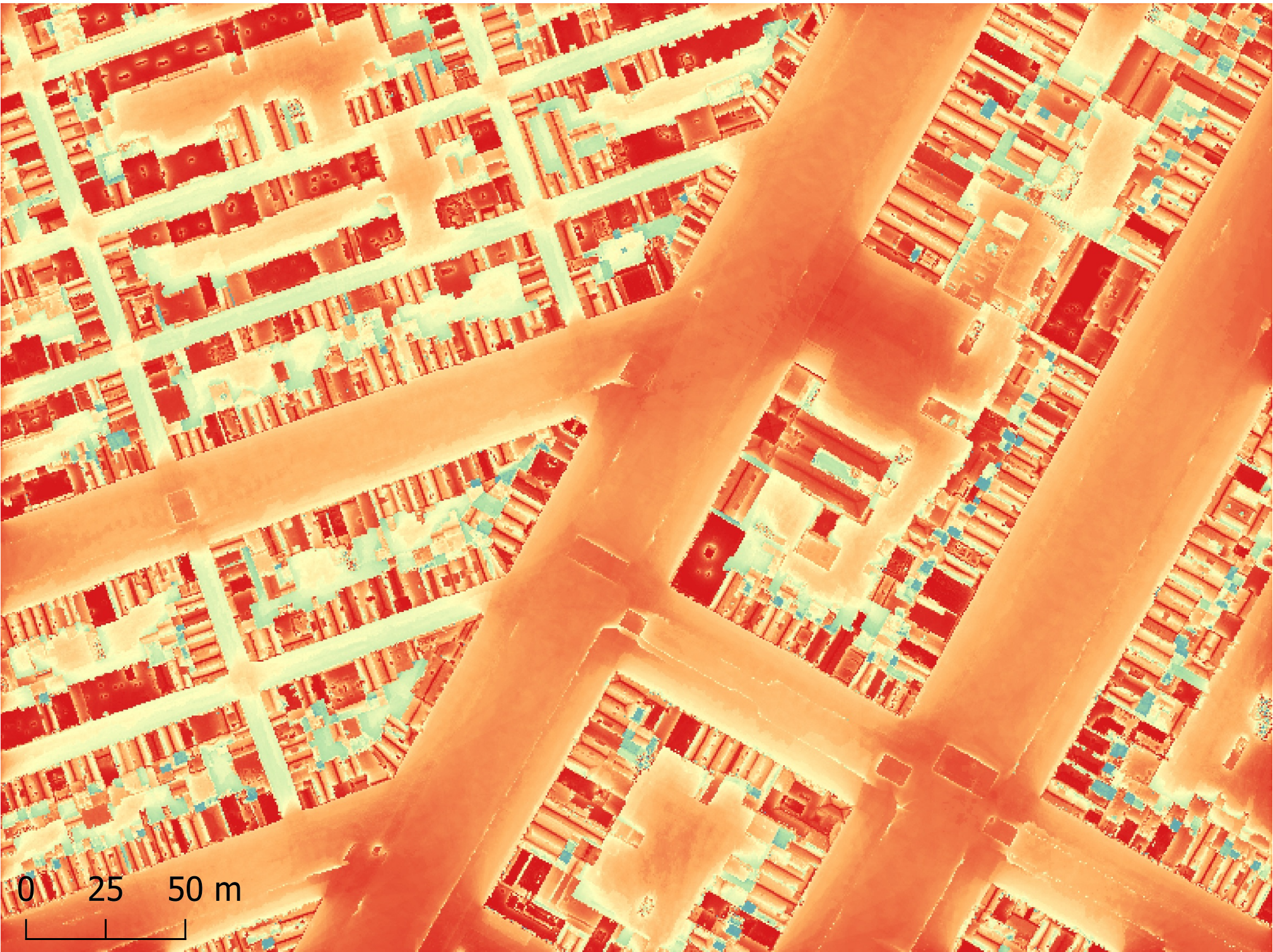
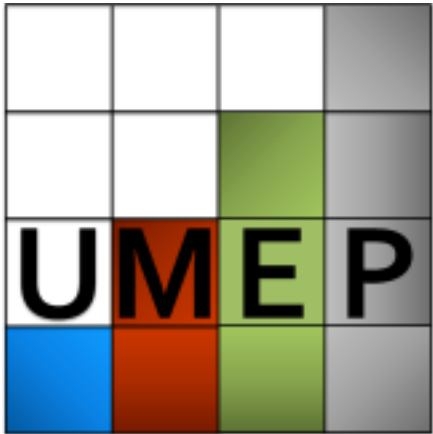


Mean radiant temperature

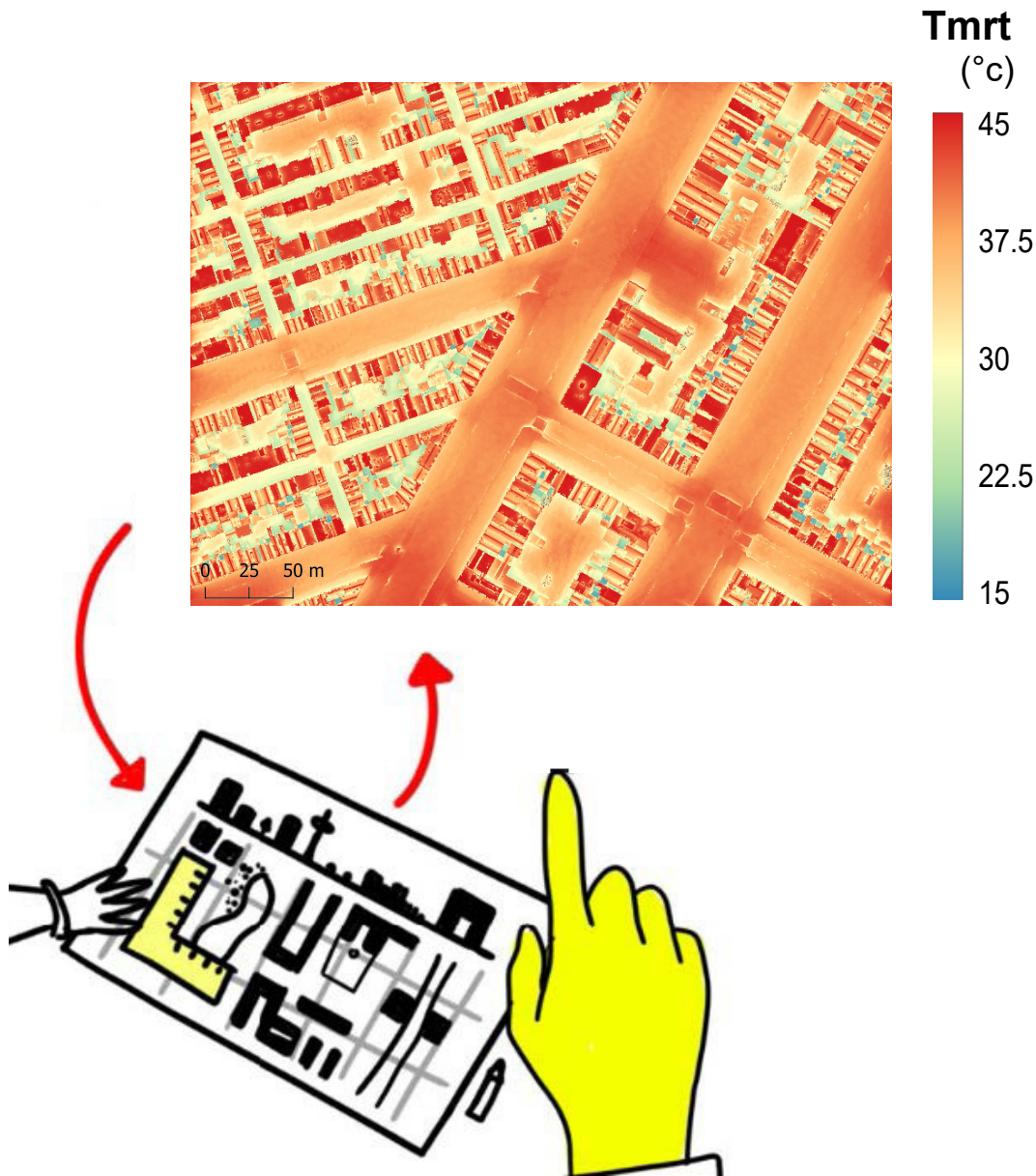
Outdoor Thermal Comfort



Tmrt at 13.00 PM



SOLWEIG



OBJECTIVE

To develop a framework for a tool (SOLFD), based on the SOLWEIG model, that enables designers to visualize current urban climate conditions at the neighborhood scale in the Netherlands and to evaluate, visualize and compare the potential impacts of proposed designs on these conditions for the human comfort.

SOLFD DEVELOPMENT

ACCURACY OF MODELS

SOLFD CASE STUDY

Research Questions

How can a tool framework be developed for visualizing current urban climate conditions and their effect on outdoor thermal comfort at the neighborhood scale in the Netherlands using SOLWEIG, and how can design alternatives be integrated and compared within this tool?

SOLFD DEVELOPMENT

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What does existing research report about the accuracy of SOLWEIG, and how well do the newly implemented 3D modifications perform when validated against sensor data?

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How can a tool framework be developed for visualizing current urban climate conditions and their effect on outdoor thermal comfort at the neighborhood scale in the Netherlands using SOLWEIG, and how can design alternatives be integrated and compared within this tool?

What does existing research report about the accuracy of SOLWEIG, and how well do the newly implemented 3D modifications perform when validated against sensor data?

How can the tool be used to analyze the effects of urban design proposals on microclimatic conditions and outdoor thermal comfort in various Dutch urban typologies?

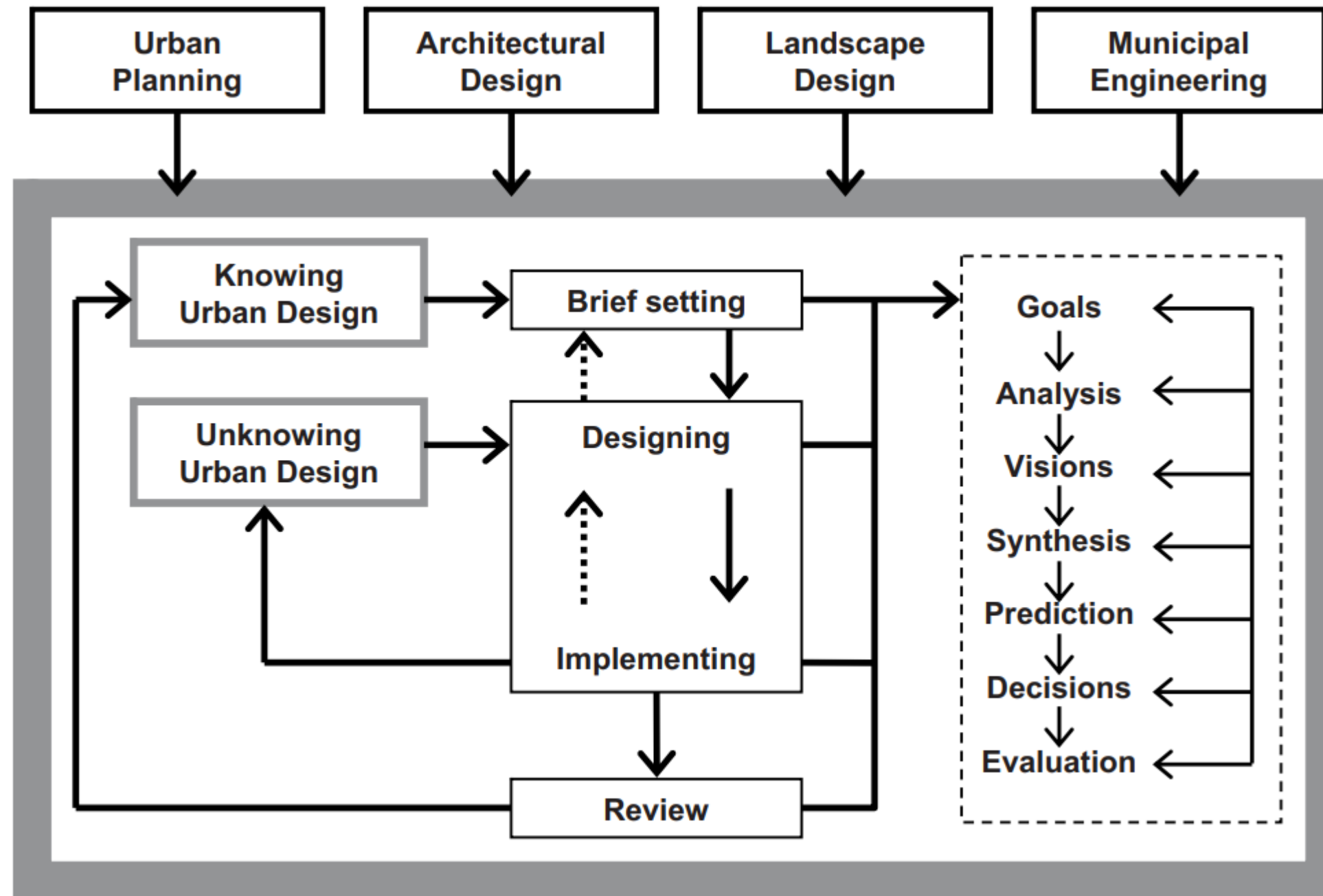
SOLFD DEVELOPMENT

ACCURACY OF MODELS

SOLFD CASE STUDY

OBJECTIVE

Urban Design Process

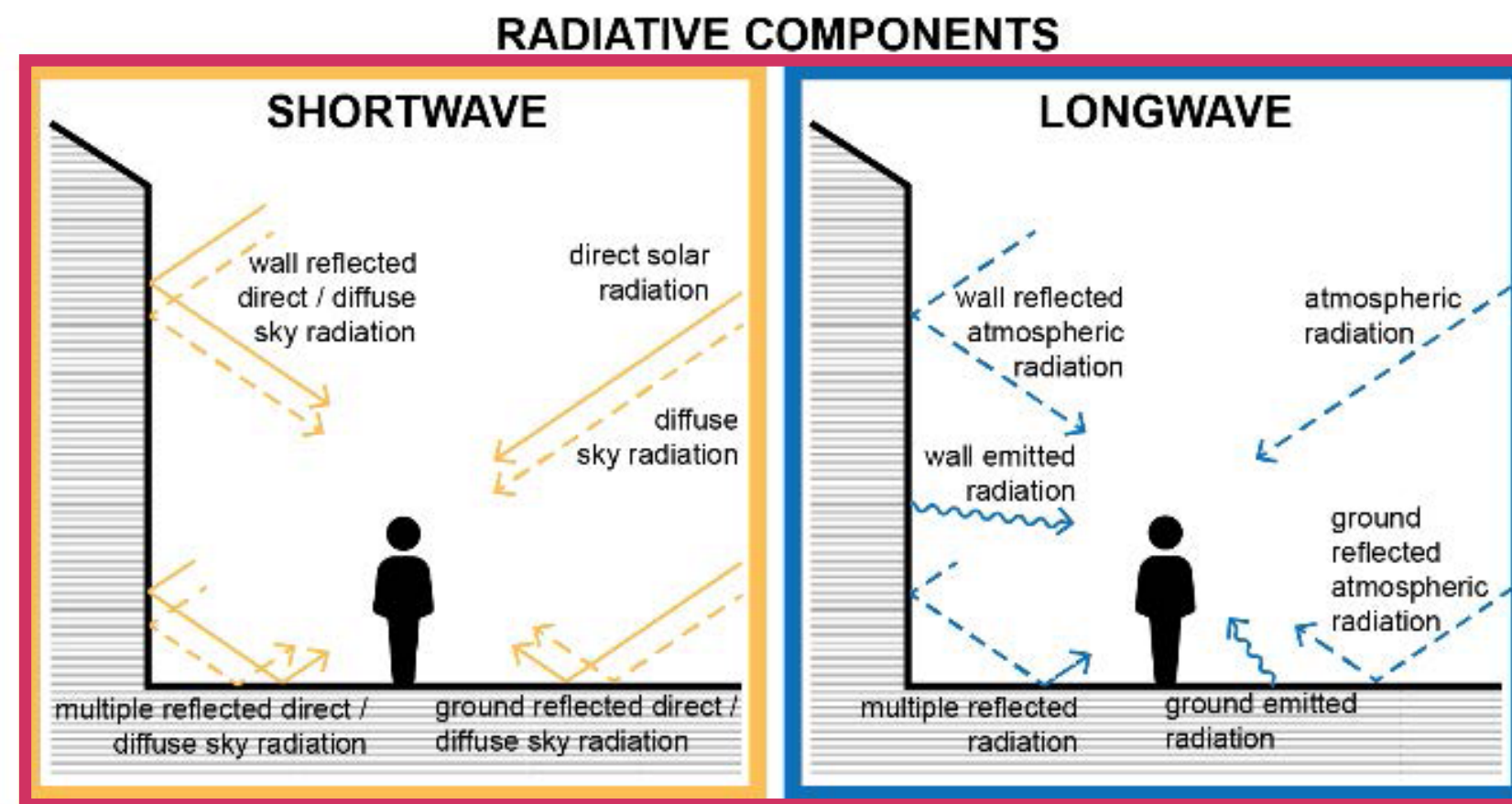


The Integrated Urban Design Process

[5] Carmona et al. (2010)

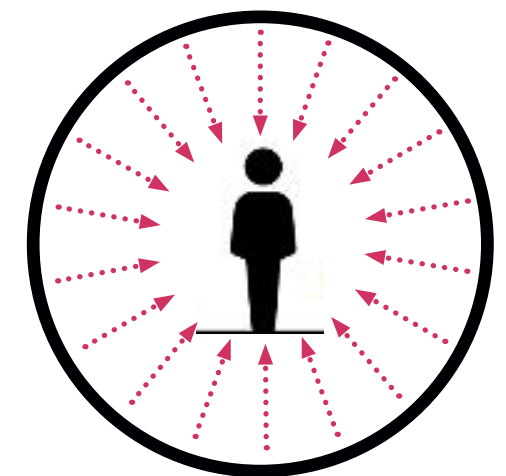
Mean Radiant Temperature

$$T_{\text{mrt}} = \sqrt[4]{\frac{S_{\text{str}}}{\epsilon_p \sigma}} + 273.15$$

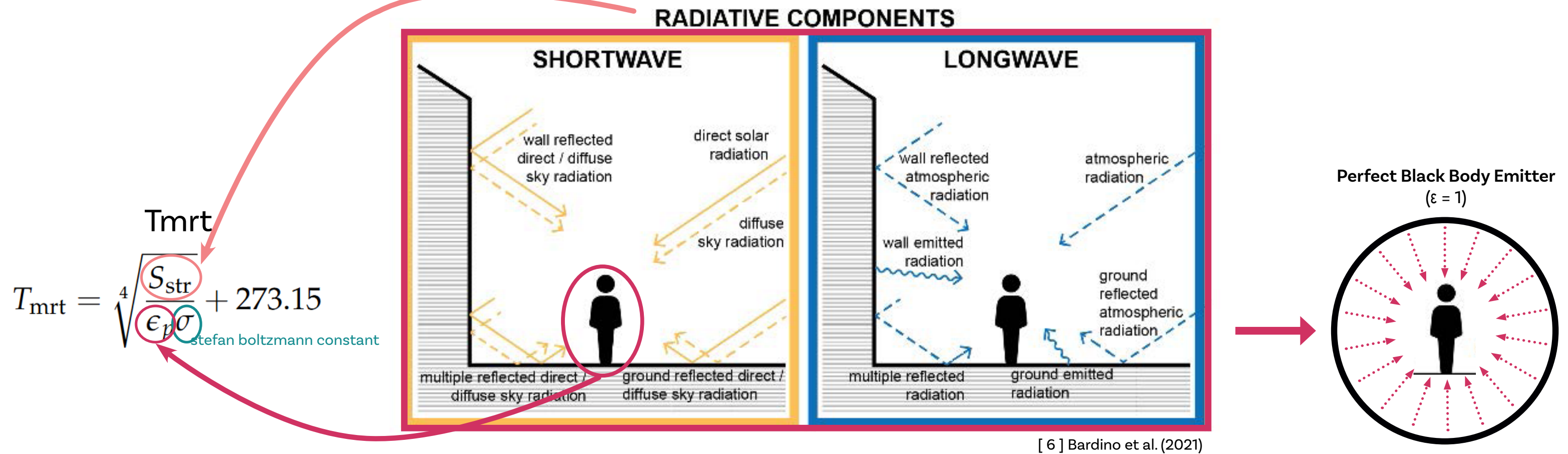


[6] Bardino et al. (2021)

Perfect Black Body Emitter
($\epsilon = 1$)



Mean Radiant Temperature



$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{\epsilon_p \sigma}} + 273.15$$

stefan boltzmann constant

Mean Radiant Temperature

- **PET** = Physiological Equivalent Temperature

Examples of PET values for different climate scenarios

Scenario	T_a (°C)	T_{mrt} (°C)	v (m/s)	VP (hPa)	PET (°C)
Typical room	21	21	0.1	12	21
Winter, sunny	-5	40	0.5	2	10
Winter, shade	-5	-5	5.0	2	-13
Summer, sunny	30	60	1.0	21	43
Summer, shade	30	30	1.0	21	29

T_a air temperature, v air velocity, VP water vapor pressure.

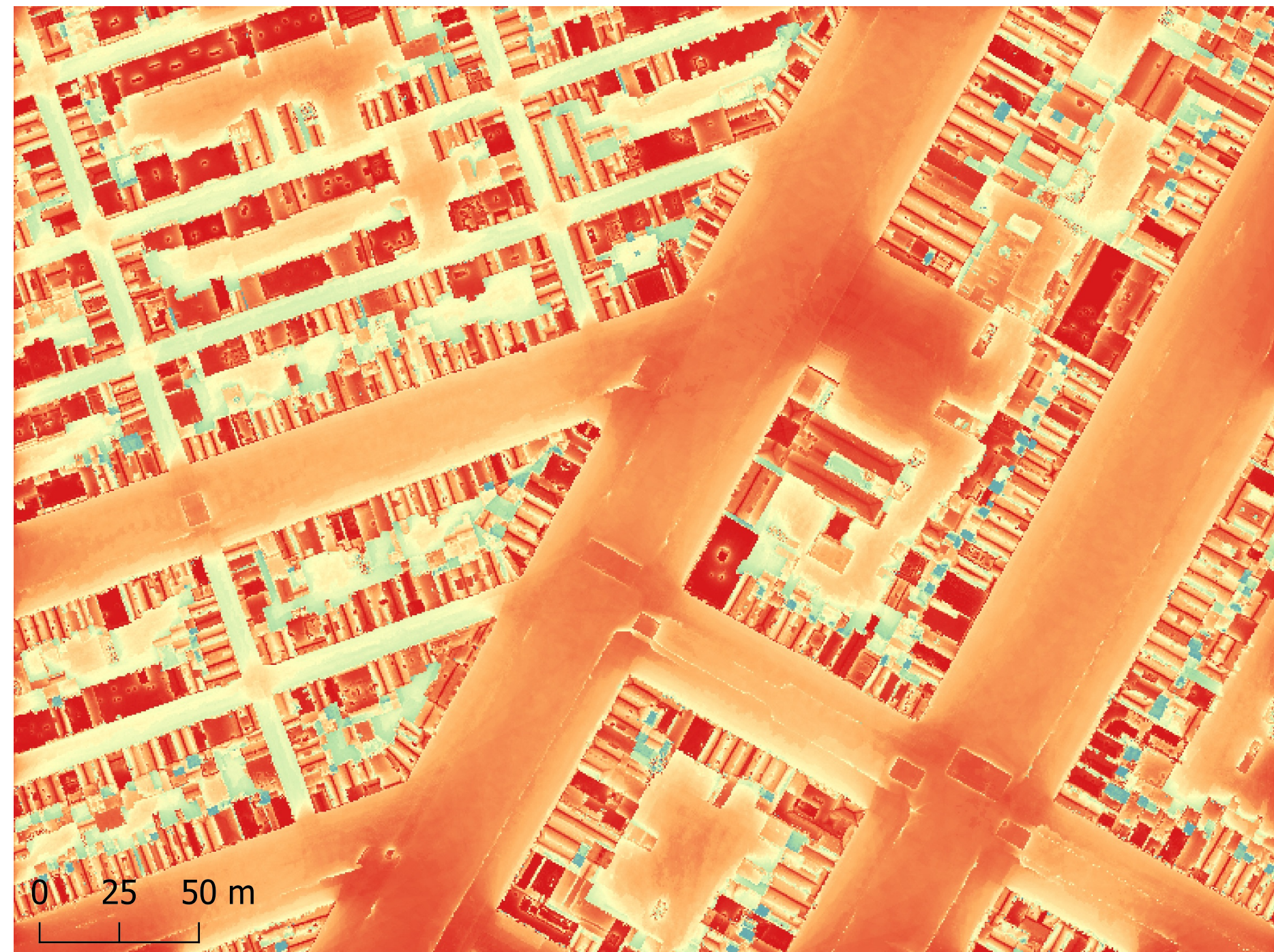
[7] Höppe (1999)

SOLWEIG

Mean radiant flux density

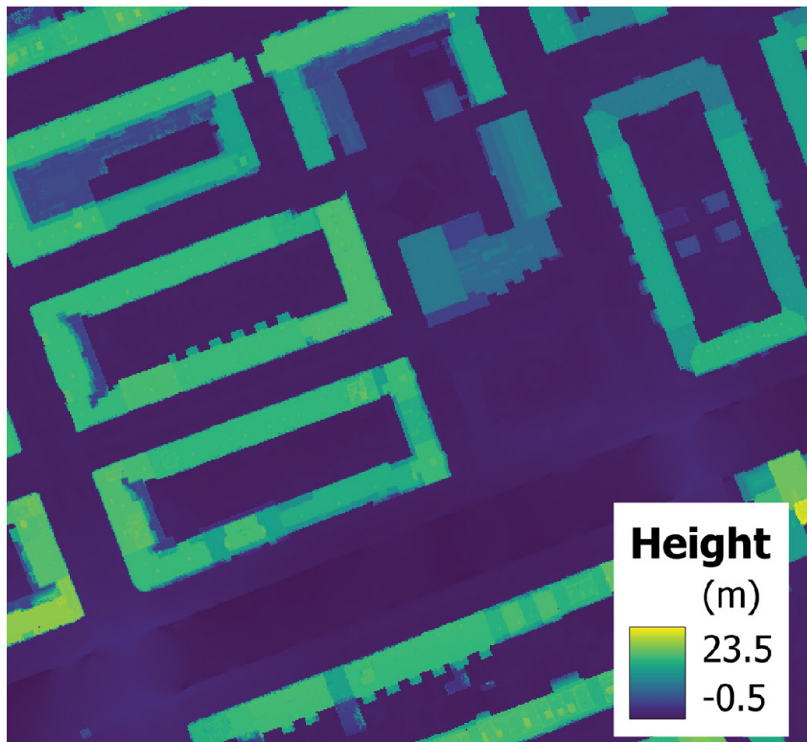
$$S_{str} = \tilde{\zeta}_k \sum_{i=1}^6 K_i F_i + \epsilon_p \sum_{i=1}^6 L_i F_i$$

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{\epsilon_p \sigma}} + 273.15$$

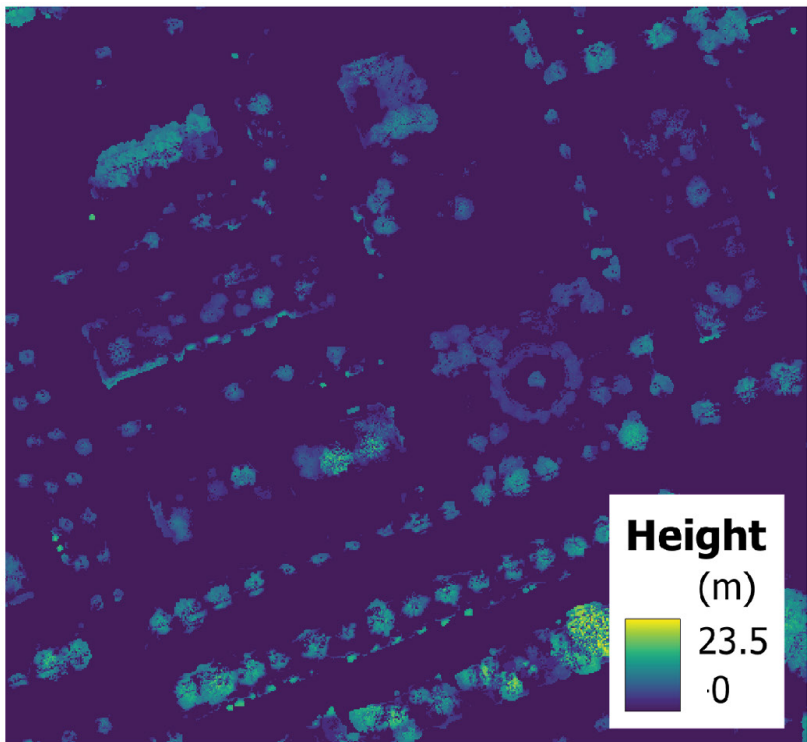


Tmrt at 13.00 PM

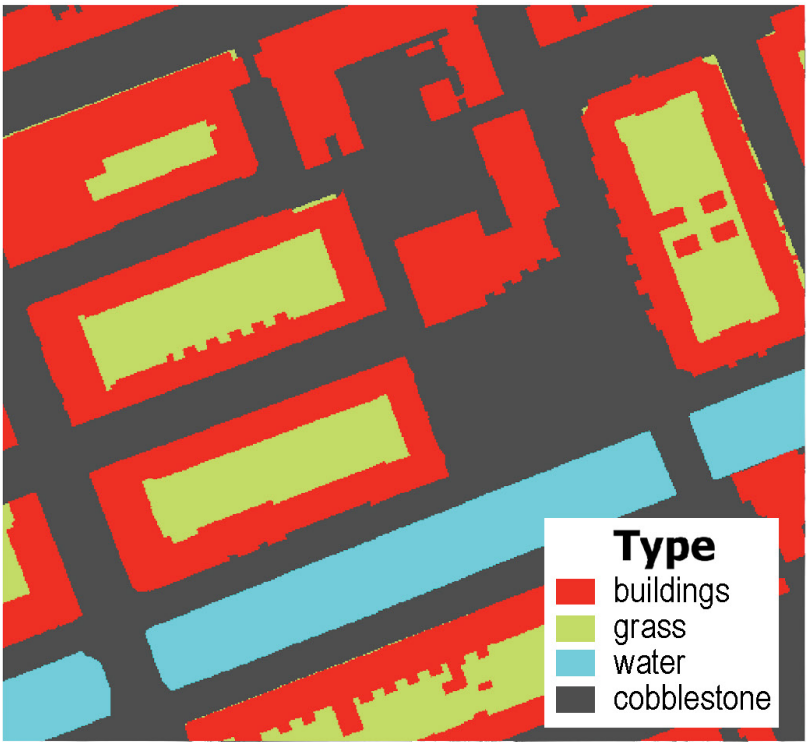
SOLWEIG input



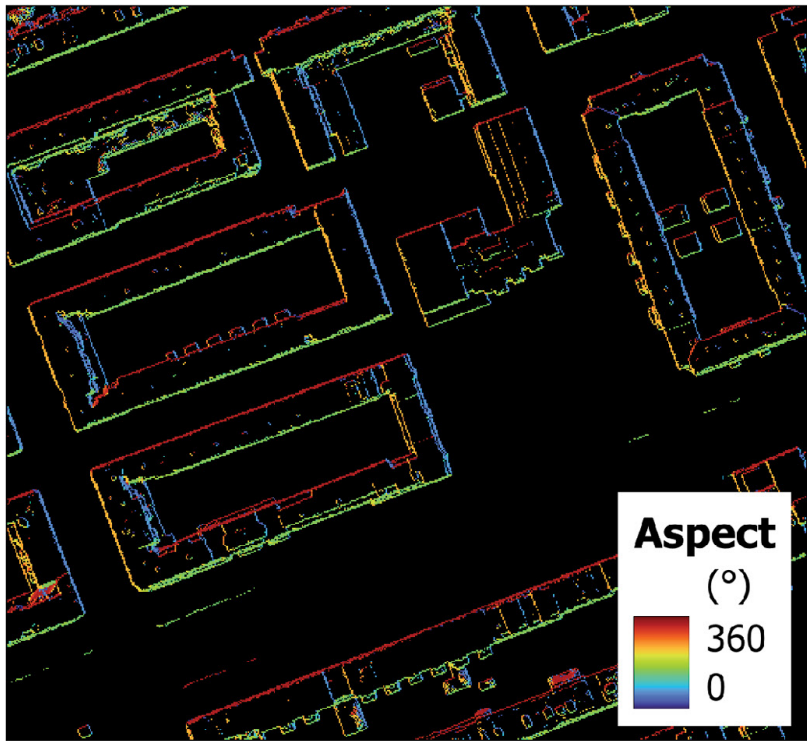
Digital Surface Model
DSM



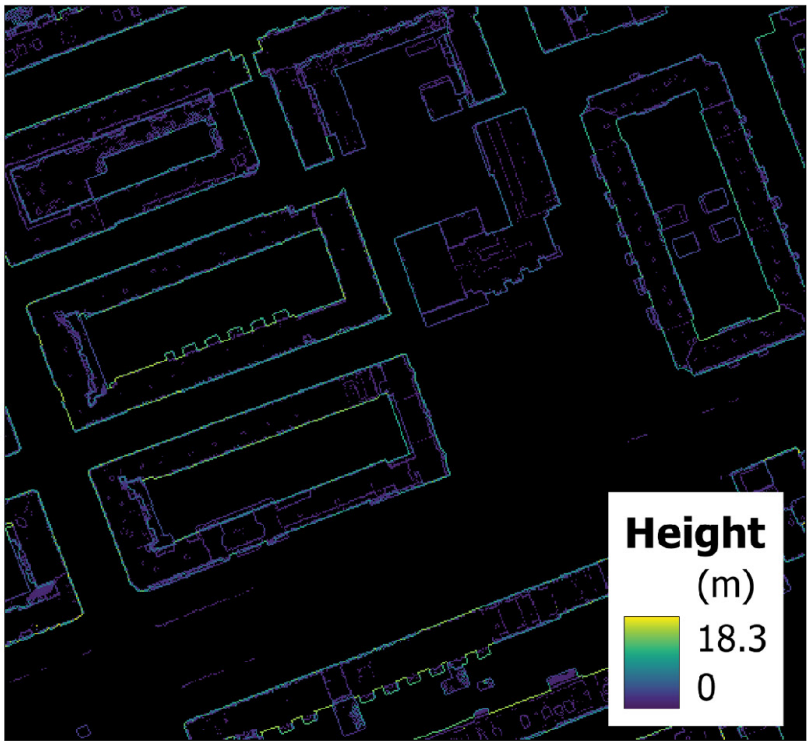
Canopy Height Model
CHM



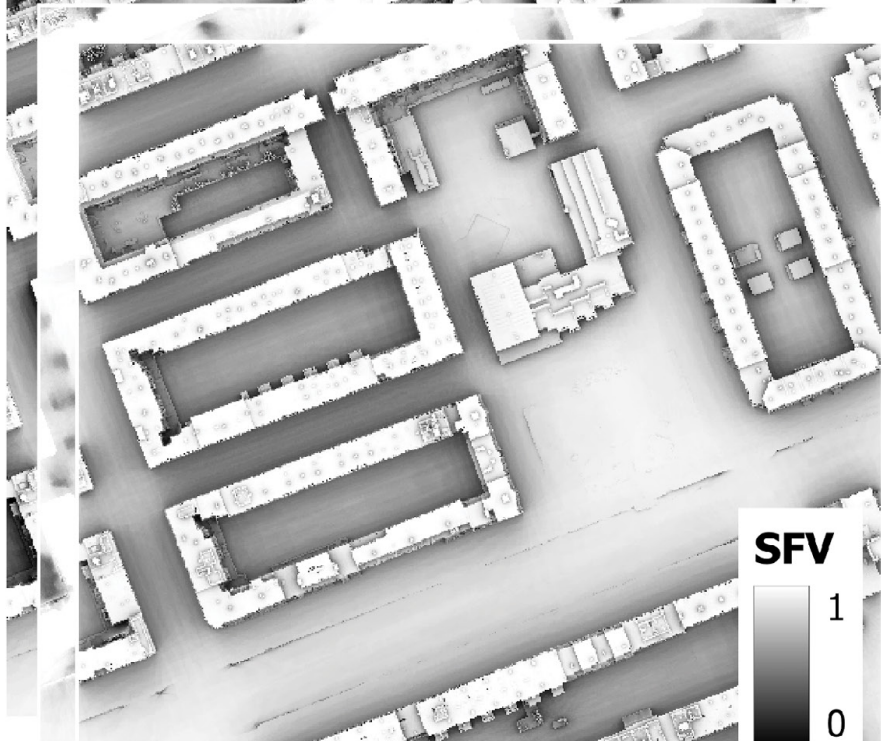
Land cover



Wall Aspect



Wall Height



Sky View Factor maps
SVF

Year	DOY	Hour	Min	RH	Td	Press	Kdn	Kdiff	Kdir
2023	213	0	0	87	16.5	101.3	0	0	0
2023	213	1	0	88	16.2	101.3	0	0	0
2023	213	2	0	89	15.9	101.3	0	0	0
2023	213	3	0	90	15.7	101.3	0	0	0
2023	213	4	0	90	15.6	101.3	1.7	1.5	3.9
2023	213	5	0	89	16	101.3	28	19	84
2023	213	6	0	87	17	101.3	86	53	187
2023	213	7	0	82	18.2	101.3	189	92	262
2023	213	8	0	77	19.3	101.3	296	128	332
2023	213	9	0	73	20.2	101.3	398	160	380
2023	213	10	0	69	21.2	101.3	478	184	407
2023	213	11	0	66	21.8	101.3	525	201	412
2023	213	12	0	64	22.2	101.3	538	206	410
2023	213	13	0	63	22.5	101.3	525	208	397
2023	213	14	0	62	22.6	101.3	479	192	383
2023	213	15	0	62	22.5	101.3	408	170	359
2023	213	16	0	63	22.1	101.3	321	138	333
2023	213	17	0	66	21.5	101.3	223	102	289
2023	213	18	0	69	20.6	101.3	127	65	224
2023	213	19	0	74	19.4	101.3	49	29	132
2023	213	20	0	80	18.1	101.3	6.7	5	33
2023	213	21	0	83	17.2	101.3	0	0	0
2023	213	22	0	86	16.6	101.3	0	0	0
2023	213	23	0	86	16.8	101.3	0	0	0

Meteorological
Data

SOLWEIG input

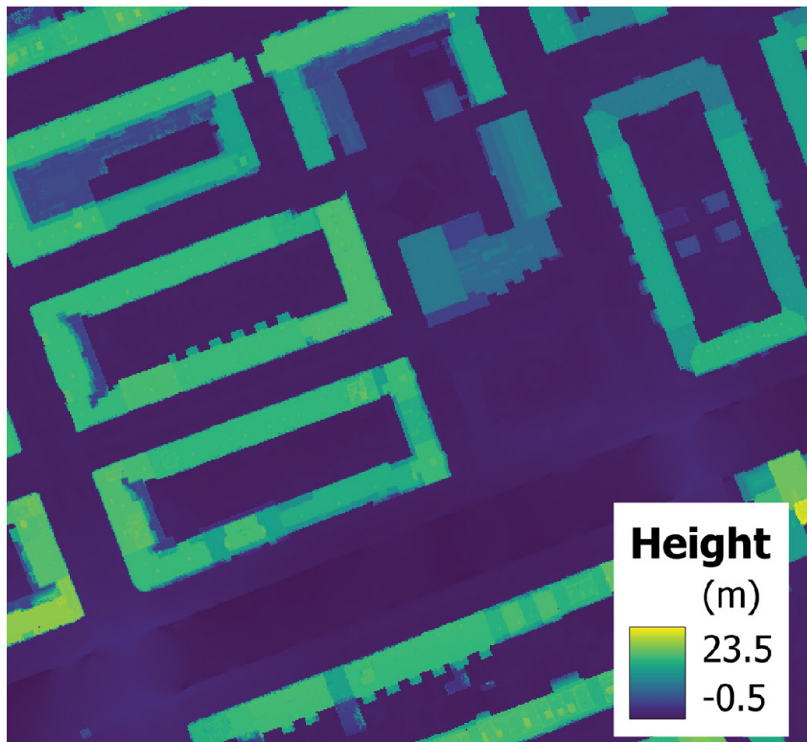
Columns 

Rows 

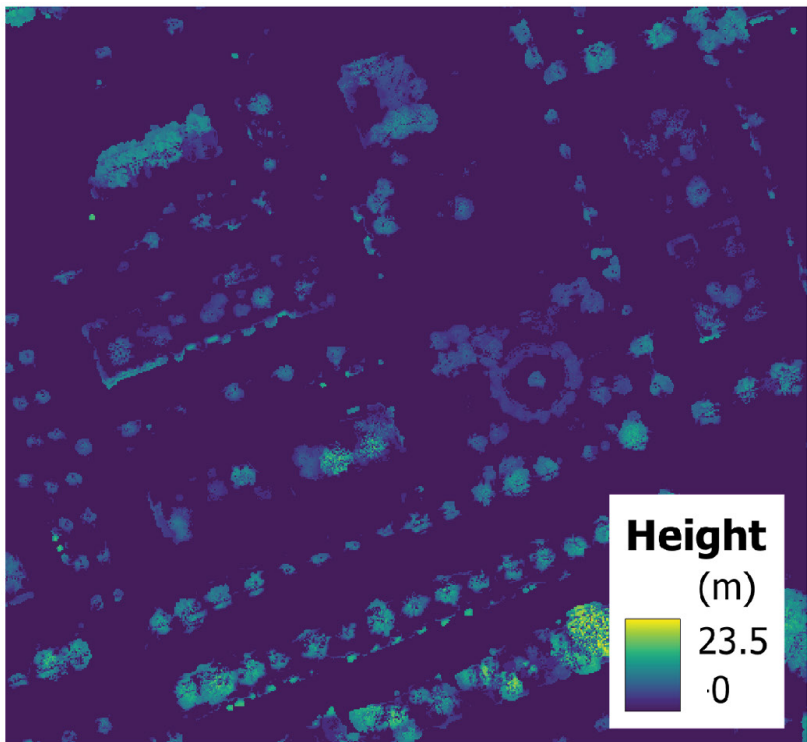
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0.06	0.51	0.44	0.96	0.94	0.55	0.61	0.23	-0.09	0.40	0.55	0.87	0.86	0.38	0.41	0.19	0.07	-0.01	1.09	0.35	0.37	0.12	0.73	0.02	0.44
0.23	0.62	0.35	0.15	0.49	0.63	0.52	0.59	0.31	0.39	0.30	0.39	0.26	-0.02	0.55	0.38	0.01	0.64	0.23	0.52	0.72	0.54	0.84	0.13	0.62
0.29	0.24	0.33	0.41	0.52	0.15	0.77	0.64	0.04	0.95	1.07	0.85	0.45	0.18	0.82	0.38	0.87	0.56	0.79	0.61	0.71	0.50	1.04	0.54	0.62
1.06	0.10	0.12	0.79	0.15	1.08	0.38	0.28	1.08	0.94	1.06	0.77	0.24	1.07	0.42	0.74	0.78	0.45	0.68	0.78	0.61	0.17	0.59	0.90	0.29
0.46	0.37	1.05	0.70	0.62	0.27	0.66	0.30	0.51	0.31	0.70	0.67	0.44	0.62	0.17	0.05	0.63	0.55	0.69	1.21	0.78	0.23	0.84	0.11	0.36
0.48	1.01	0.28	0.25	0.47	0.30	0.84	0.18	0.16	0.37	0.35	1.08	0.78	0.53	0.13	0.75	0.20	0.04	0.86	0.60	0.78	0.60	0.76	0.30	0.19
0.70	0.26	0.29	0.36	0.51	0.39	0.09	0.31	-0.17	0.69	0.02	0.17	0.52	0.28	0.96	0.11	0.58	0.49	0.15	0.66	0.45	0.73	0.75	1.15	0.90
0.39	0.43	0.83	0.70	0.69	0.01	0.49	0.28	0.58	0.47	0.77	0.60	0.74	0.36	0.22	0.38	0.49	0.61	1.18	0.49	0.21	0.40	0.36	0.64	0.04
0.52	0.55	0.57	0.32	0.43	0.07	0.35	0.34	0.62	0.15	0.73	0.95	-0.12	0.63	0.70	0.31	0.38	0.46	0.41	0.41	0.00	0.85	0.82	0.26	0.06
0.66	0.33	0.54	0.40	0.71	0.71	0.28	0.08	0.03	0.68	0.14	0.35	0.32	0.48	-0.08	0.56	0.66	0.53	0.41	0.53	0.62	-0.33	1.09	0.62	0.30
0.38	0.65	0.47	-0.11	1.12	0.47	0.81	0.29	0.96	0.59	0.68	0.19	0.86	0.71	0.89	0.31	0.36	1.19	0.18	0.46	0.84	0.53	0.67	0.38	0.61
0.11	1.00	0.46	0.30	0.70	0.36	0.10	0.10	0.71	0.45	0.46	0.82	0.16	0.28	0.38	0.53	0.49	0.41	0.48	0.47	0.28	0.26	0.58	0.23	0.15
0.41	0.45	1.18	0.29	0.78	0.72	0.14	0.73	0.14	-0.30	0.68	-0.03	0.64	0.29	1.00	0.82	0.36	0.29	0.14	0.37	0.42	0.39	0.55	0.67	0.60
0.27	0.07	0.91	0.29	0.30	0.34	-0.05	0.36	0.36	0.69	0.71	0.50	0.78	0.60	0.50	0.55	0.44	0.38	0.42	0.16	0.58	0.20	0.75	0.43	0.51
0.65	0.69	0.03	0.44	0.76	-0.01	0.62	-0.18	0.19	0.51	0.00	0.20	0.06	0.99	0.55	0.67	0.43	0.39	0.02	0.41	0.27	0.76	0.84	0.94	0.76
0.32	0.17	0.73	0.61	-0.03	0.61	0.74	0.52	0.44	0.26	0.07	0.74	0.41	0.43	1.02	0.71	0.61	0.54	0.96	1.02	0.78	0.67	-0.13	0.54	0.46
0.53	0.78	-0.32	0.33	0.58	0.36	0.07	0.76	0.58	0.21	0.59	0.75	0.50	0.74	0.52	0.38	0.15	0.47	0.56	0.76	0.47	0.64	0.21	0.27	0.47
0.18	0.75	0.64	0.58	0.60	1.11	0.36	-0.16	0.56	0.48	0.34	0.21	0.37	0.55	0.35	1.22	0.21	0.26	-0.19	0.58	-0.10	0.34	0.42	0.29	1.02
0.80	0.90	0.24	0.84	0.65	0.73	0.81	0.23	0.37	0.76	-0.30	0.95	0.67	0.49	0.57	0.19	0.40	0.83	0.89	1.31	0.48	0.30	0.35	0.19	0.48
0.61	0.49	0.83	0.43	0.40	0.33	0.01	0.03	0.15	0.89	0.77	0.91	0.10	-0.09	0.30	0.55	0.65	0.81	0.59	1.02	0.43	0.23	0.00	0.23	0.57
0.23	0.78	0.92	-0.21	0.76	-0.17	0.62	0.87	0.52	0.12	0.32	0.42	0.45	0.44	0.47	0.56	0.14	0.43	0.96	0.38	0.37	0.82	-0.27	0.85	0.31
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0.03	0.63	0.22	0.57	0.08	0.32	0.47	0.00	0.53	0.39	-0.02	0.11	0.68	0.77	0.46	0.62	0.57	0.60	0.89	0.05	0.70	0.39	0.43	0.41	0.39

Example of a 2D array

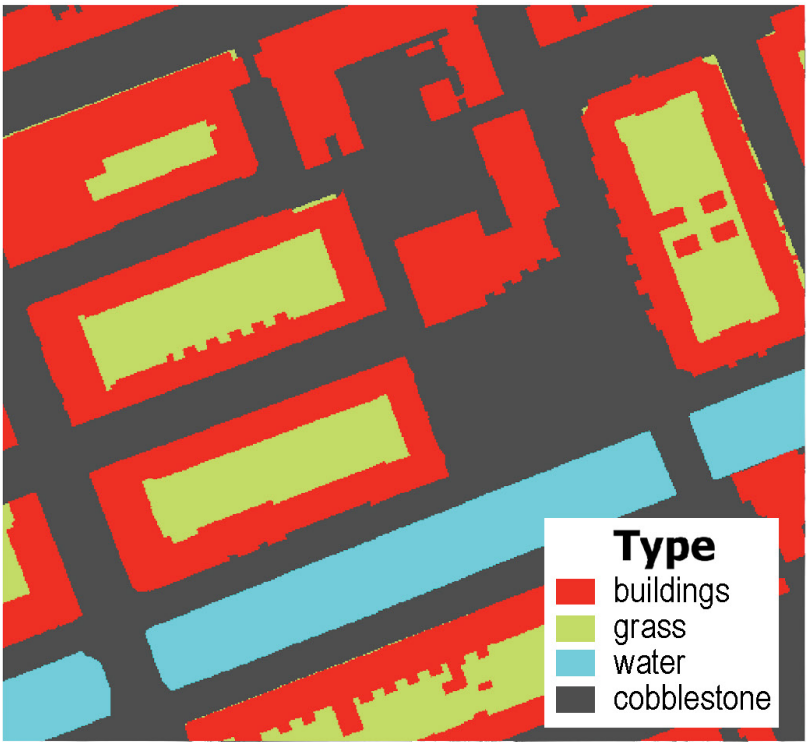
SOLWEIG input



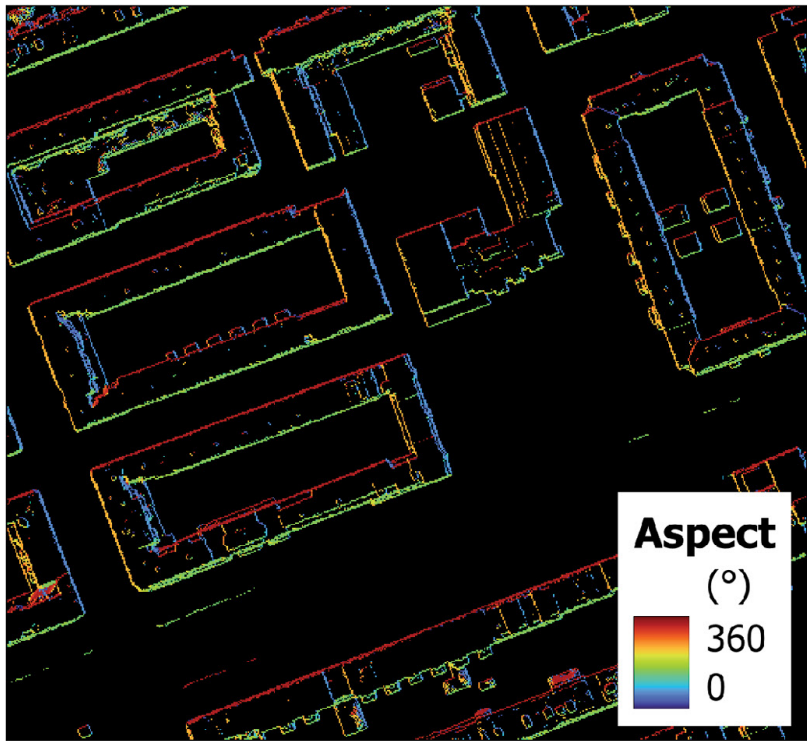
Digital Surface Model
DSM



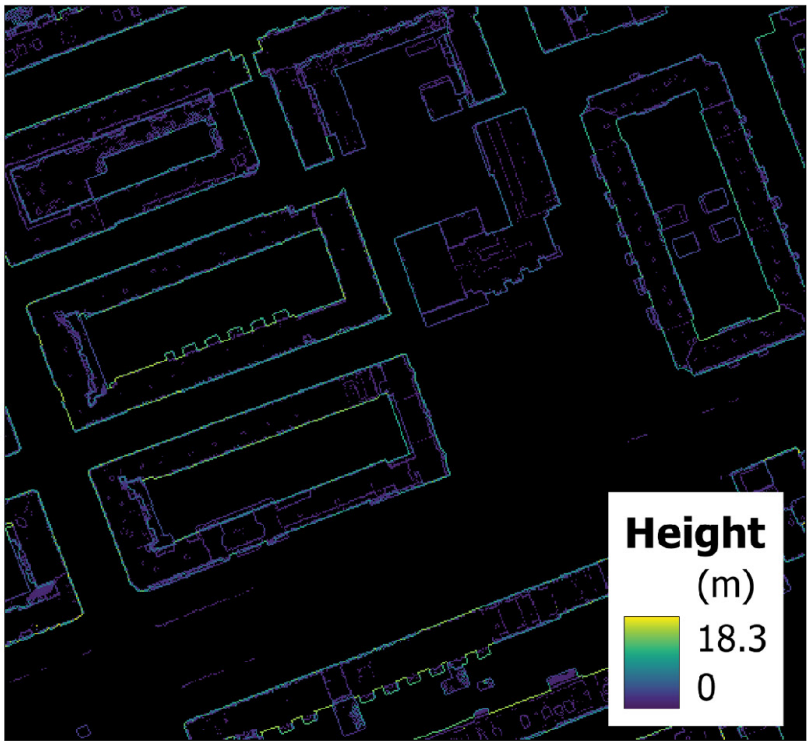
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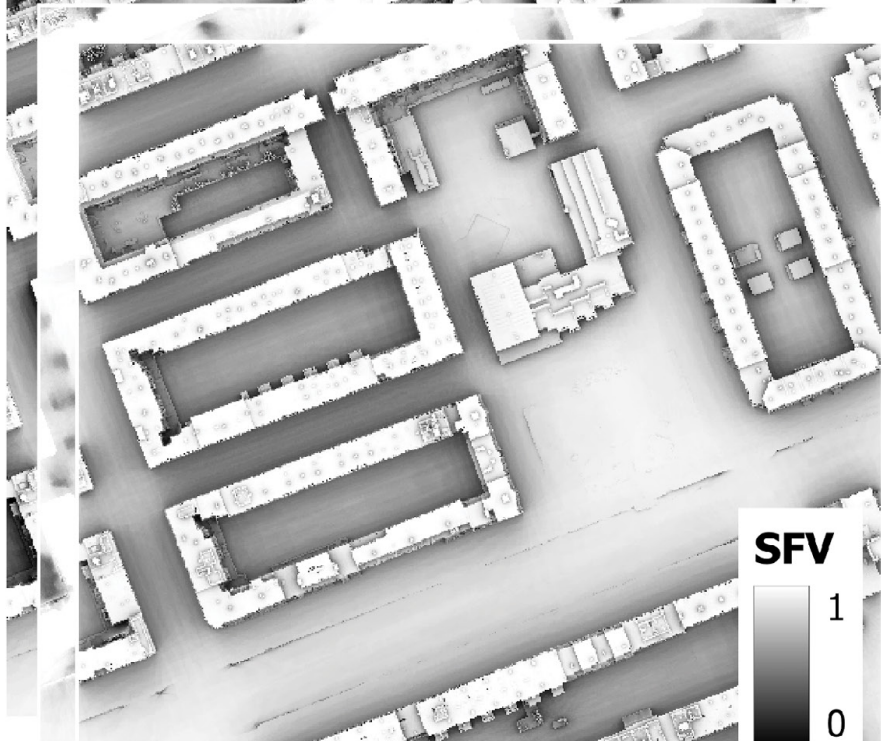
Land cover



Wall Aspect



Wall Height



Sky View Factor maps
SVF

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2023	213	22	0	86	16.6	101.3	0	0	0
2023	213	23	0	86	16.8	101.3	0	0	0

Meteorological
Data

Research Questions

SOLFD DEVELOPMENT

ACCURACY OF MODELS

SOLFD CASE STUDY

OBJECTIVE

Research Questions

SOLFD DEVELOPMENT

Code Development

1. Allows 3D designs
2. Automatically collects data
3. Allows user input
4. Allows comparison
5. Operates fast

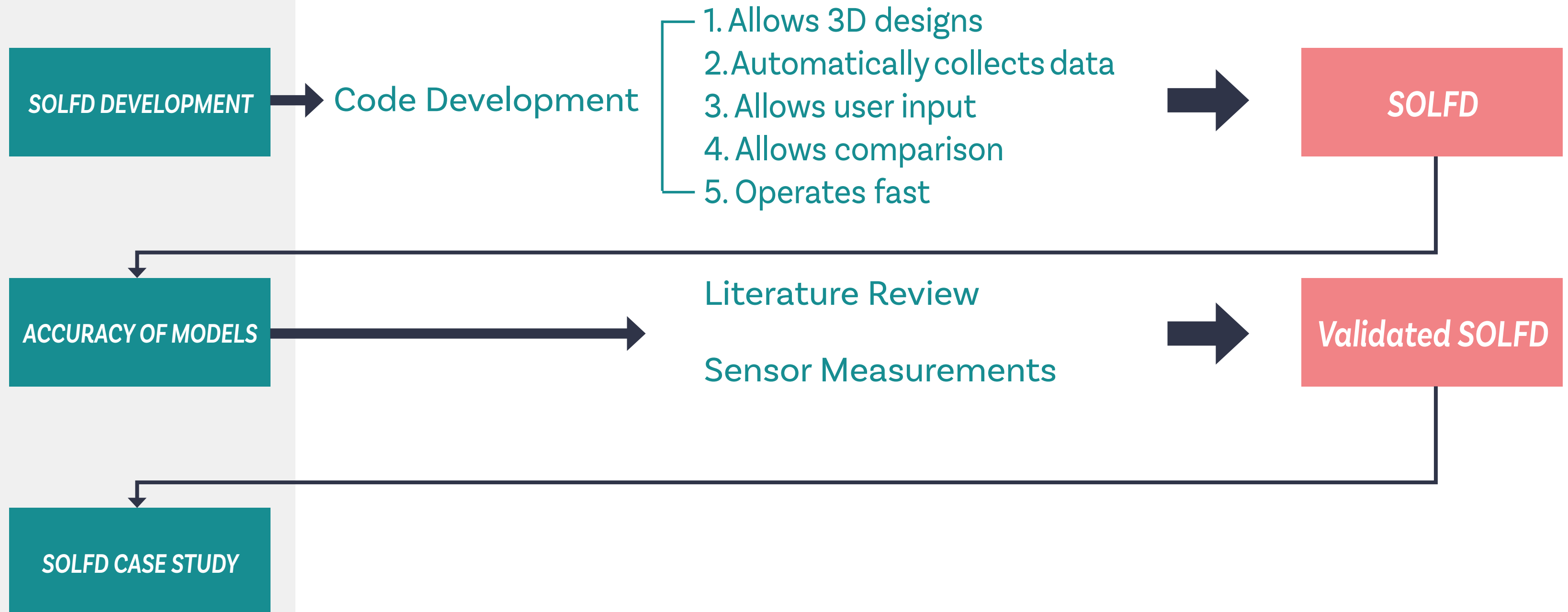
SOLFD

ACCURACY OF MODELS

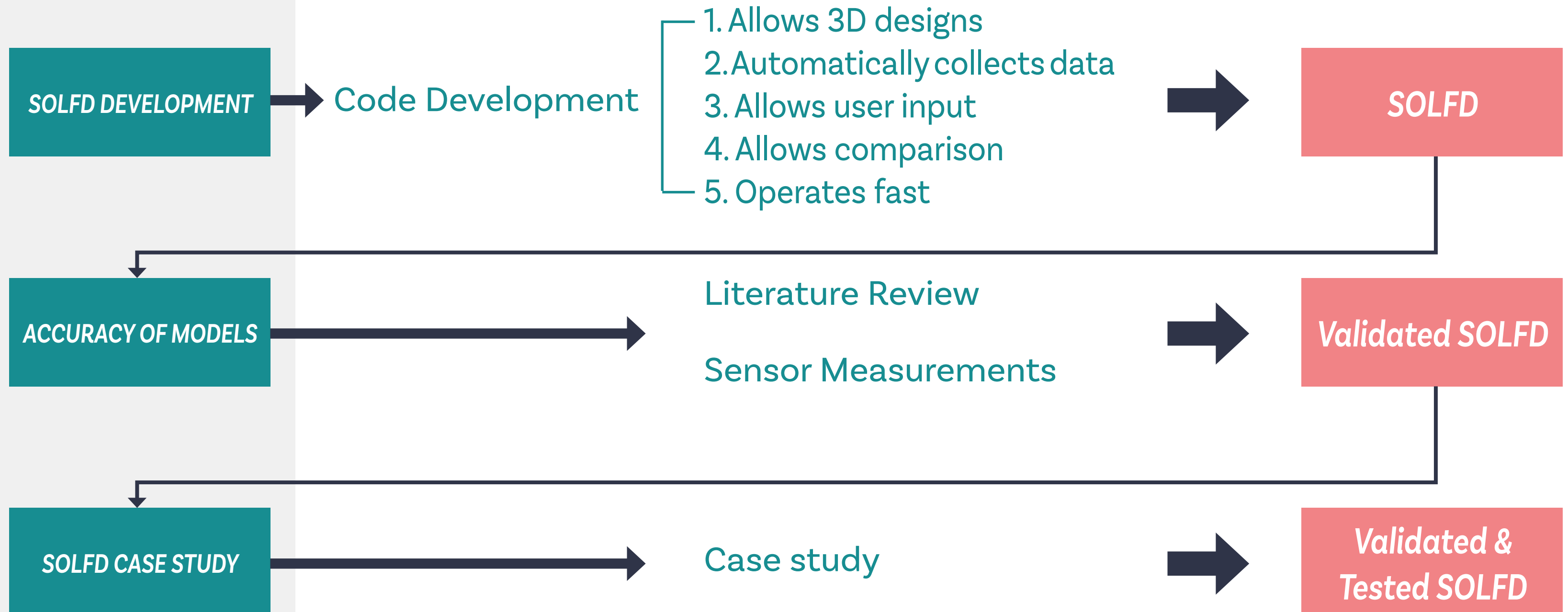
SOLFD CASE STUDY

OBJECTIVE

Research Questions



Research Questions



RQ 1: How can a tool framework be developed for visualizing current urban climate conditions using SOLWEIG, and how can design alternatives be integrated and compared within this tool?

*SOLFD allows
3D designs*

*SOLFD automatically
collects required
location data*

*SOLFD allows input
designs and changing
the urban scene*

*SOLFD allows
evaluation, comparison
and improvement of
designs*

*SOLFD operates within
an acceptable time
frame*

RQ 1: How can a tool framework be developed for visualizing current urban climate conditions using SOLWEIG, and how can design alternatives be integrated and compared within this tool?



Five goals for SOLFD development

**SOLFD allows
3D designs**

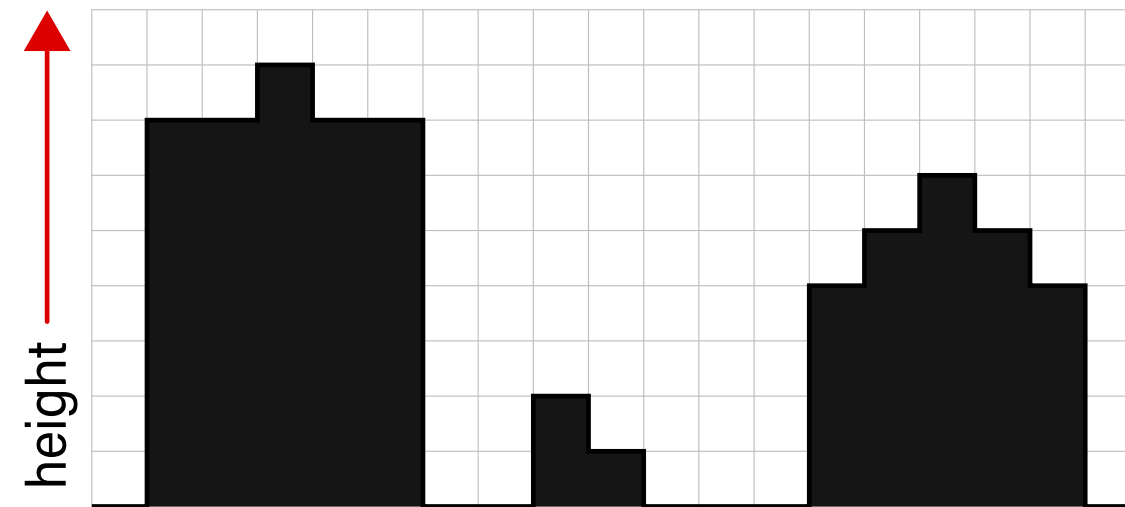
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SOLFD allows input
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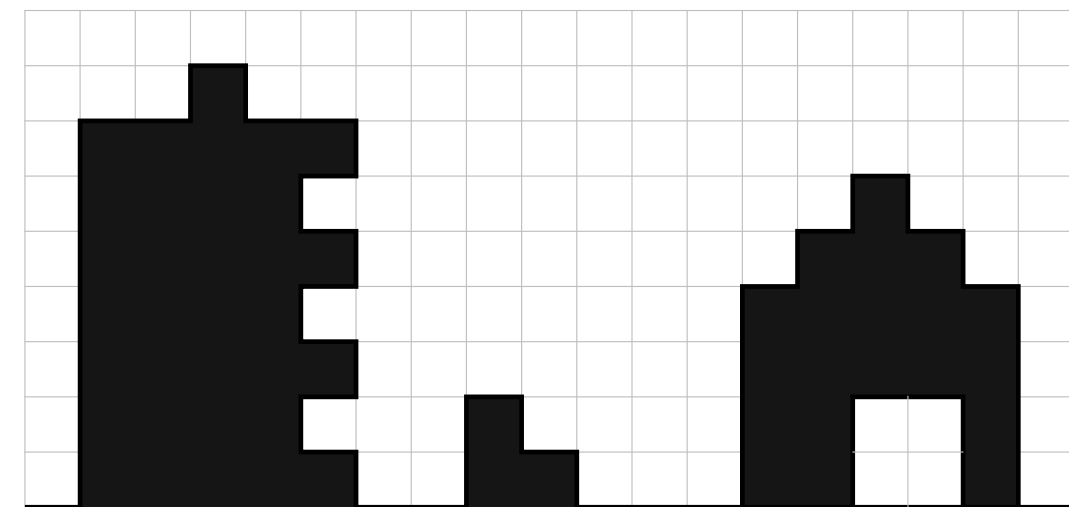
SOLFD allows
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Extending SOLWEIG for 3D



current 2.5D



desired 3D



*SOLFD allows
3D designs*

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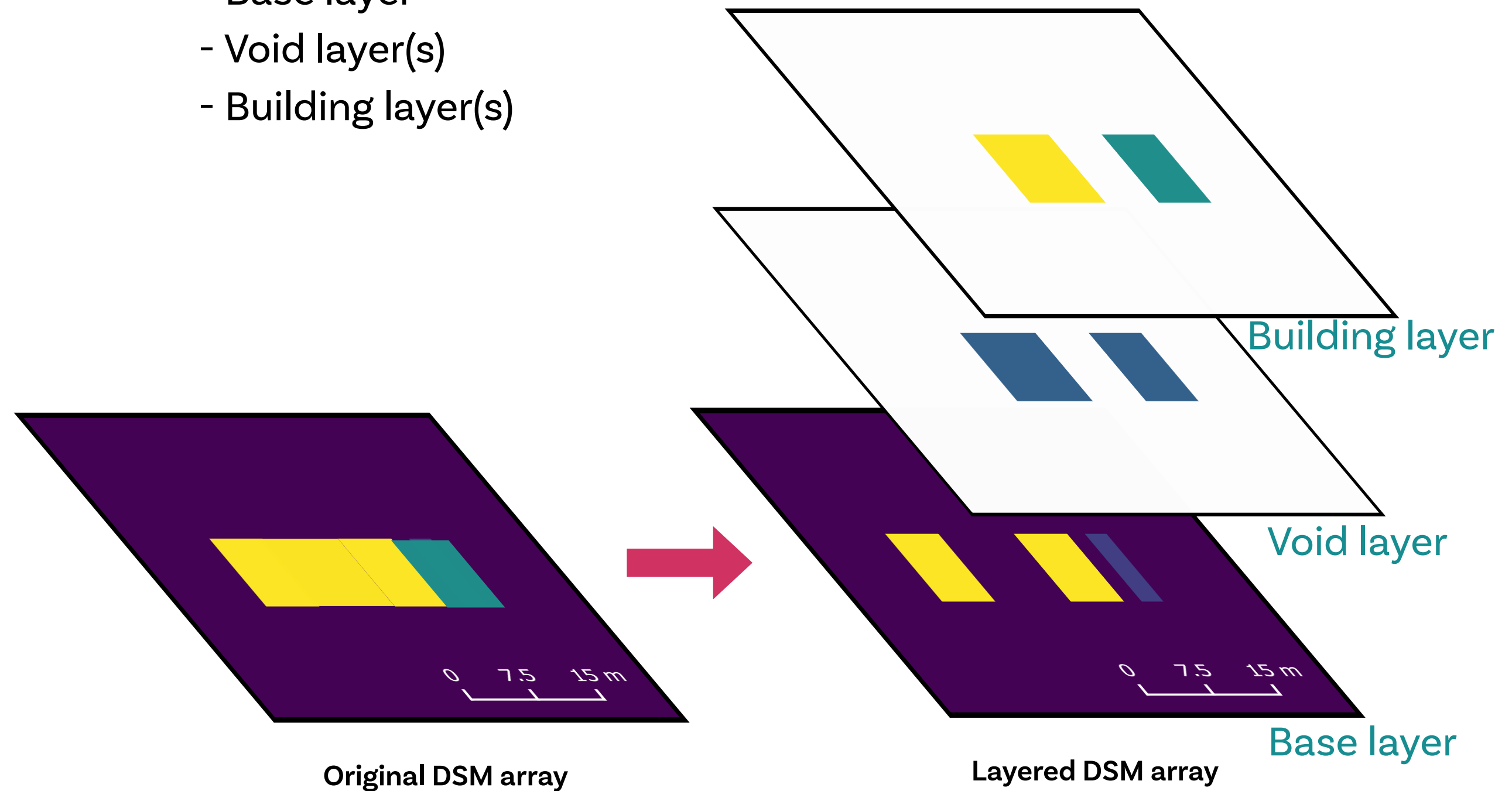
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Extending SOLWEIG for 3D

- **Solution:** layered array
 - Base layer
 - Void layer(s)
 - Building layer(s)



*SOLFD allows
3D designs*

*SOLFD automatically
collects required
location data*

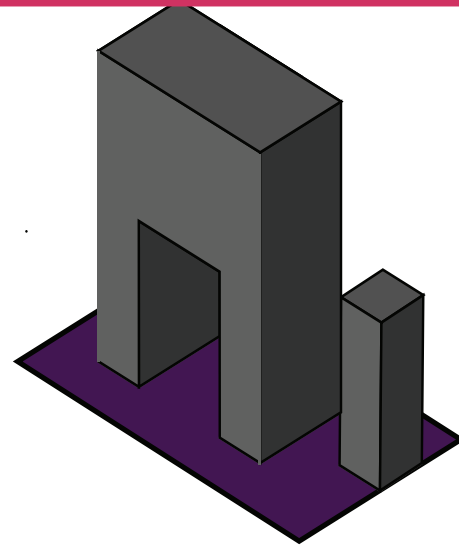
*SOLFD allows input
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*SOLFD allows
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designs*

*SOLFD operates within
an acceptable time
frame*

Extending SOLWEIG for 3D

- **Solution:** layered array



View		Input	Base Layer	1st Void	1st Building	2nd Void	2nd Building
one void	Profile						
	Top						

Height (cells)

- 4
- 3
- 2
- 1
- 0
- No Data

*SOLFD allows
3D designs*

*SOLFD automatically
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location data*

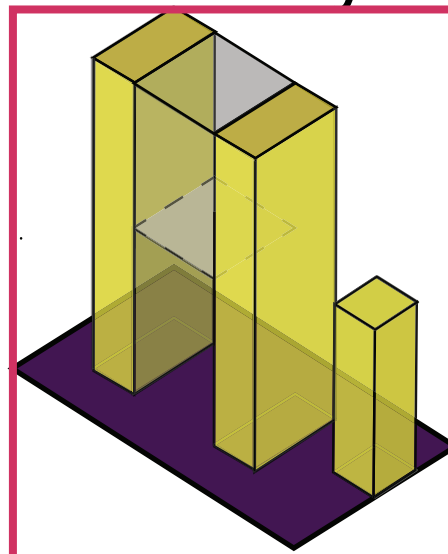
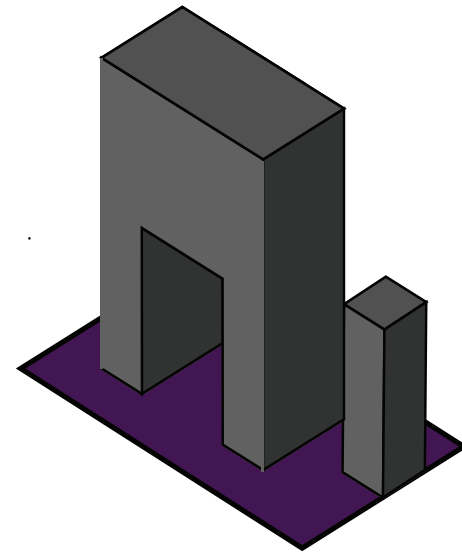
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Extending SOLWEIG for 3D

- **Solution:** layered array



		View	Input	Base Layer	1st Void	1st Building	2nd Void	2nd Building
one void	Profile							
	Top							

Height (cells)

- 4
- 3
- 2
- 1
- 0
- No Data

**SOLFD allows
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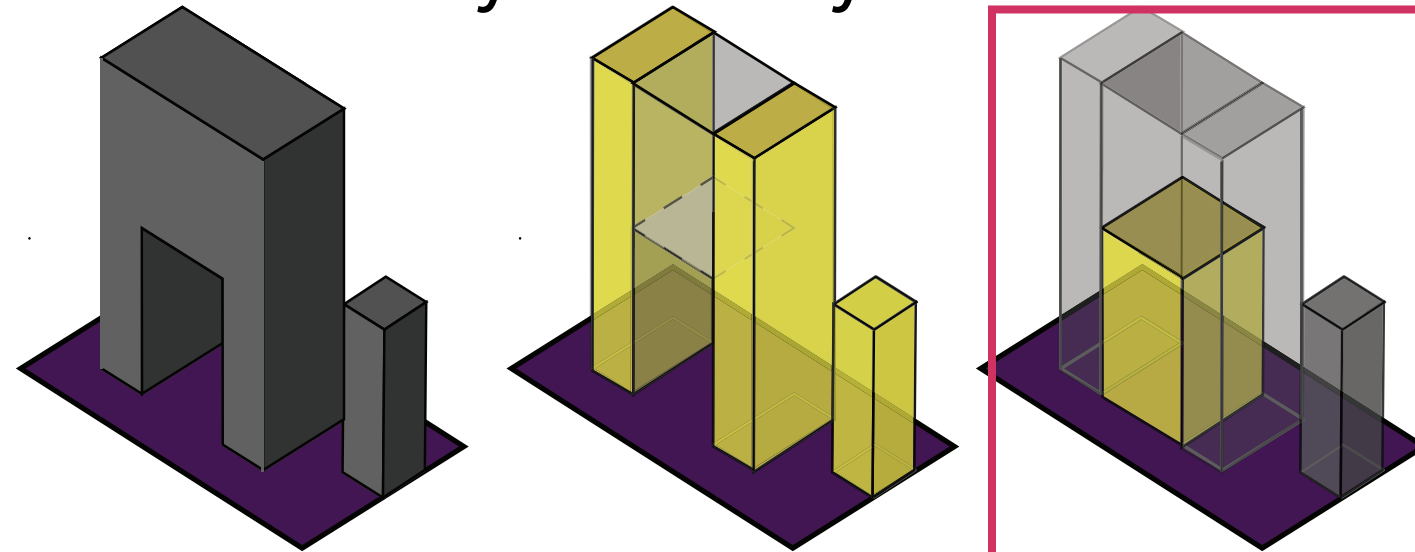
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Extending SOLWEIG for 3D

- Solution: layered array**



		View	Input	Base Layer	1st Void	1st Building	2nd Void	2nd Building
one void	Profile						X	
	Top							

Height (cells)

- 4
- 3
- 2
- 1
- 0
- No Data

**SOLFD allows
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SOLFD automatically
collects required
location data

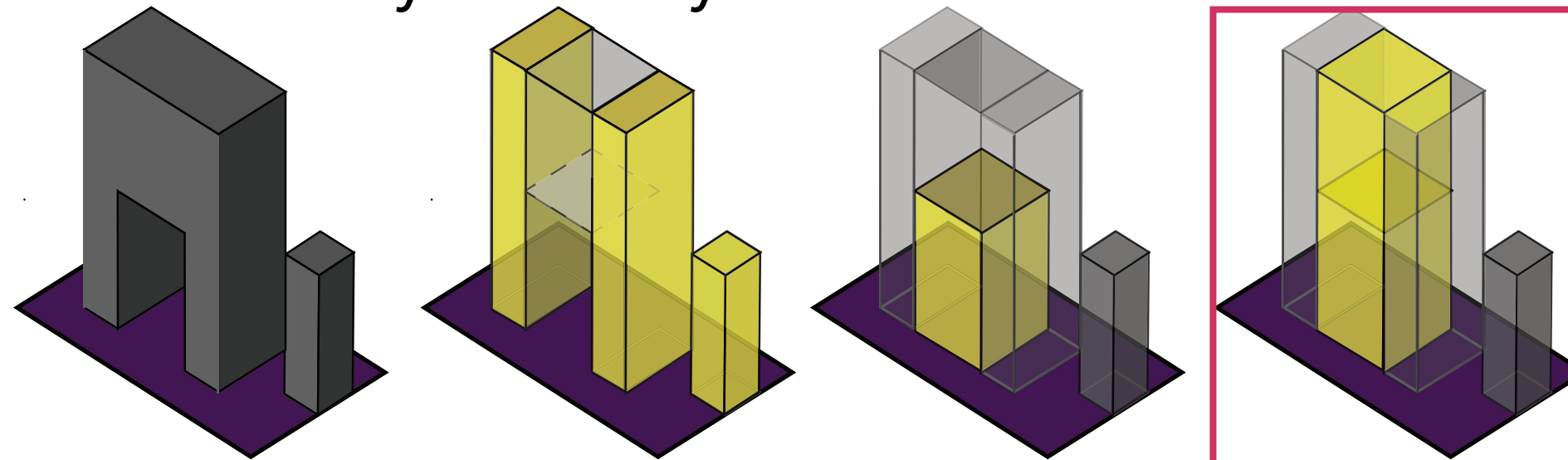
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Extending SOLWEIG for 3D

- Solution: layered array**



		View	Input	Base Layer	1st Void	1st Building	2nd Void	2nd Building
one void	Profile							
	Top							

Height (cells)

- 4
- 3
- 2
- 1
- 0
- No Data

**SOLFD allows
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SOLFD automatically
collects required
location data

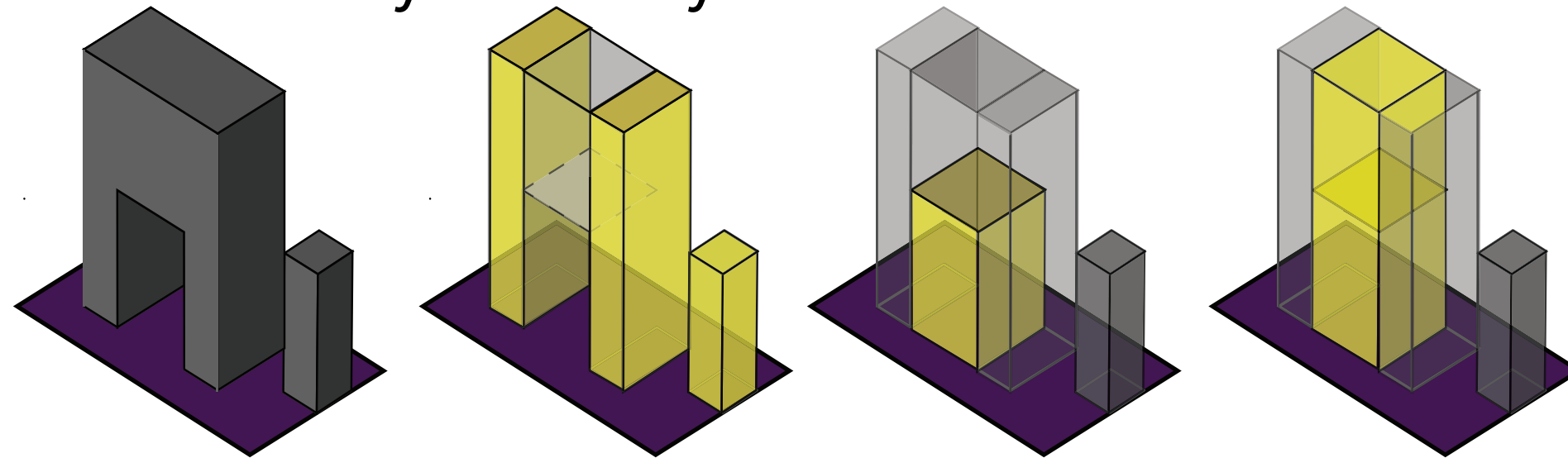
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Extending SOLWEIG for 3D

- Solution:** layered array



	View	Input	Base Layer	1st Void	1st Building	2nd Void	2nd Building
one void	Profile						
	Top						
two void	Profile						
	Top						

Height (cells)

- 4
- 3
- 2
- 1
- 0
- No Data

***SOLFD allows
3D designs***

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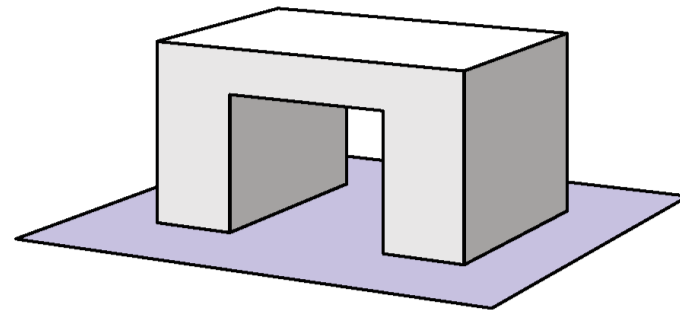
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Extending SOLWEIG for 3D

BEFORE: 2.5D



**SOLFD allows
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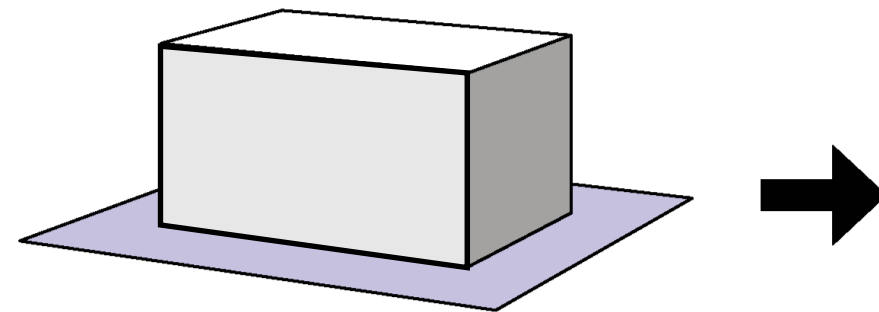
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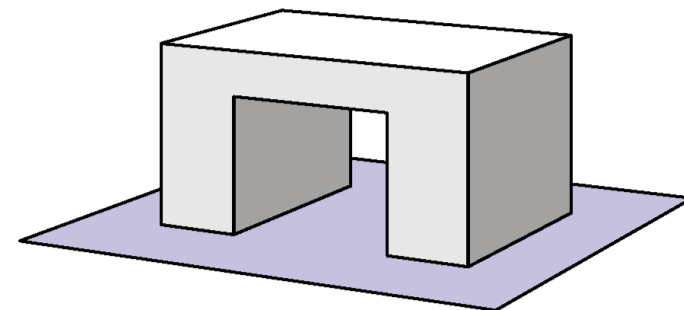
SOLFD operates within
an acceptable time
frame

Extending SOLWEIG for 3D

BEFORE: 2.5D



SOLFD: 3D



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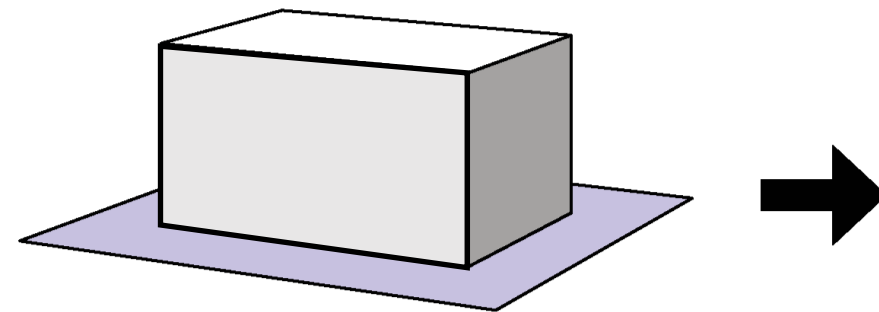
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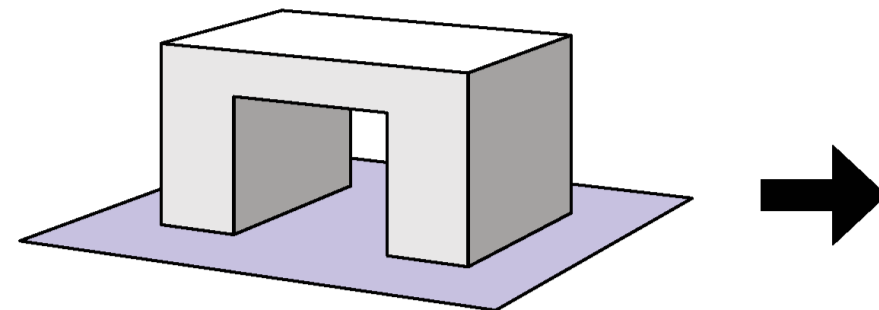
SOLFD operates within
an acceptable time
frame

Extending SOLWEIG for 3D

BEFORE: 2.5D



SOLFD: 3D



*SOLFD allows
3D designs*

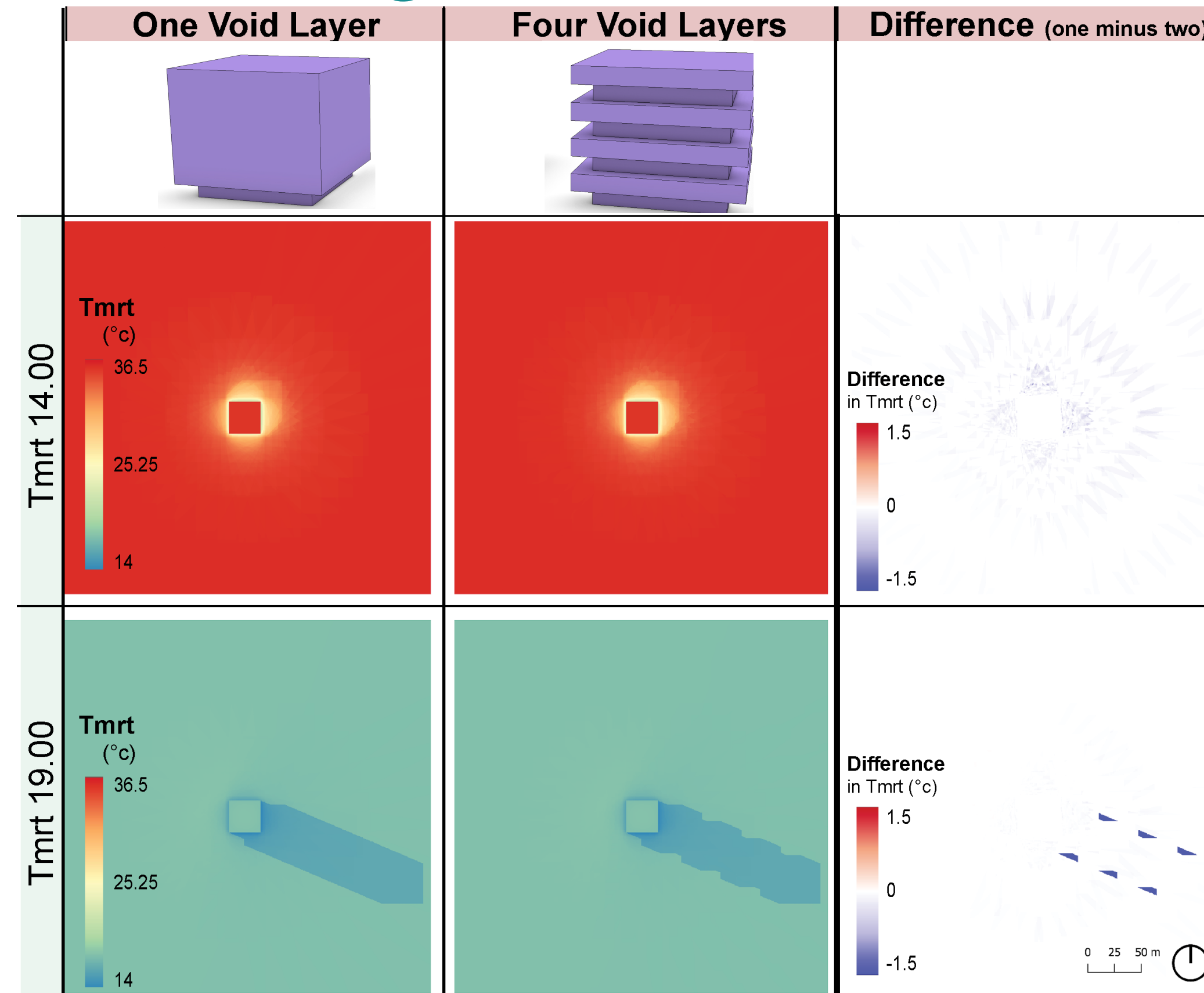
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Extending SOLWEIG for 3D



Automatic Data Collection

*SOLFD allows
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Automatic Data Collection

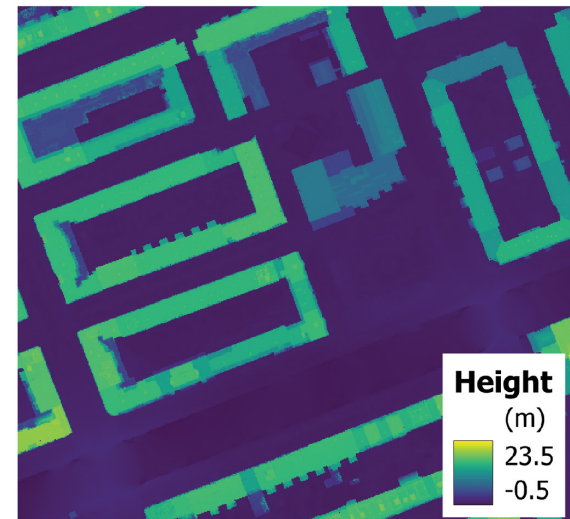
- **Bounding Box + Calculation day =**

SOLFD automatically collects required location data

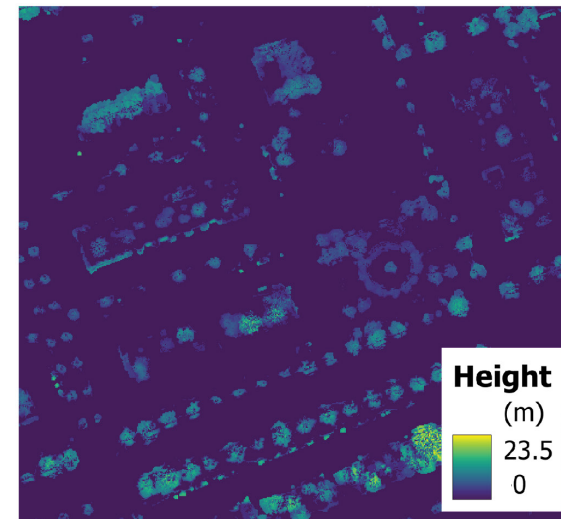
SOLFD allows input designs and changing the urban scene

SOLFD allows evaluation, comparison and improvement of designs

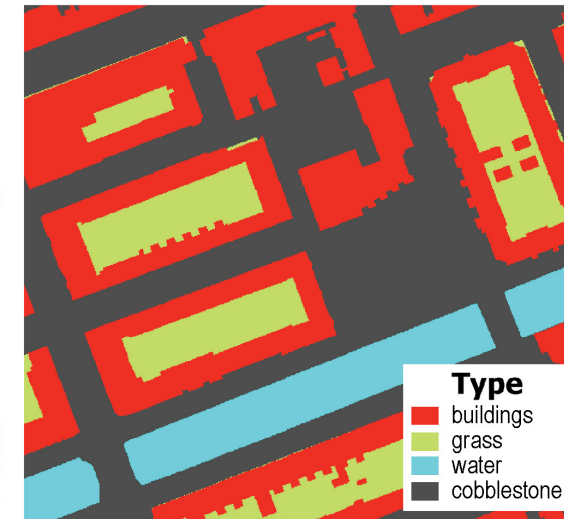
SOLFD operates within an acceptable time frame



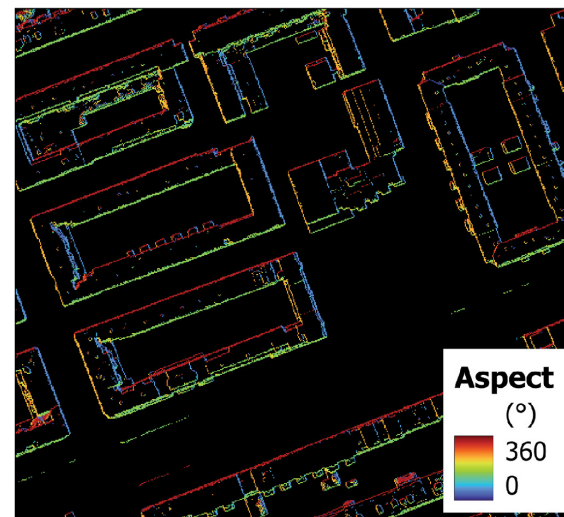
Digital Surface Model
DSM



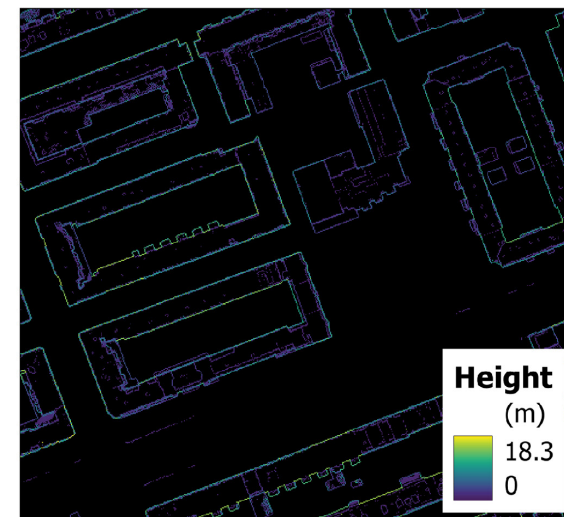
Canopy Height Model
CHM



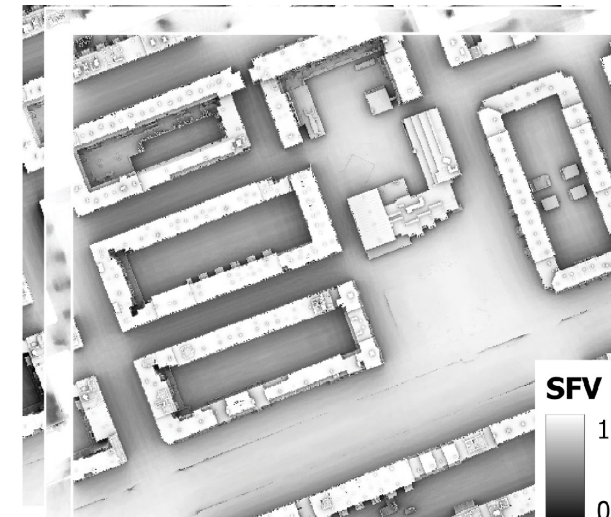
Land cover



Wall Aspect



Wall Height



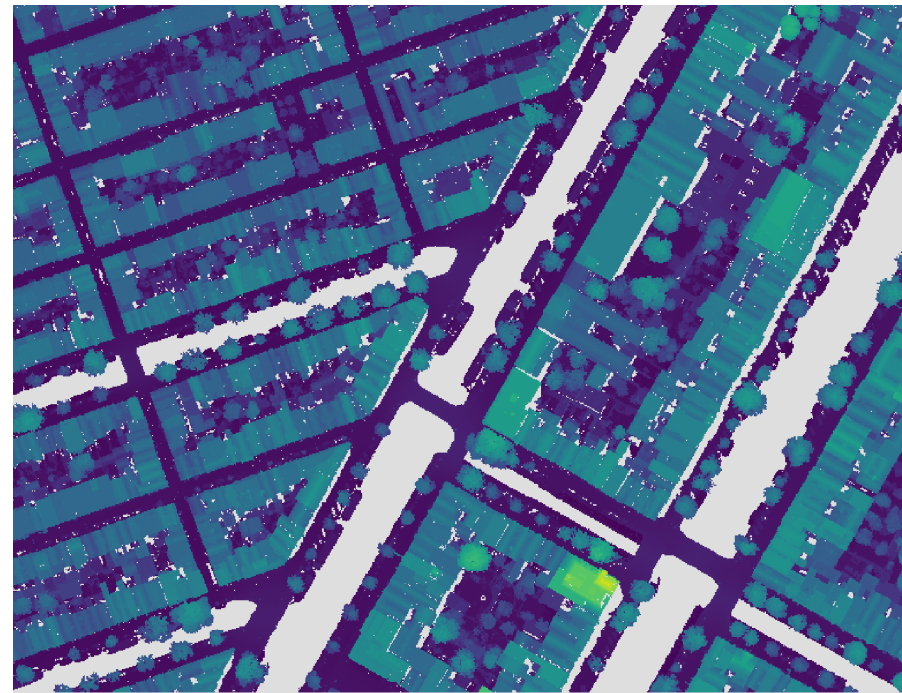
Sky View Factor maps
SVF

Year	DOY	Hour	Min	RH	Td	Press	Kdn	Kdiff	Kdir
2023	213	0	0	87	16.5	101.3	0	0	0
2023	213	1	0	88	16.2	101.3	0	0	0
2023	213	2	0	89	15.9	101.3	0	0	0
2023	213	3	0	90	15.7	101.3	0	0	0
2023	213	4	0	90	15.6	101.3	1.7	1.5	3.9
2023	213	5	0	89	16	101.3	28	19	84
2023	213	6	0	87	17	101.3	86	53	187
2023	213	7	0	82	18.2	101.3	189	92	262
2023	213	8	0	77	19.3	101.3	296	128	332
2023	213	9	0	73	20.2	101.3	398	160	380
2023	213	10	0	69	21.2	101.3	478	184	407
2023	213	11	0	66	21.8	101.3	525	201	412
2023	213	12	0	64	22.2	101.3	538	206	410
2023	213	13	0	63	22.5	101.3	525	208	397
2023	213	14	0	62	22.6	101.3	479	192	383
2023	213	15	0	62	22.5	101.3	408	170	359
2023	213	16	0	63	22.1	101.3	321	138	333
2023	213	17	0	66	21.5	101.3	223	102	289
2023	213	18	0	69	20.6	101.3	127	65	224
2023	213	19	0	74	19.4	101.3	49	29	132
2023	213	20	0	80	18.1	101.3	6.7	5	33
2023	213	21	0	83	17.2	101.3	0	0	0
2023	213	22	0	86	16.6	101.3	0	0	0
2023	213	23	0	86	16.8	101.3	0	0	0

Meteorological
Data

Automatic Data Collection

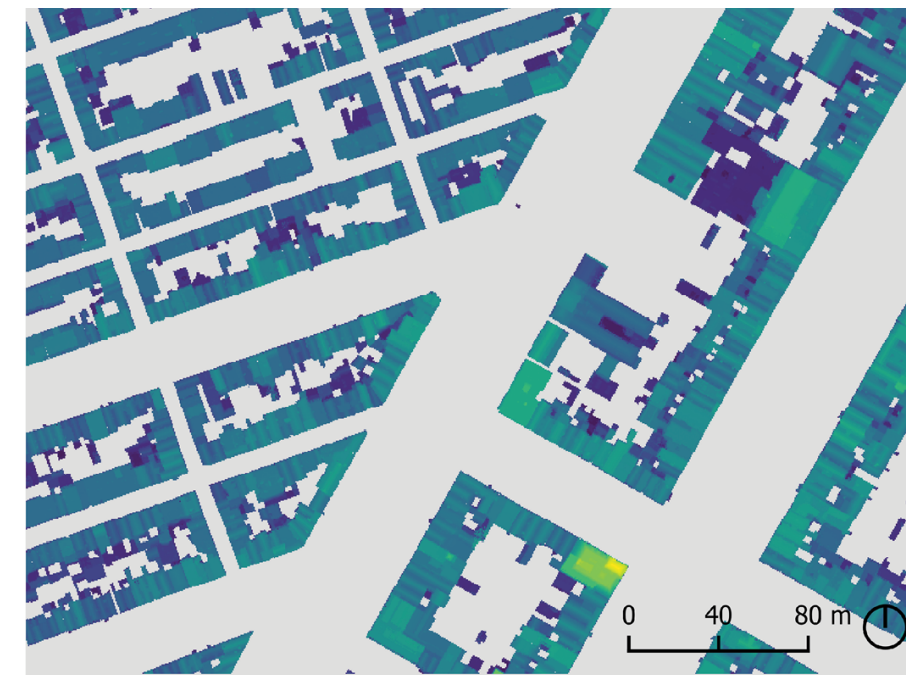
- **DSM**



AHN DSM

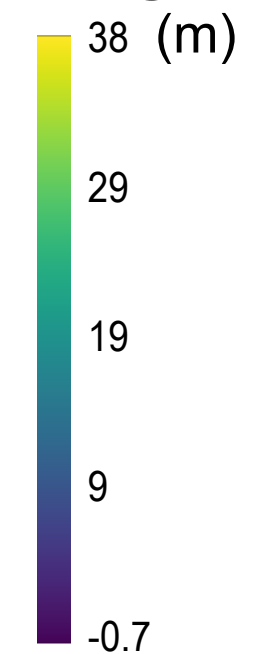


3DBAG building footprints



Isolated building heights

Height



SOLFD allows
3D designs

SOLFD automatically
collects required
location data

SOLFD allows input
designs and changing
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SOLFD allows
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SOLFD operates within
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frame

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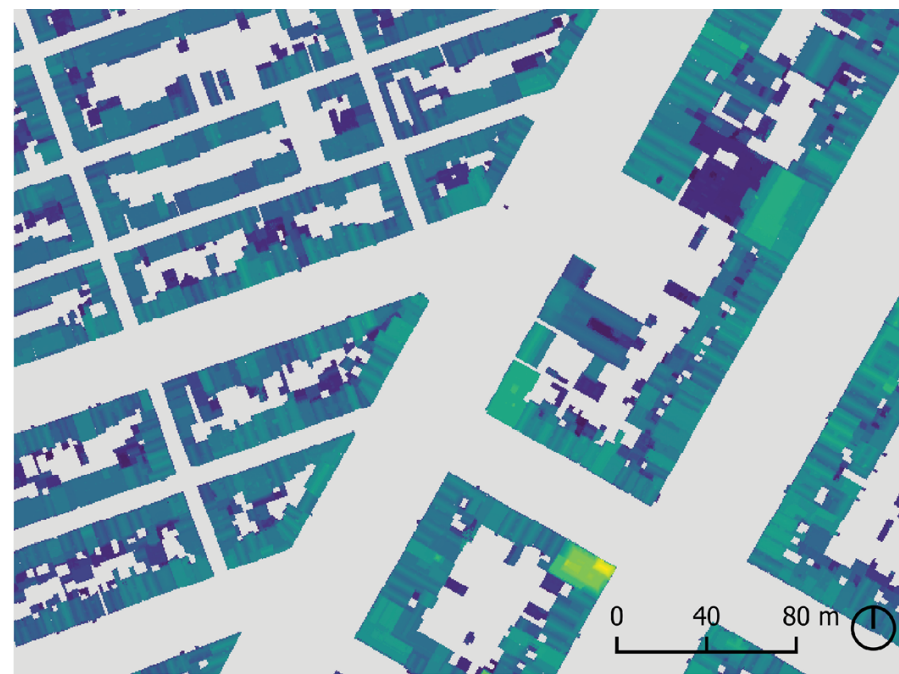
SOLFD operates within
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Automatic Data Collection

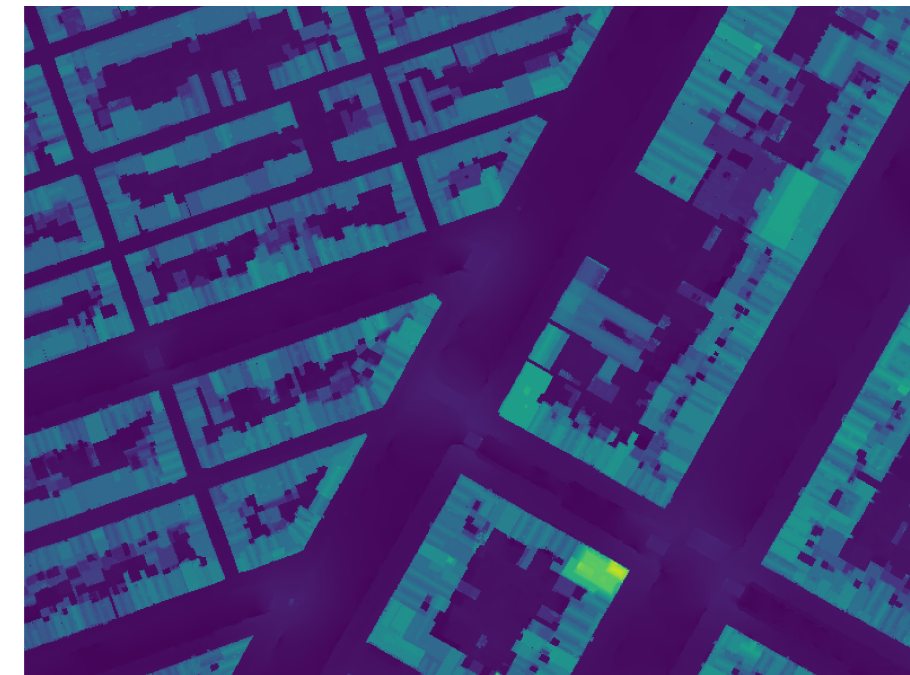
- **DSM**



Filled AHN DTM

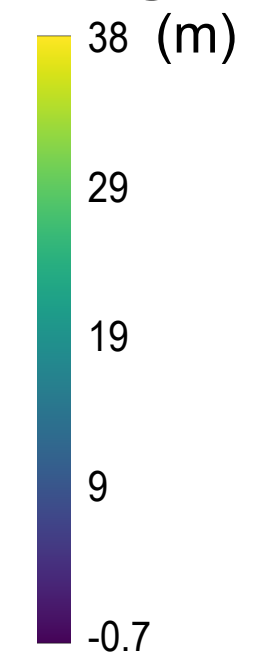


Isolated Building Heights



DSM ground + buildings

Height



Automatic Data Collection

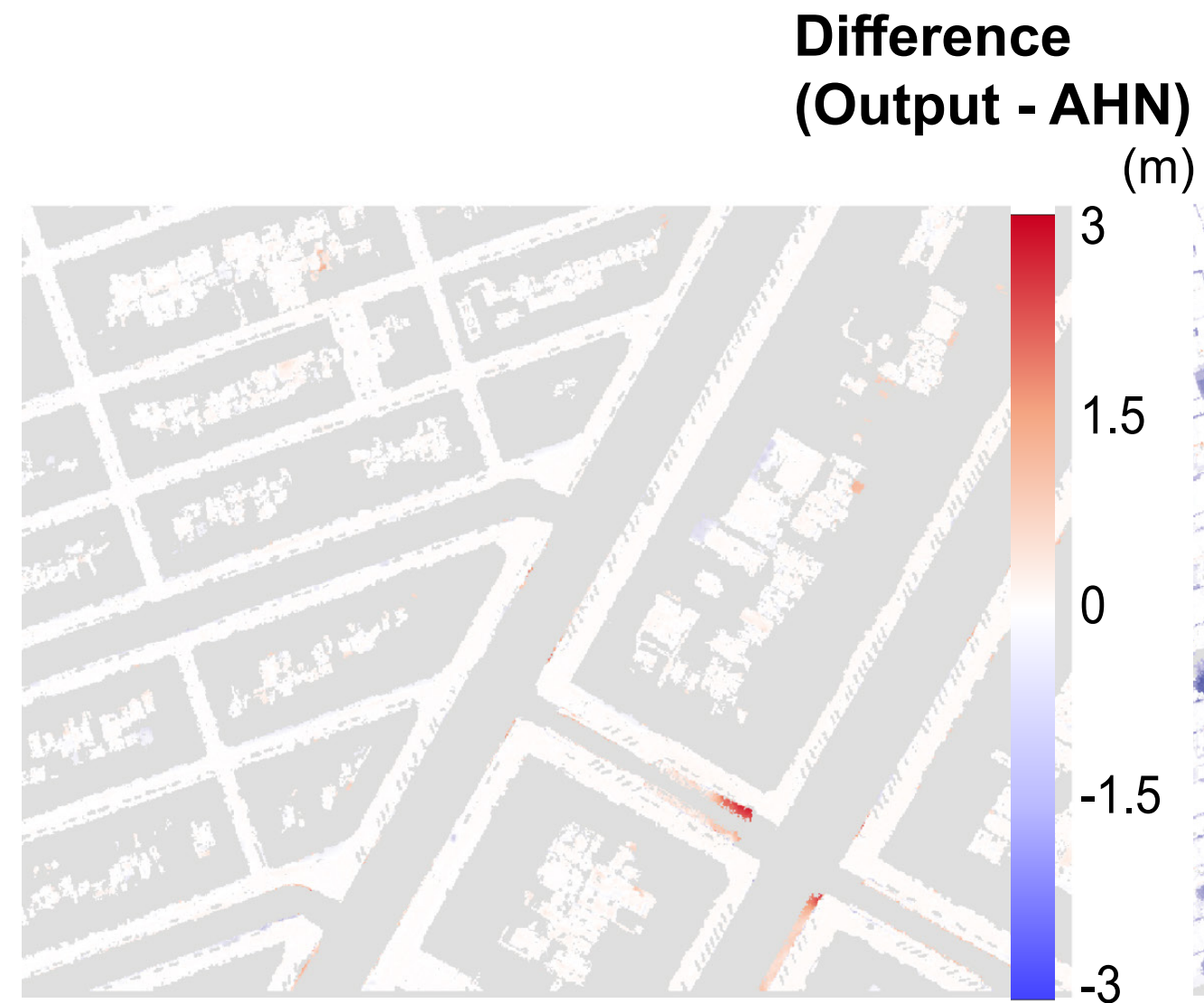
SOLFD allows
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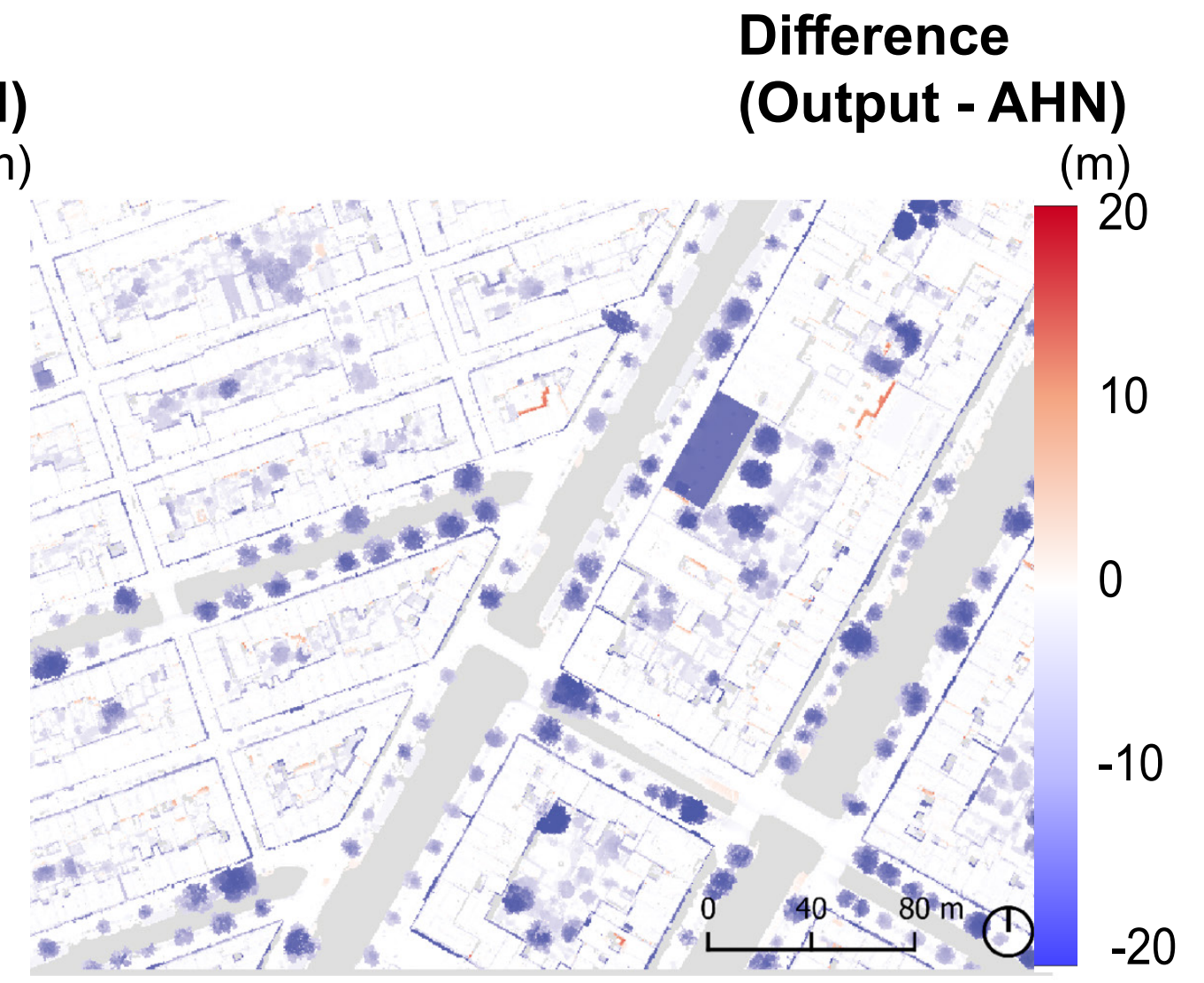
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frame



Difference in meters between the input AHN
DTM and the output filled DTM



Difference in meters between the input AHN
DSM and the output filled DSM

*SOLFD allows
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Automatic Data Collection

- **CHM**



AHN pointcloud from GeoTiles

*SOLFD allows
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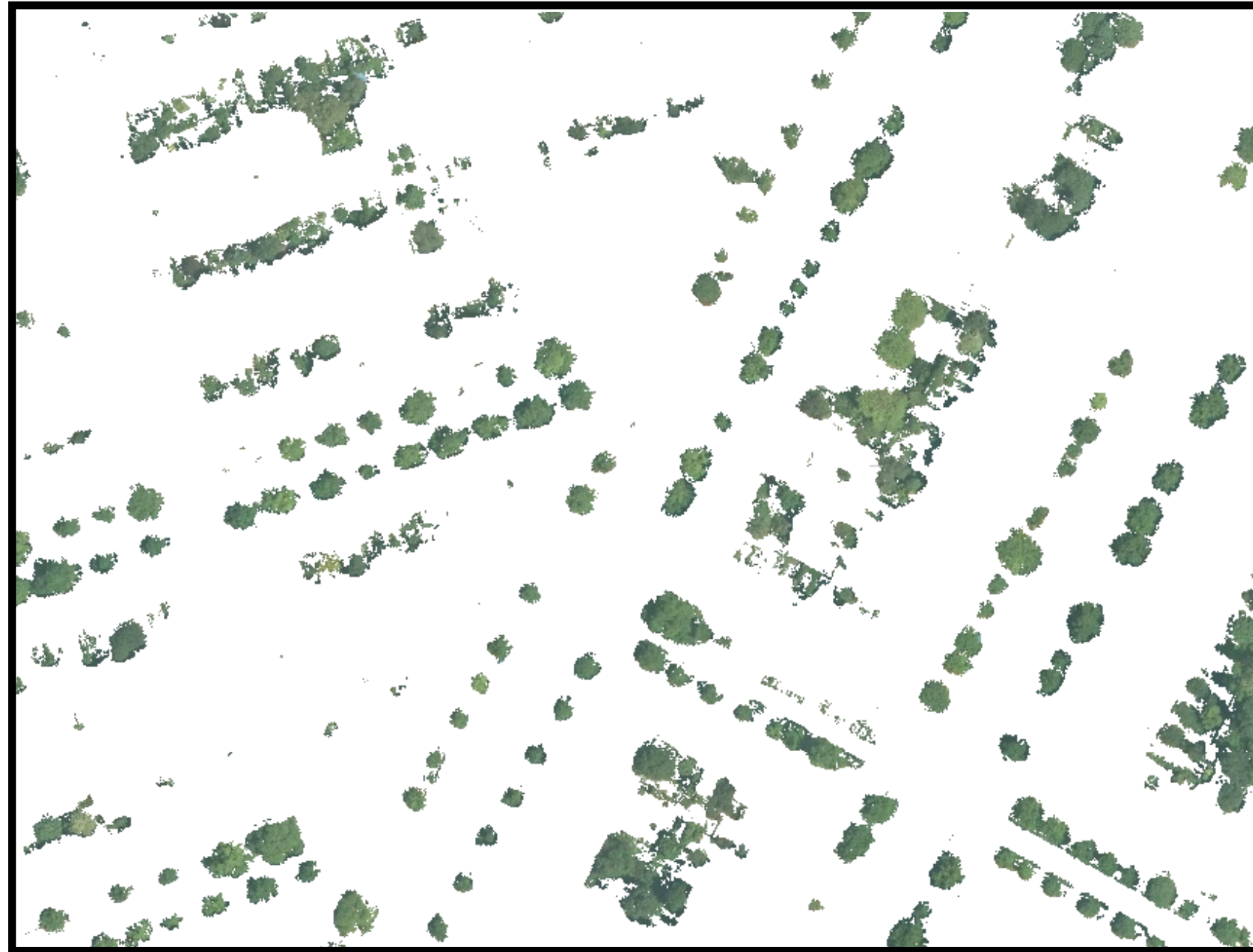
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Automatic Data Collection

- **CHM**



AHN pointcloud from GeoTiles

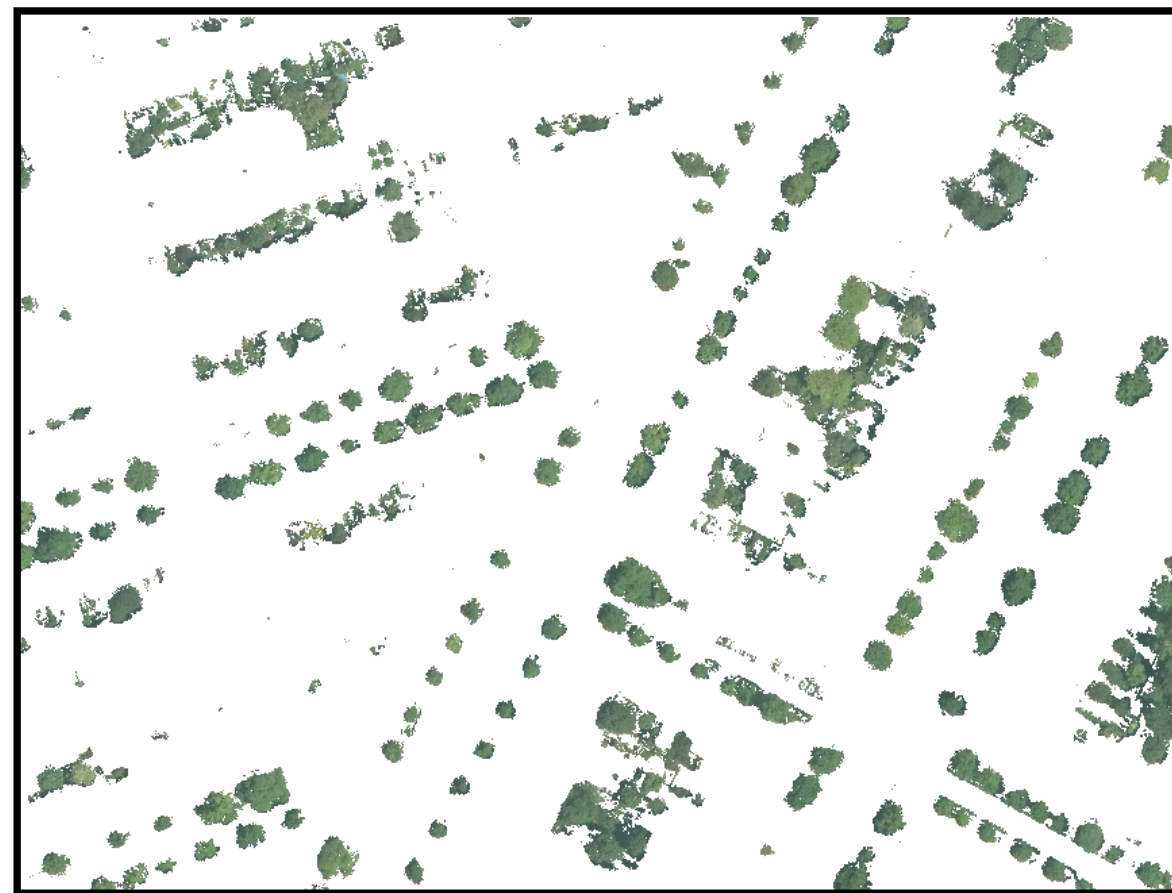
$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

Automatic Data Collection

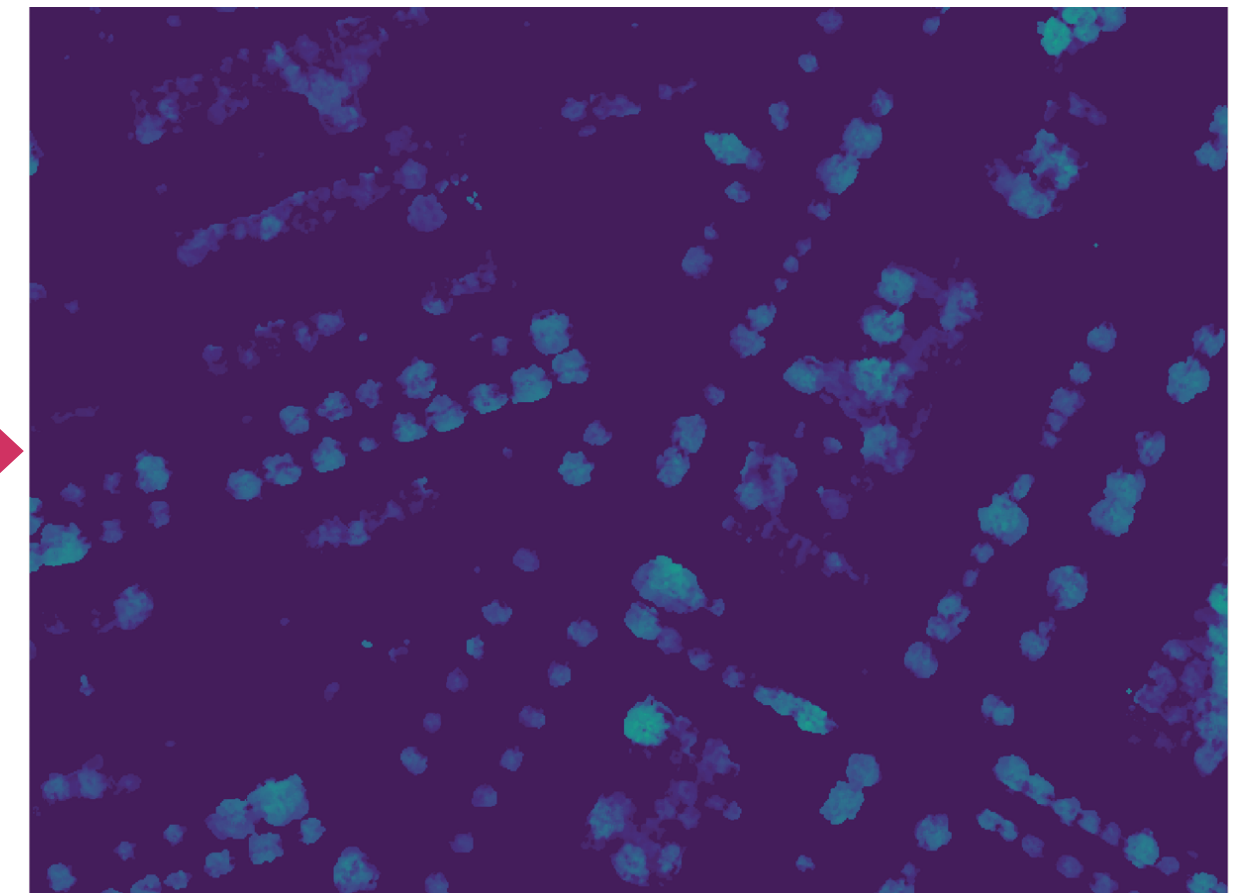
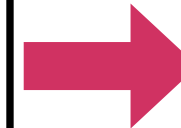
- **CHM**

Pointcloud -> raster (array)

Laplace interpolate at cell centers in max 1m radius around vegetation point



Pointcloud



CHM

SOLFD allows
3D designs

SOLFD automatically
collects required
location data

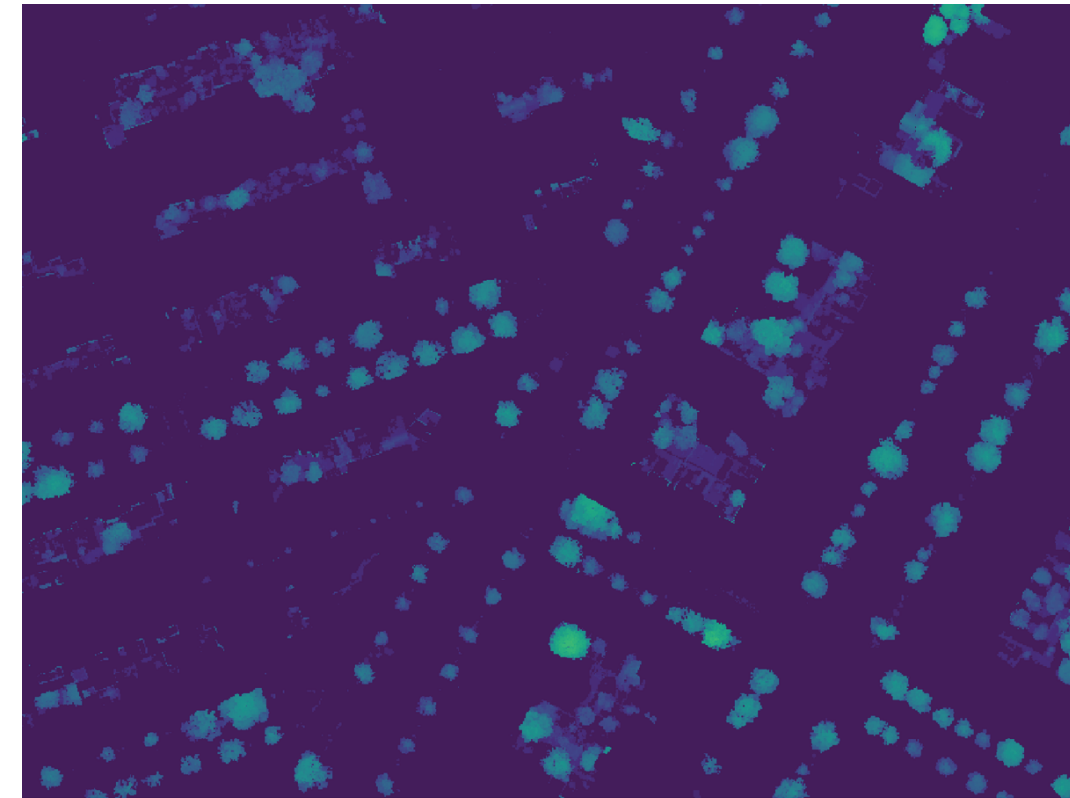
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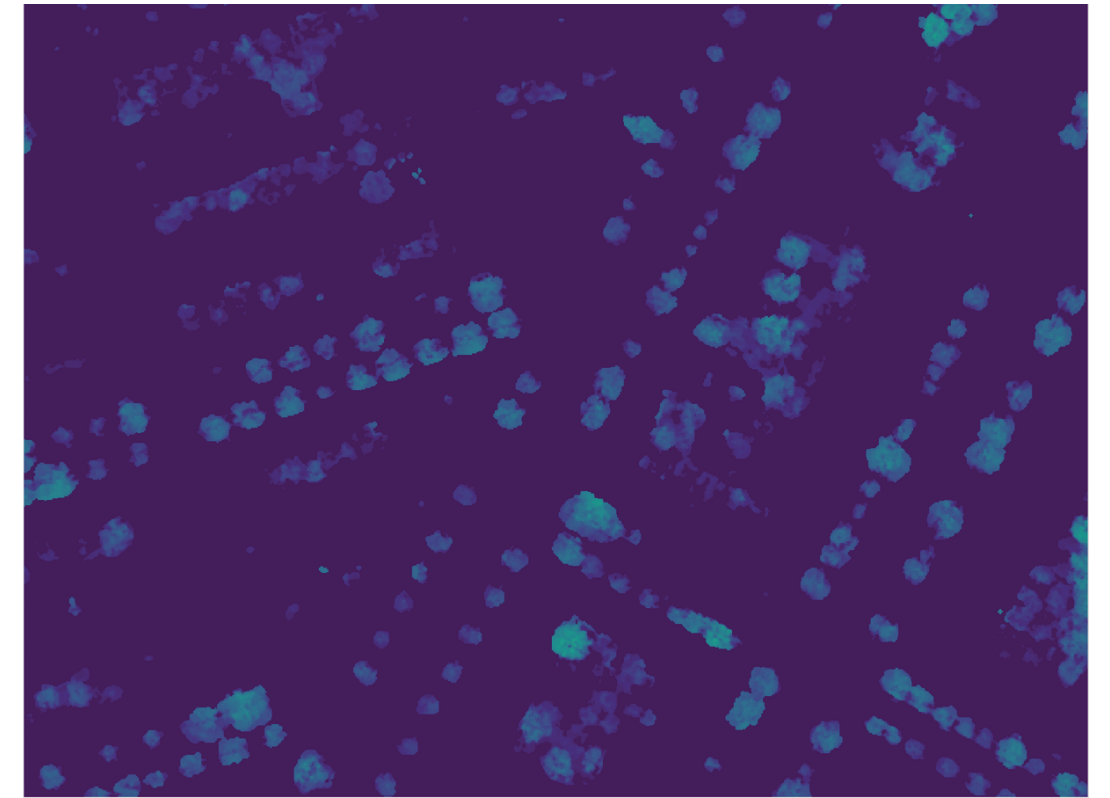
SOLFD operates within
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Automatic Data Collection

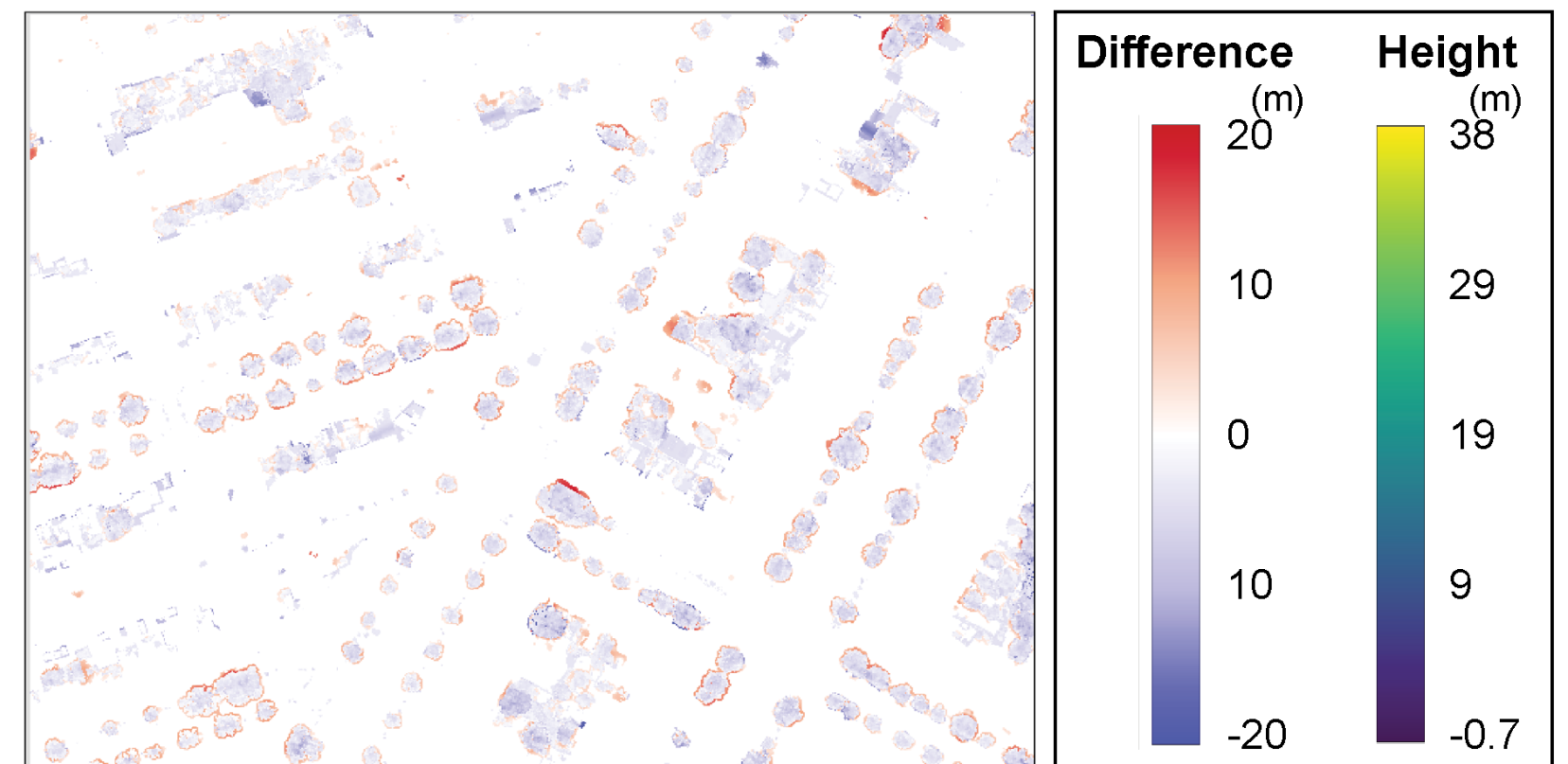
- **CHM**



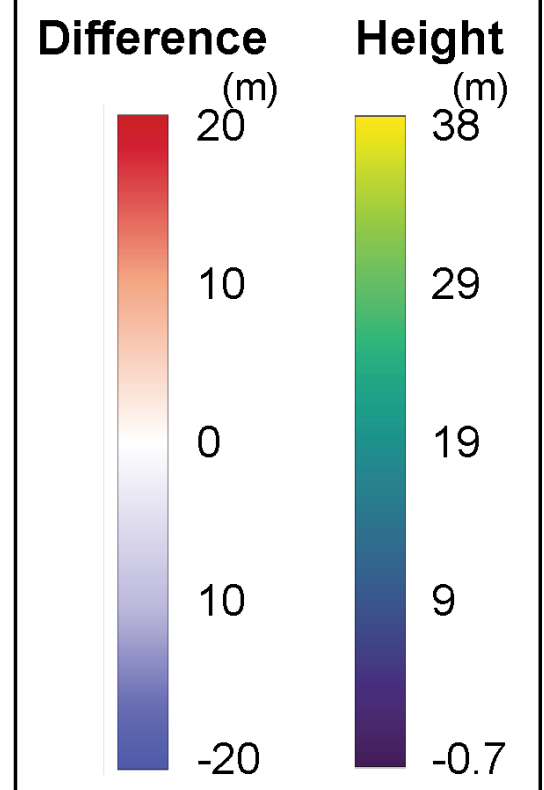
AHN DSM with (almost) only trees



Output CHM



Difference in height (Output - AHN)



SOLFD allows
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Automatic Data Collection

- **Land cover**
BGT dataset



SOLFD allows
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location data

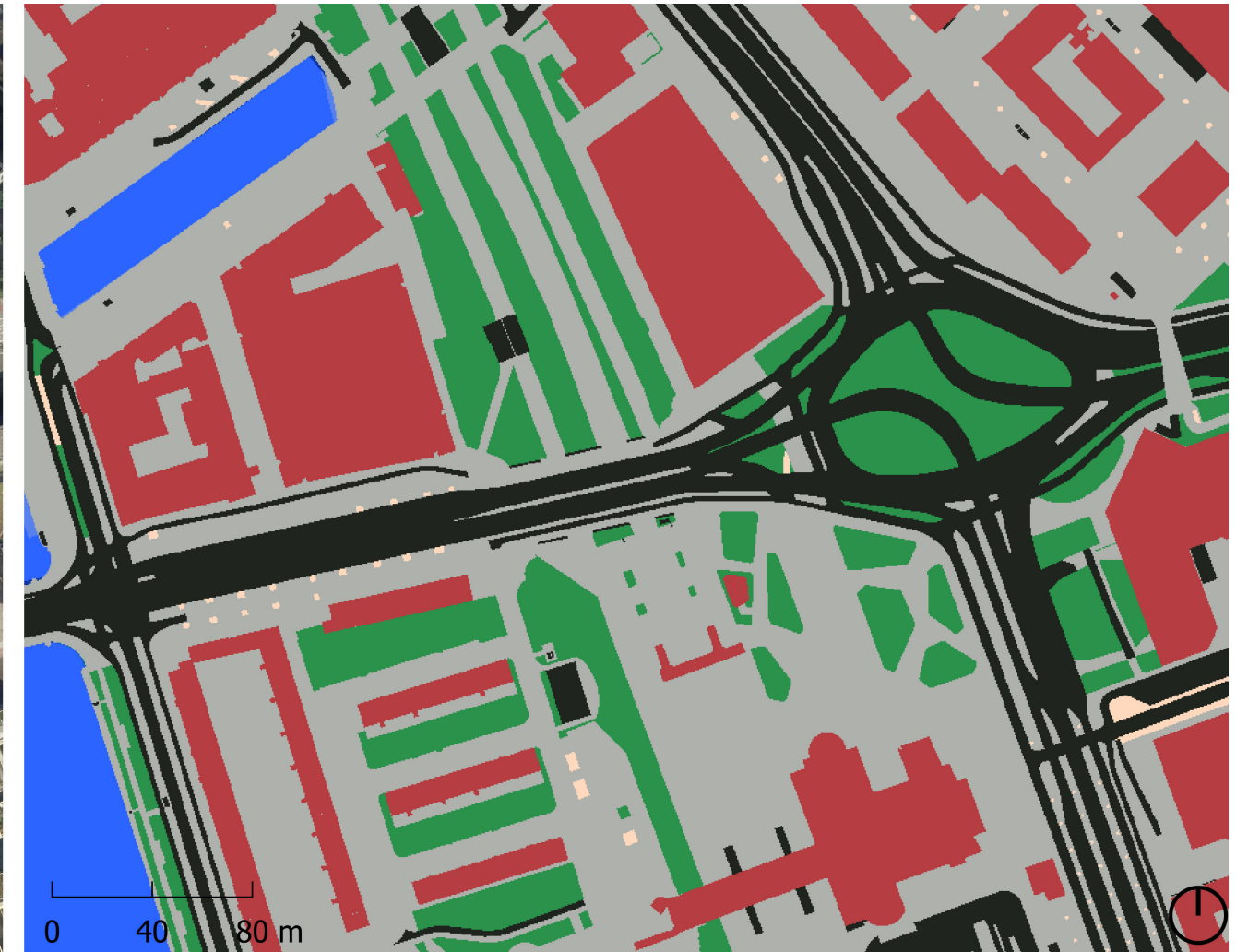
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Automatic Data Collection

- **Land cover**



Land cover

- Cobblestone
- Dark Asphalt
- Building
- Grass
- Bare Soil
- Water

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Automatic Data Collection

- **Wall Height and Wall Aspect**
 - Wall height: cross-filter method kept

*SOLFD allows
3D designs*

***SOLFD automatically
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*SOLFD allows input
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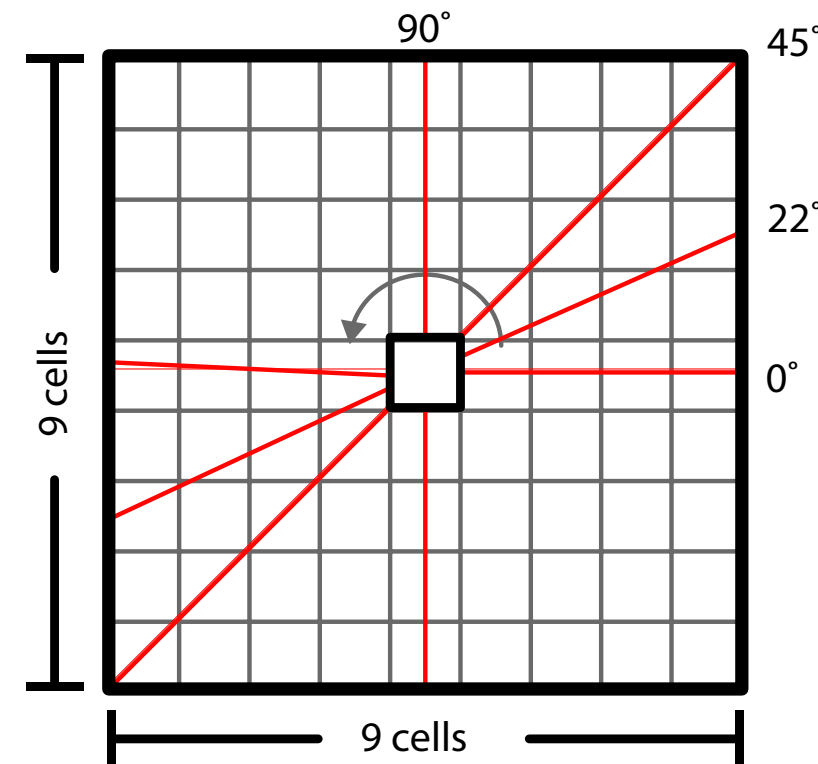
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Automatic Data Collection

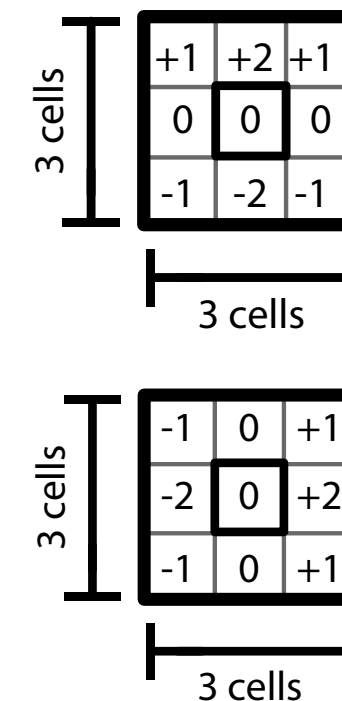
- **Wall Height and Wall Aspect**
 - Wall height: cross-filter method kept
 - Wall Aspect: linear filter method replaced with Sobel filter method

180x for each wall cell



Linear filter method

1x for each wall cell



Sobel filter method

SOLFD allows
3D designs

SOLFD automatically
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location data

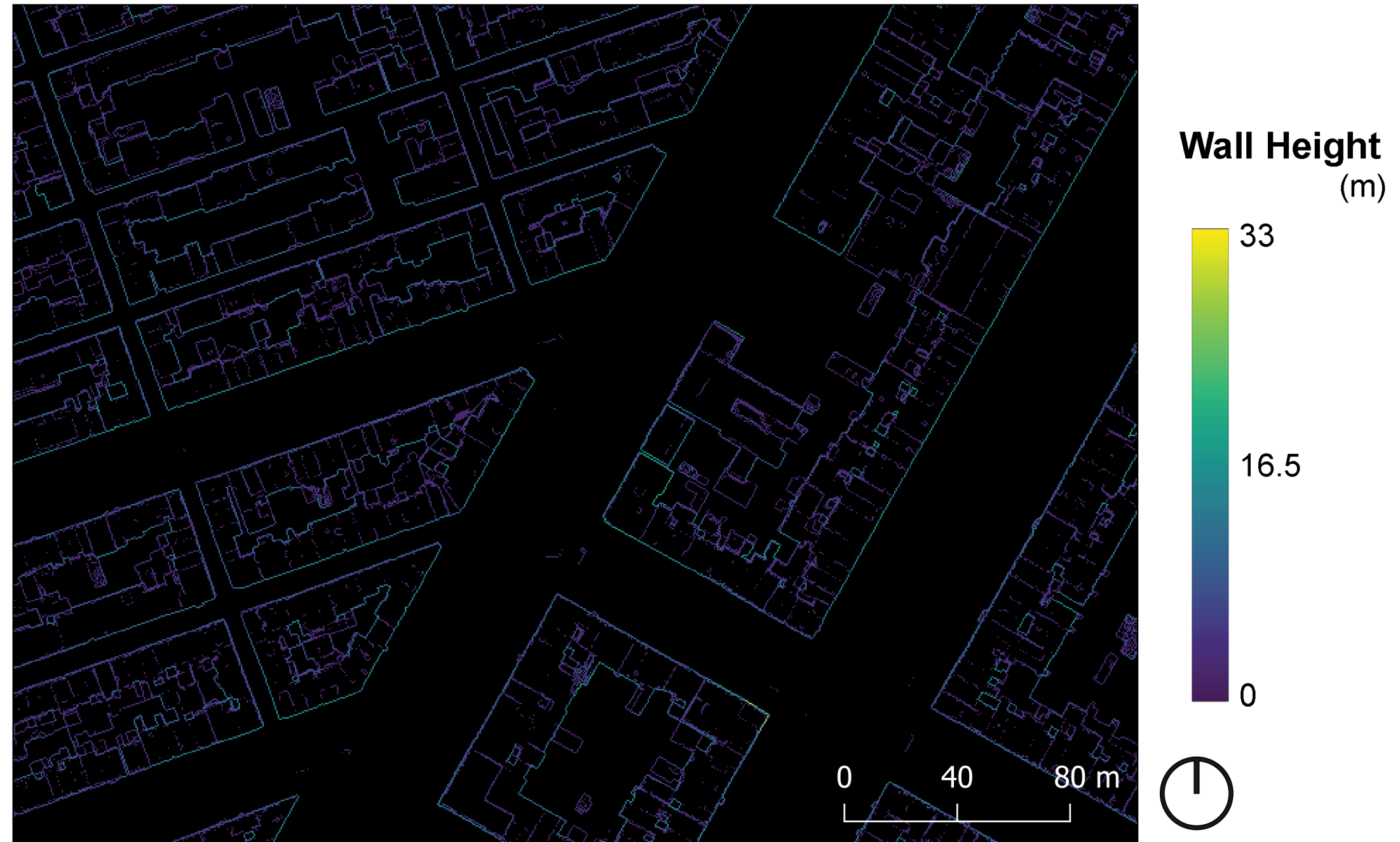
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Automatic Data Collection

- **Wall Height and Wall Aspect**



Output wall height

SOLFD allows
3D designs

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location data**

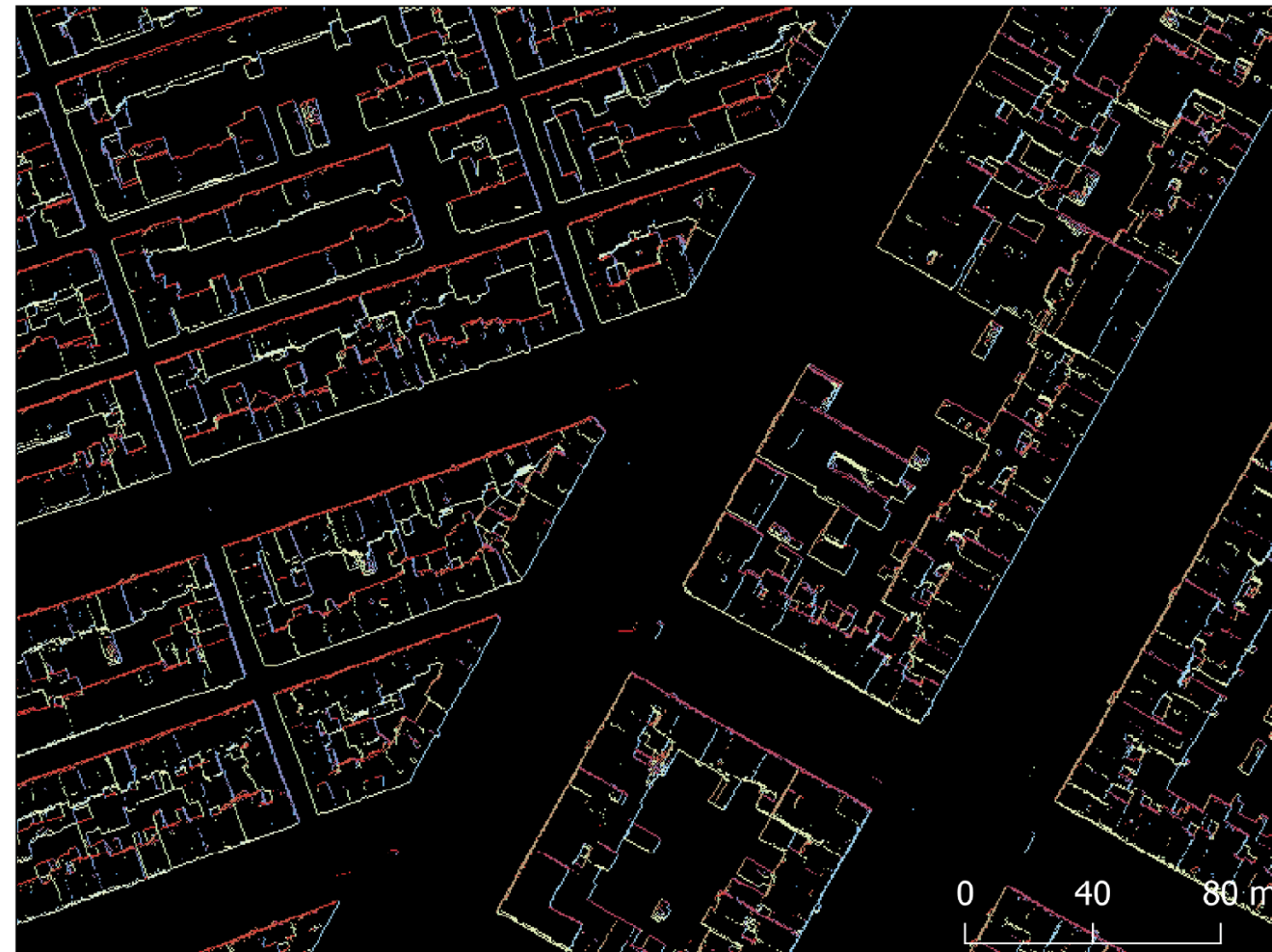
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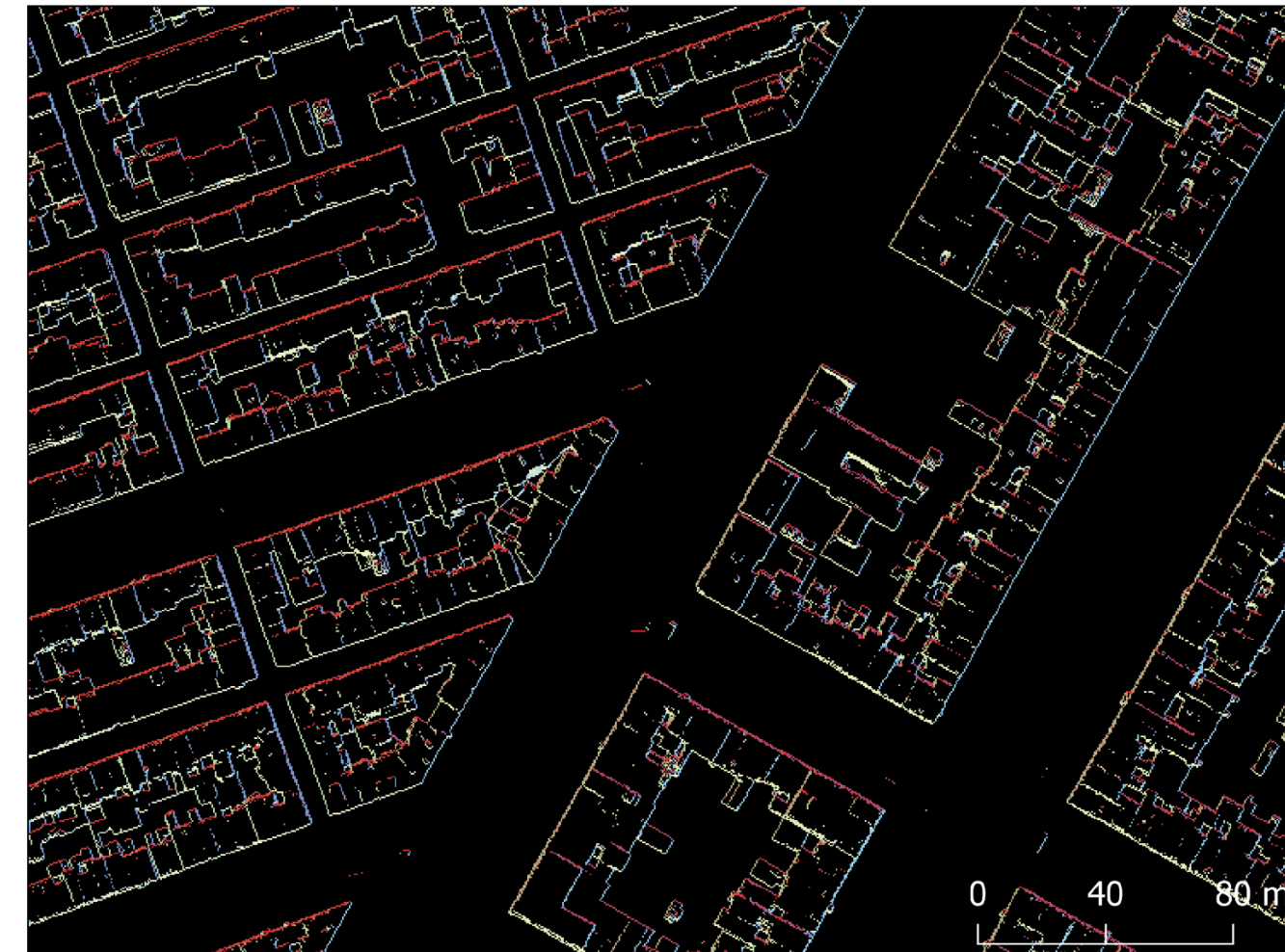
SOLFD operates within
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Automatic Data Collection

- **Wall Height and Wall Aspect**

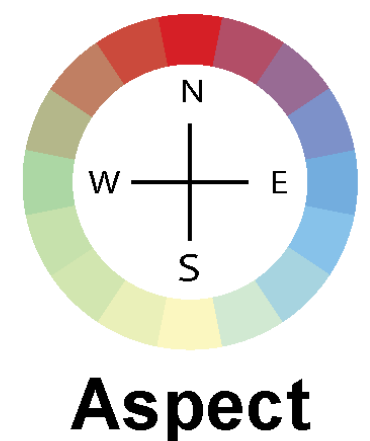


Linear filter method



Sobel filter method

800x600 array: 223.89 seconds ->
0.02 seconds



SOLFD allows
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Automatic Data Collection

- **Meteorological Data**

- Prepare 3 types of days:

20–25°C (mild summer days),	mean
25–30°C (warm summer days),	mean
>30°C (hot/tropical days),	97th

- Into 4 meteorological data sets:

3x ‘average day’: August 1st 2023, midsummer solar angles
1x ‘extreme day’: June 21st 2023, solstice solar angles

SOLFD allows
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SOLFD allows
3D designs

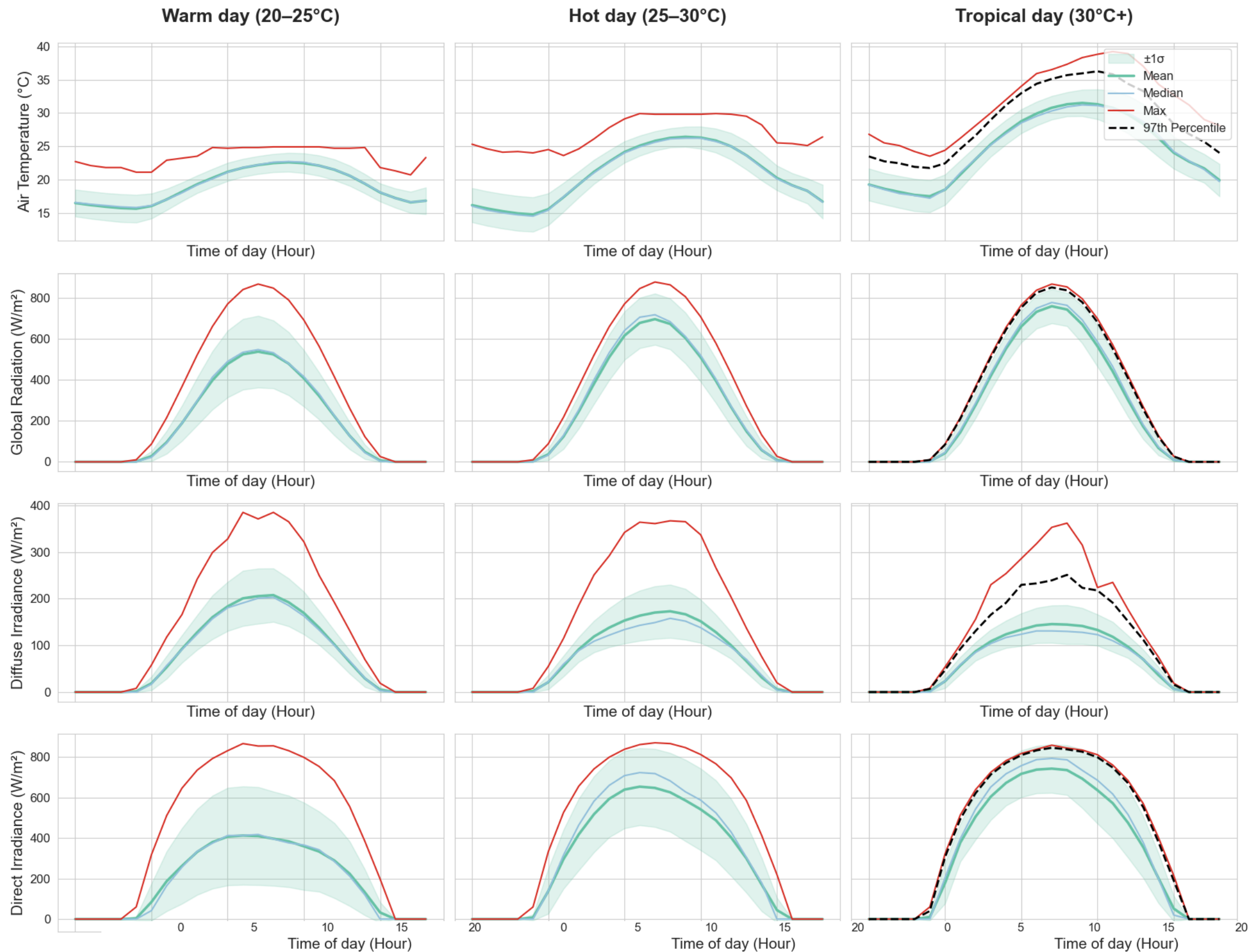
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SOLFD operates within
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User Input

- Modifying existing elements
 - remove buildings and trees in urban scene.

*SOLFD allows
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***SOLFD allows input
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User Input

- Modifying existing elements
- Tree insertion
 - Insert a tree using parameters or tree species

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*SOLFD automatically
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location data*

***SOLFD allows input
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*SOLFD operates within
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User Input

- Modifying existing elements
- Tree insertion
- 3D urban design integration
 - Insert a design as 3D triangulated mesh .OBJ

*SOLFD allows
3D designs*

*SOLFD automatically
collects required
location data*

***SOLFD allows input
designs and changing
the urban scene***

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*SOLFD operates within
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User Input

- Modifying existing elements
- Tree insertion
- 3D urban design integration
- Urban design integration for materials
 - Insert new materials in the land cover.

SOLFD allows
3D designs

SOLFD automatically
collects required
location data

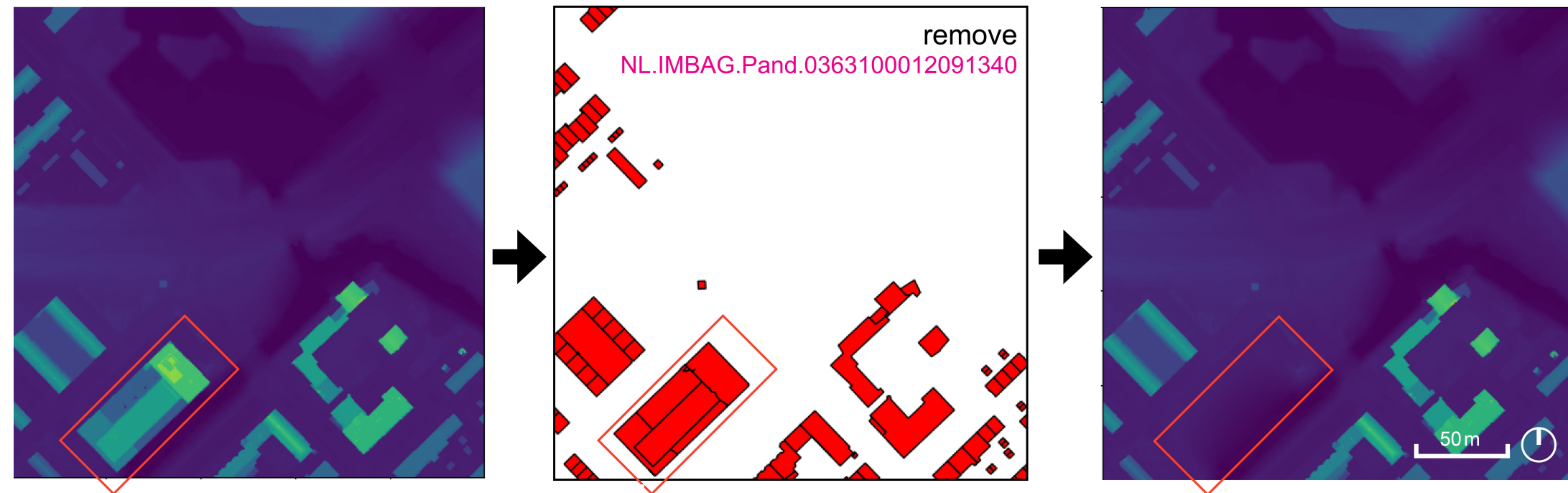
**SOLFD allows input
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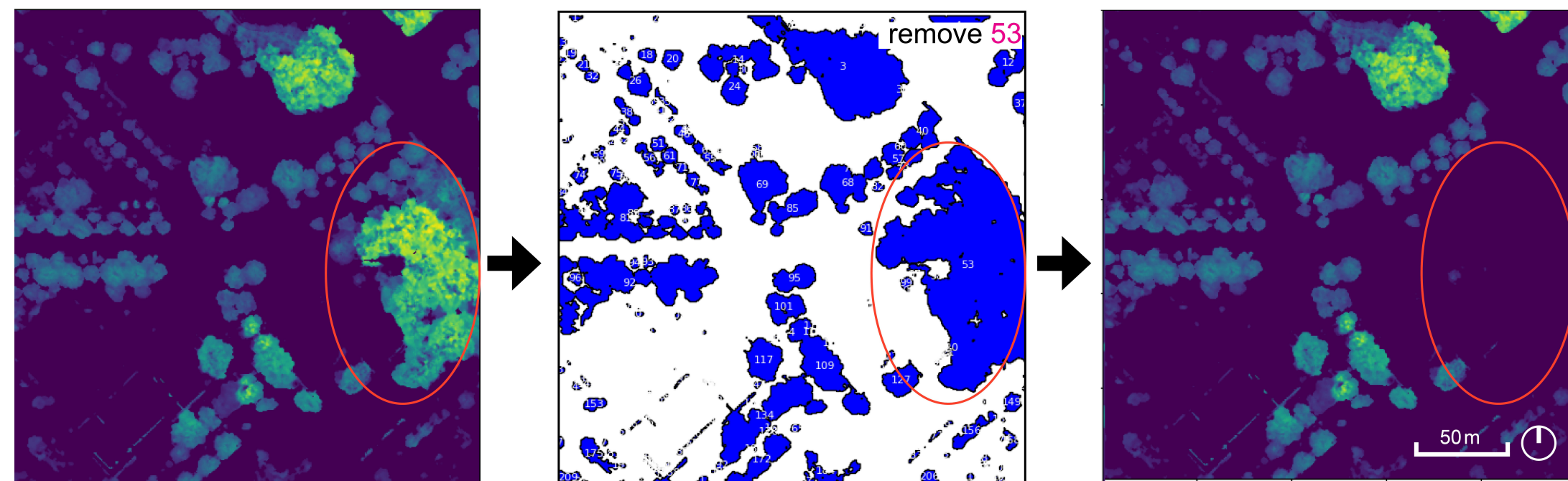
SOLFD operates within
an acceptable time
frame

User Input

- **Modifying existing elements**



Removal of a building



Removal of a tree (cluster)

SOLFD allows
3D designs

SOLFD automatically
collects required
location data

**SOLFD allows input
designs and changing
the urban scene**

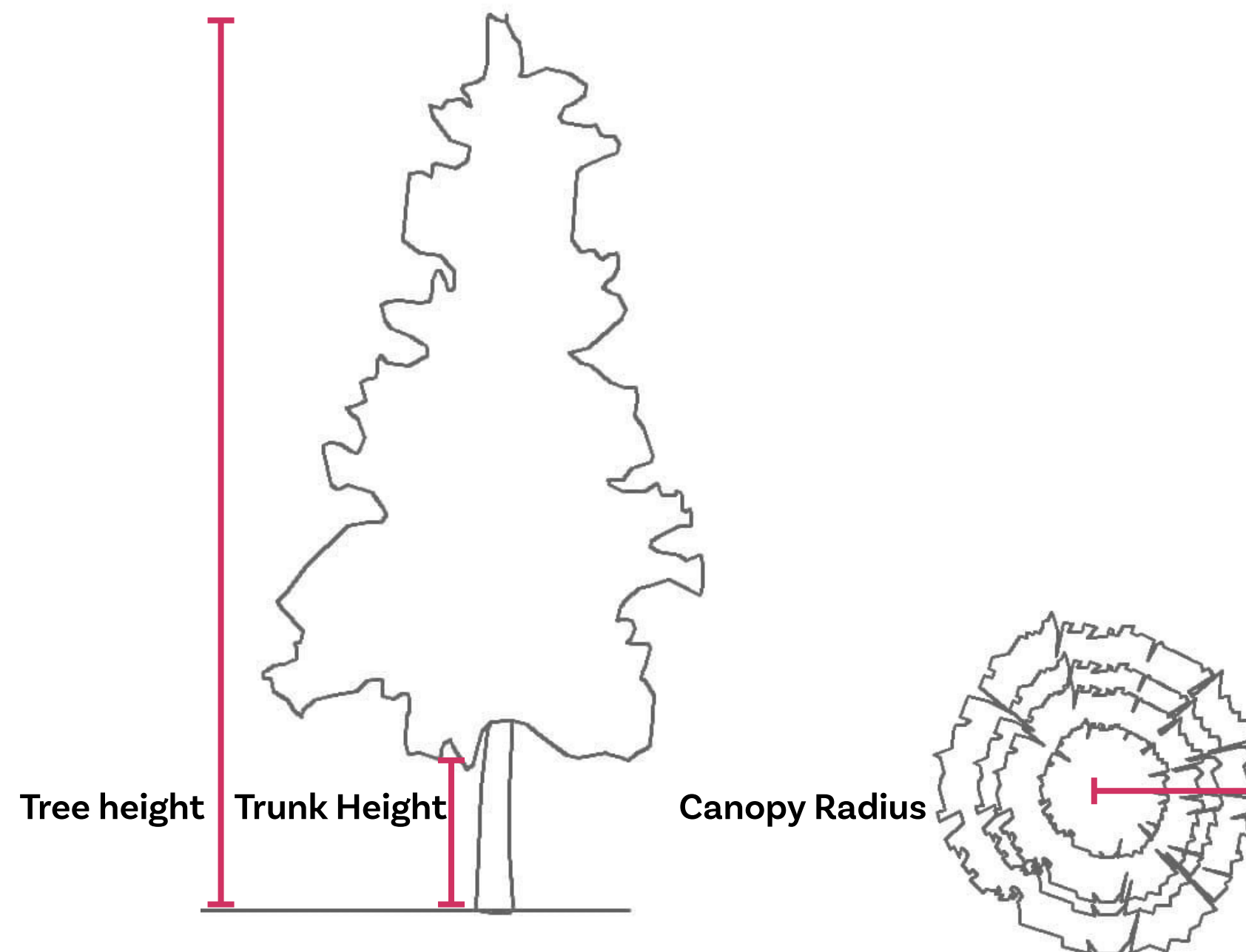
SOLFD allows
evaluation, comparison
and improvement of
designs

SOLFD operates within
an acceptable time
frame

User Input

- **Tree insertion**

Simple mathematical models based on:



+ Shape
+ Random Noise

SOLFD allows 3D designs

SOLFD automatically collects required location data

SOLFD allows input designs and changing the urban scene

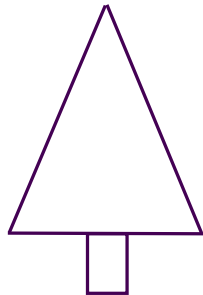
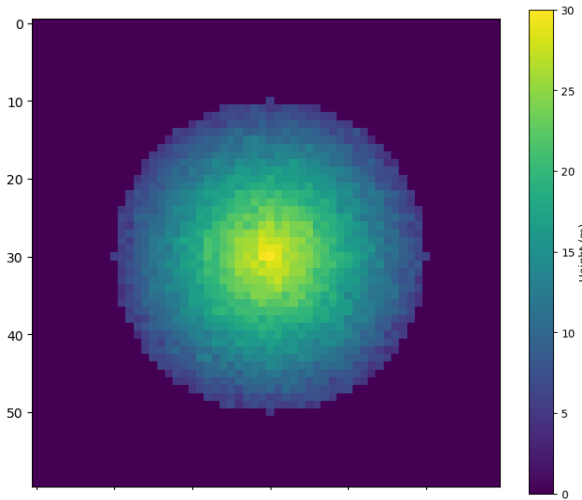
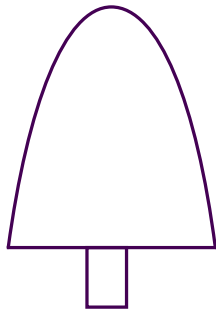
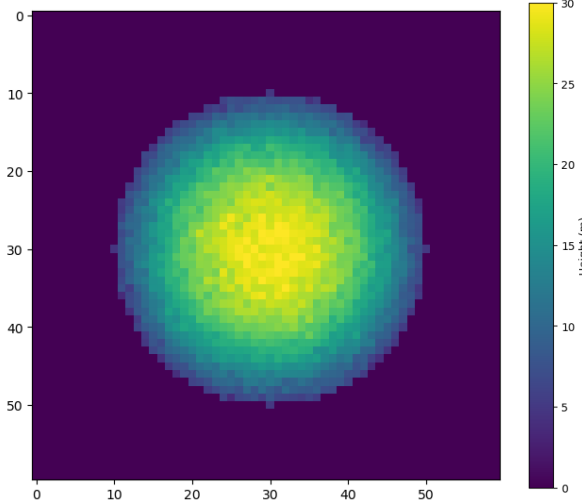
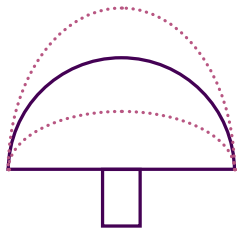
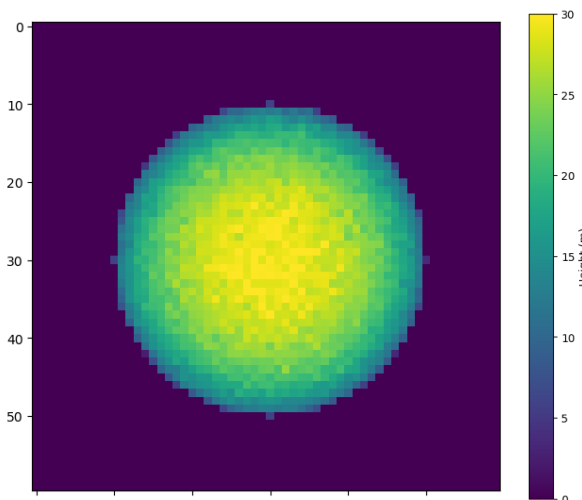
SOLFD allows evaluation, comparison and improvement of designs

SOLFD operates within an acceptable time frame

User Input

- Tree insertion

Also random input & given parameters of 5 most common Dutch trees

Shape	Formula	Output
Cone 	$\text{canopy}(x,y) = \max\left(\left(\text{height} - \text{trunk_height}\right) \times \left(1 - \frac{\sqrt{x^2 + y^2}}{\text{crown_radius}}\right), 0\right) + \text{trunk_height}$	
Parabolic 	$\text{canopy}(x,y) = \max\left(\left(\text{height} - \text{trunk_height}\right) \times \left(1 - \left(\frac{\sqrt{x^2 + y^2}}{\text{crown_radius}}\right)^2\right), 0\right) + \text{trunk_height}$	
Hemisphere 	$\text{canopy}(x,y) = \frac{\sqrt{\max(\text{crown_radius}^2 - (x^2 + y^2), 0)}}{\text{crown_radius}} \times (\text{height} - \text{trunk_height}) + \text{trunk_height}$	

SOLFD allows
3D designs

SOLFD automatically
collects required
location data

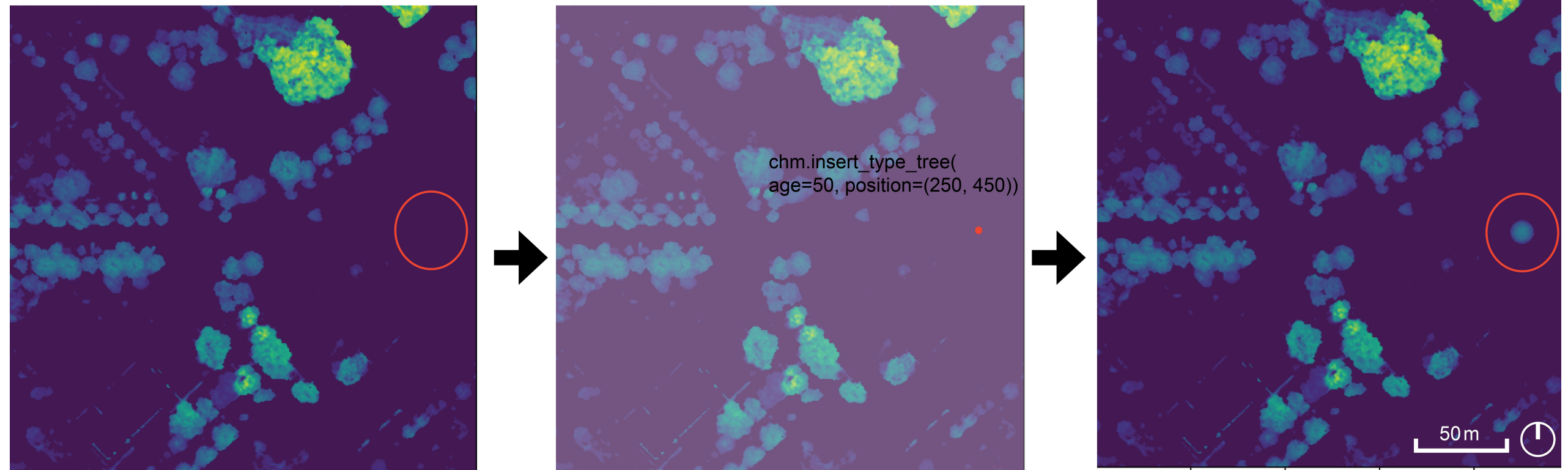
**SOLFD allows input
designs and changing
the urban scene**

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User Input

- Tree insertion



Insertion of a 50 year old ash

SOLFD allows
3D designs

SOLFD automatically
collects required
location data

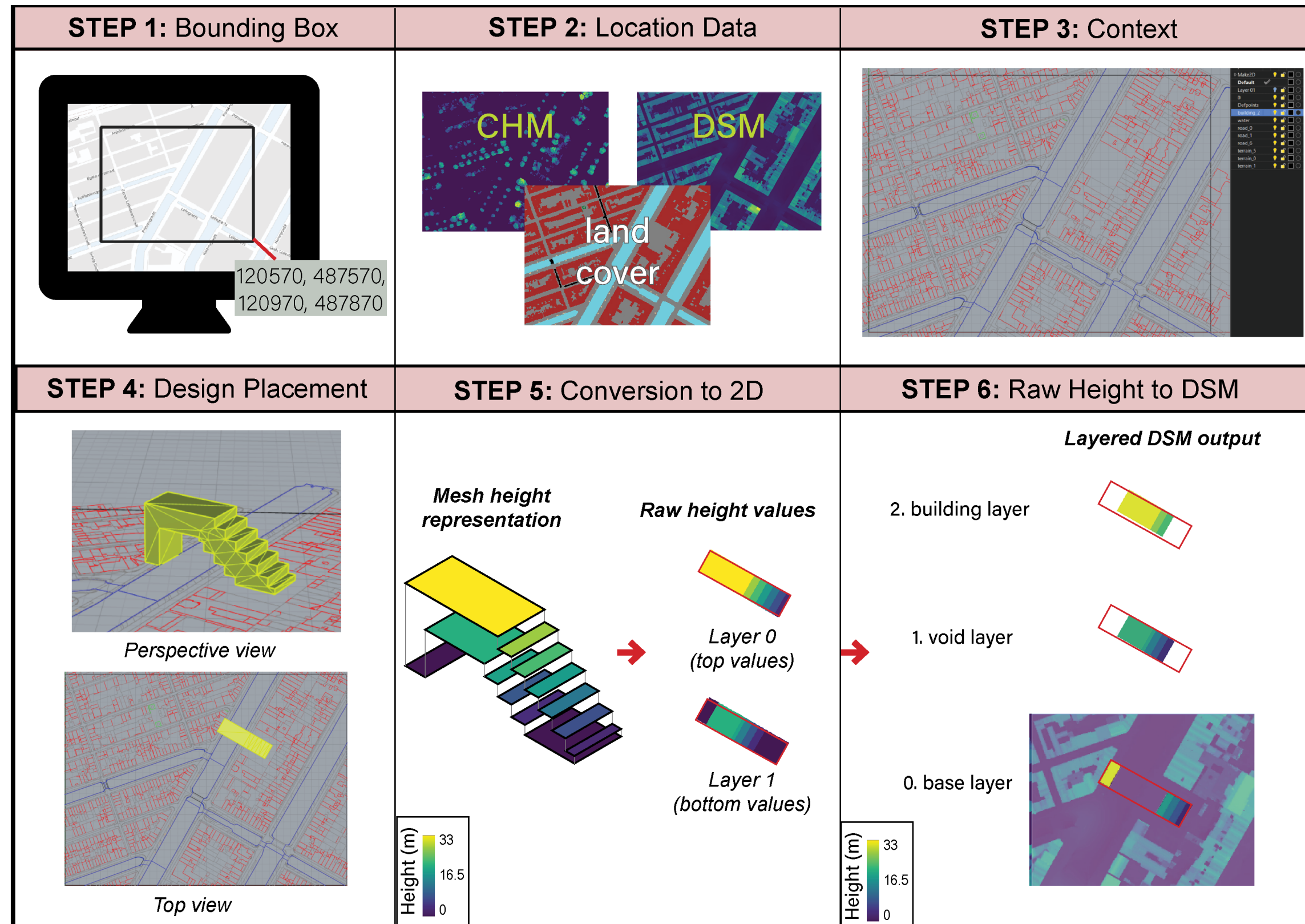
SOLFD allows input
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User Input

- 3D urban design integration



SOLFD allows
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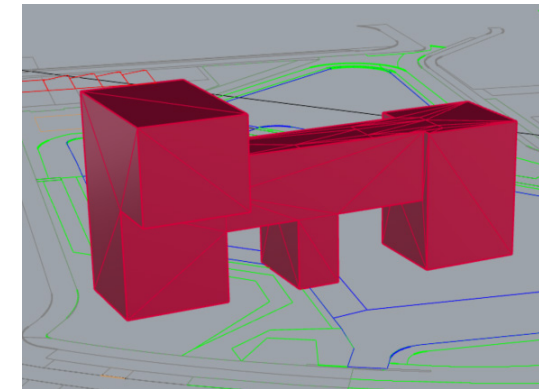
User Input

- 3D urban design integration

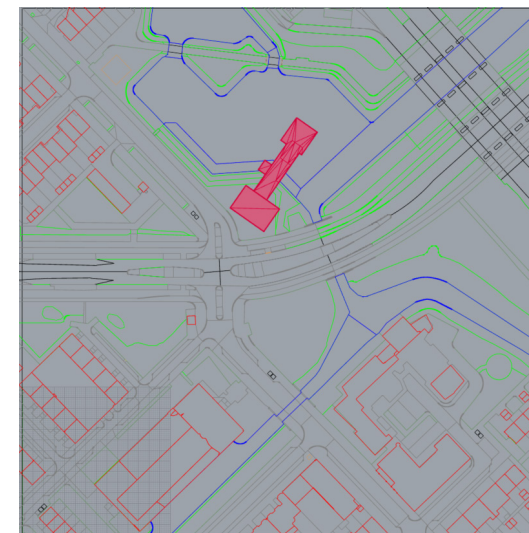
INPUT

1. Triangulated mesh of user design

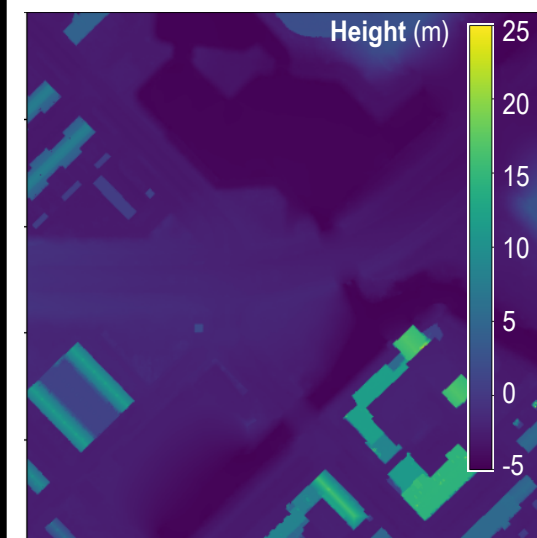
Perspective view



Top view



2. DSM



SOLFD allows
3D designs

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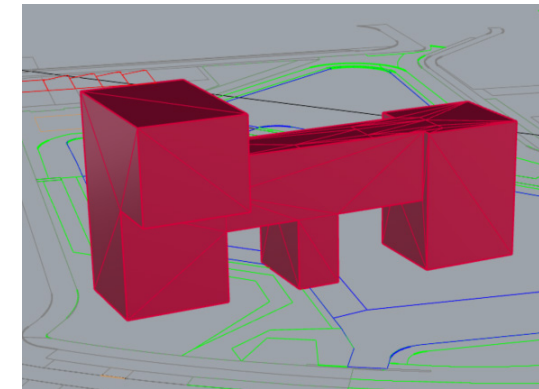
User Input

- 3D urban design integration

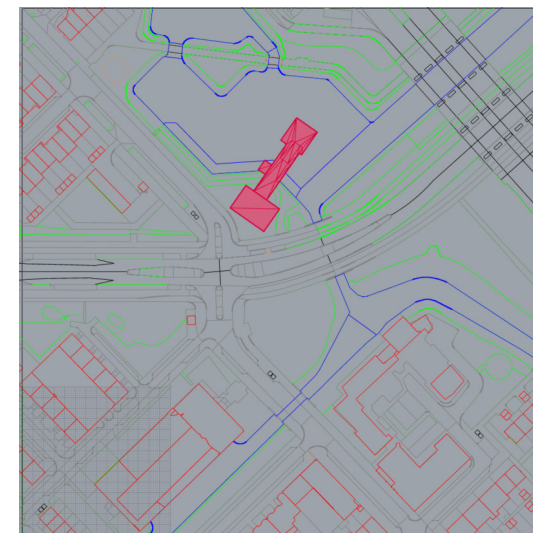
INPUT

1. Triangulated mesh of user design

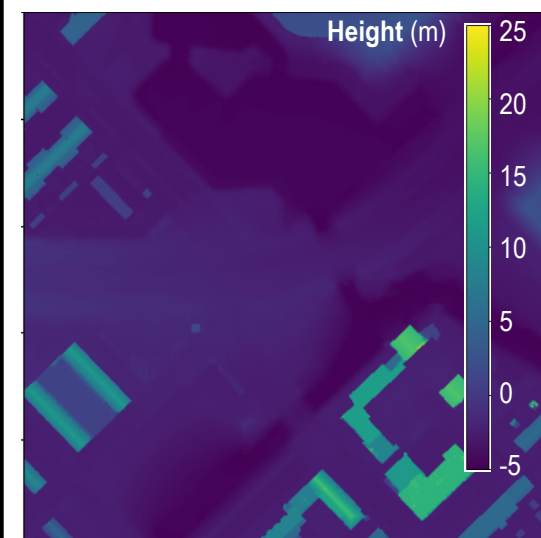
Perspective view



Top view

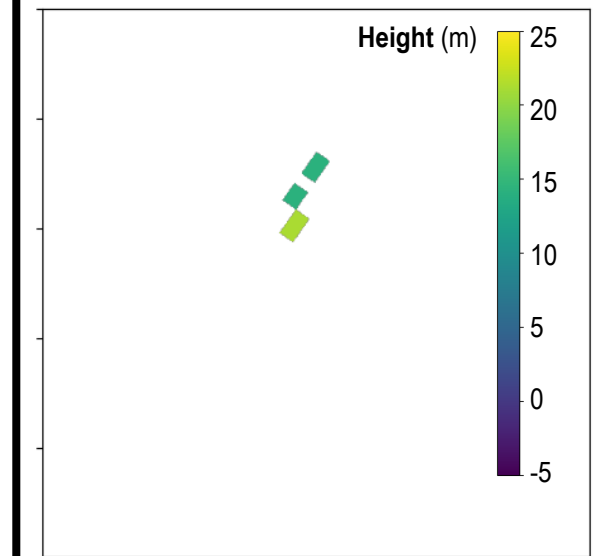


2. DSM

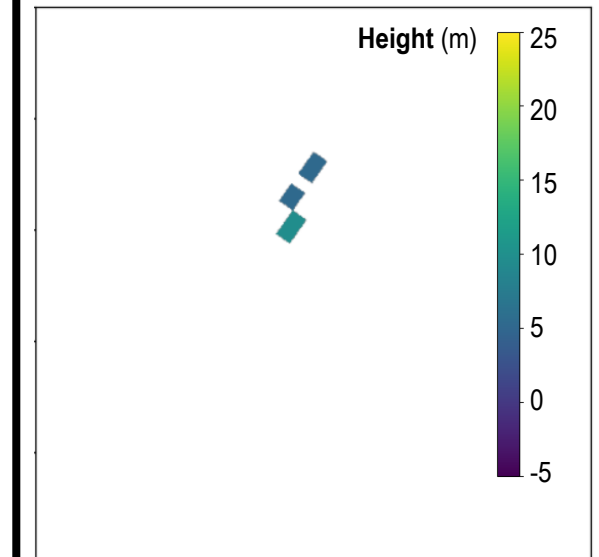


OUTPUT

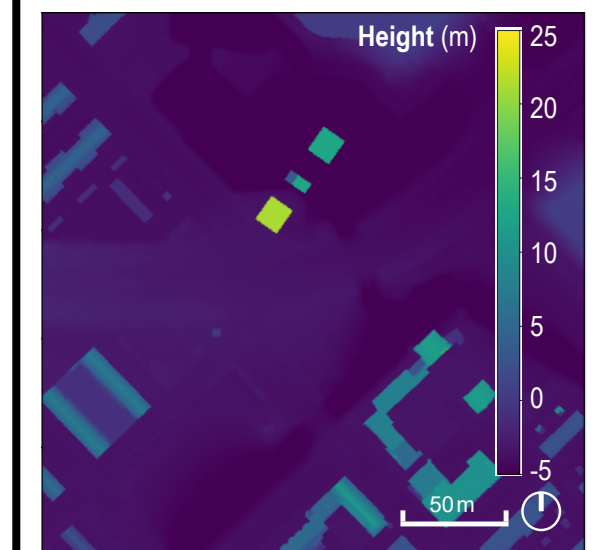
DSM layer 2: building layer



DSM layer 1: void layer



DSM layer 0: base layer



SOLFD allows
3D designs

SOLFD automatically
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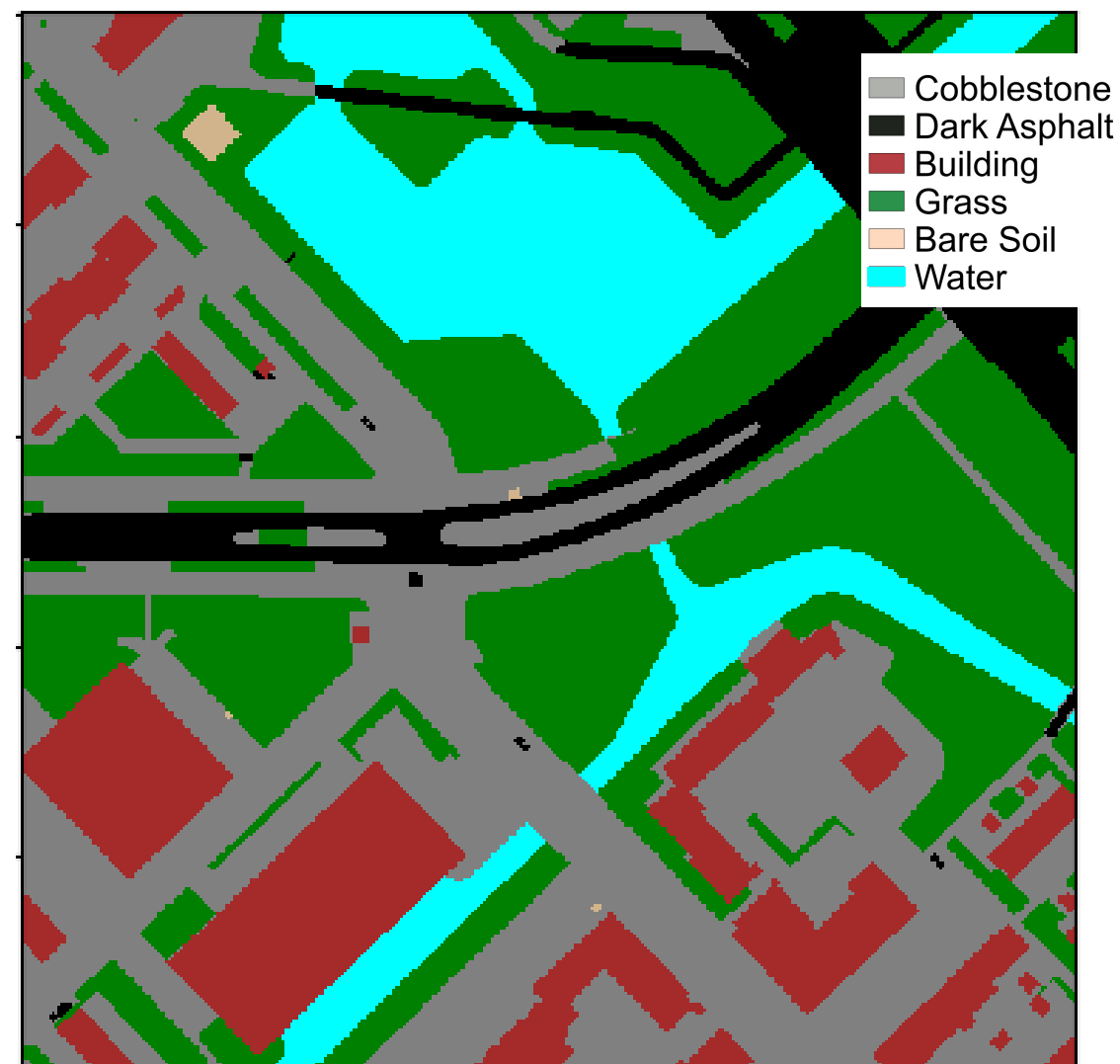
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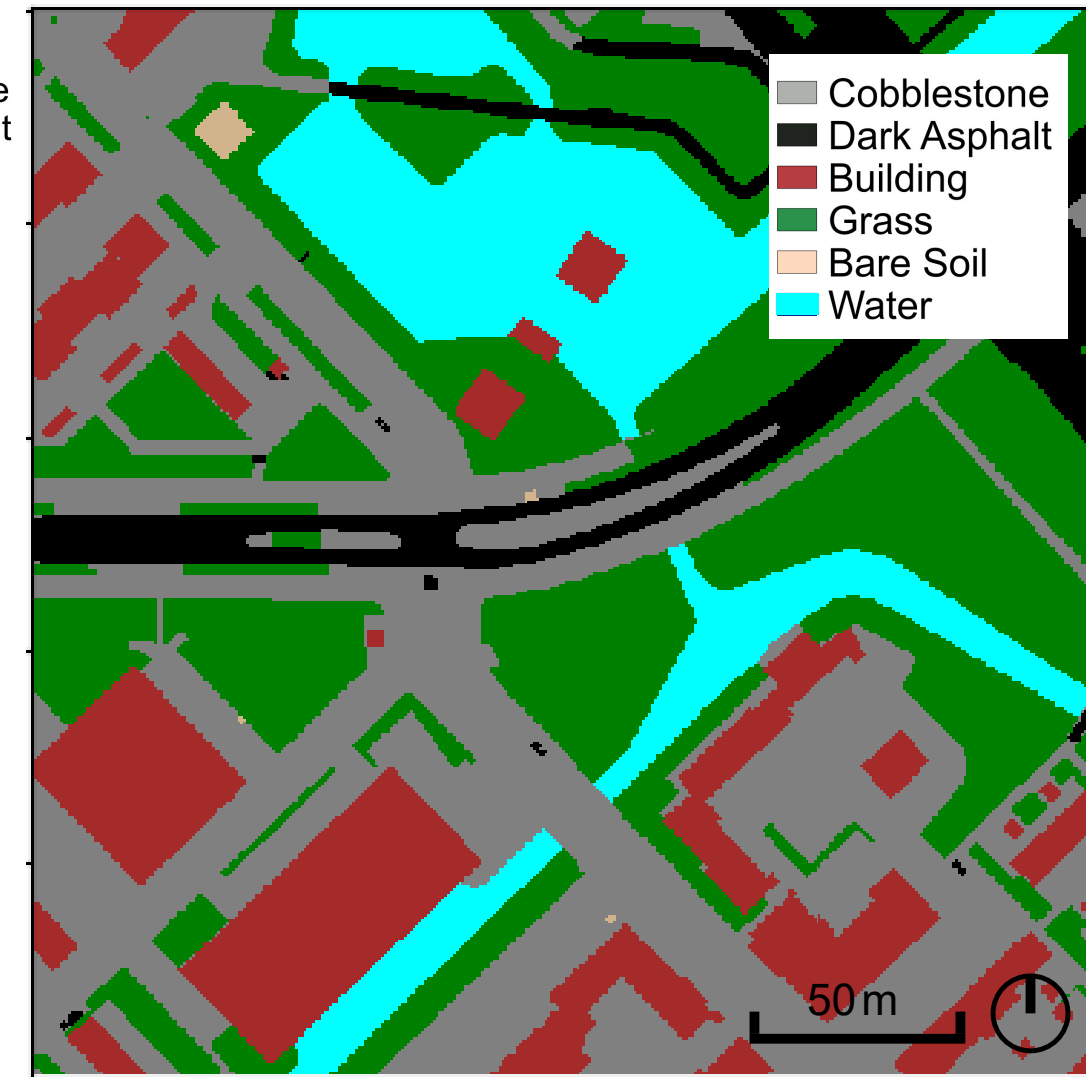
SOLFD operates within
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frame

User Input

- 3D urban design integration



Original Land cover



Updated land cover

SOLFD allows
3D designs

SOLFD automatically
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location data

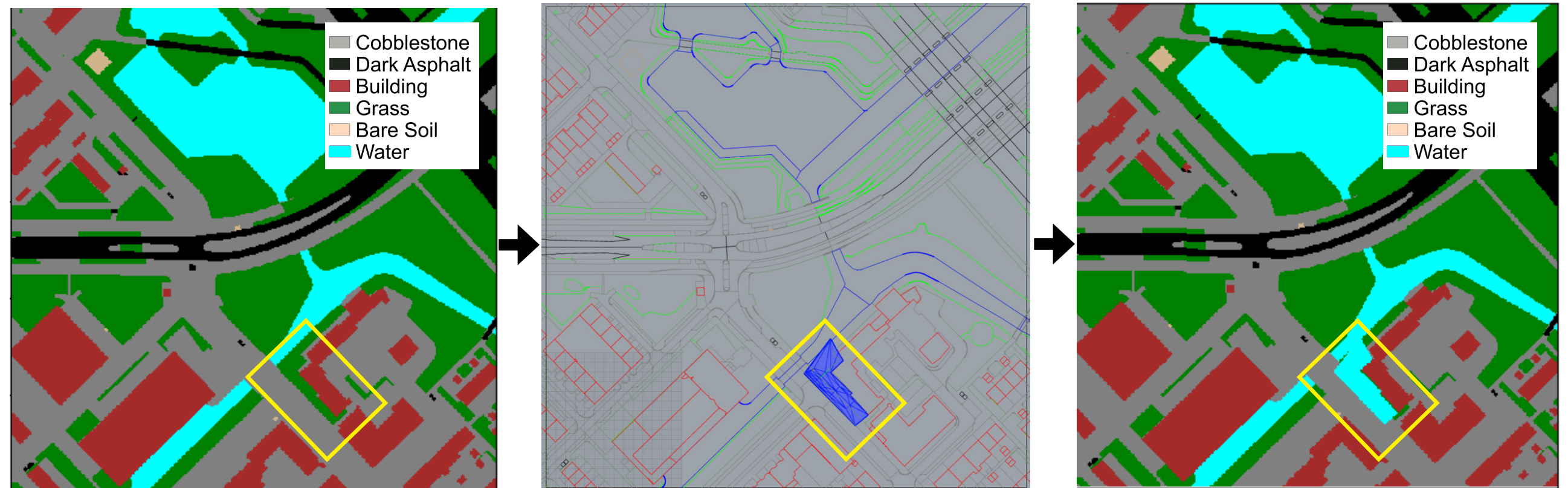
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User Input

- Urban design integration for materials



Outputs for Design and Analysis

*SOLFD allows
3D designs*

*SOLFD automatically
collects required
location data*

*SOLFD allows input
designs and changing
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Outputs for Design and Analysis

- **Hourly Tmrt Maps**
- **Aggregated Tmrt maps**
 - Morning (06.00-11.00)
 - Afternoon (12.00-17.00)
 - Evening (18.00-21.00)
- **Tmrt Statistics**
 - Mean, median, maximum, minimum
 - Area distributions across temperature bins
- **Derived PET**
 - Modelled Tmrt + global air temp, humidity and wind speed
 - Thermal stress classifications

SOLFD allows
3D designs

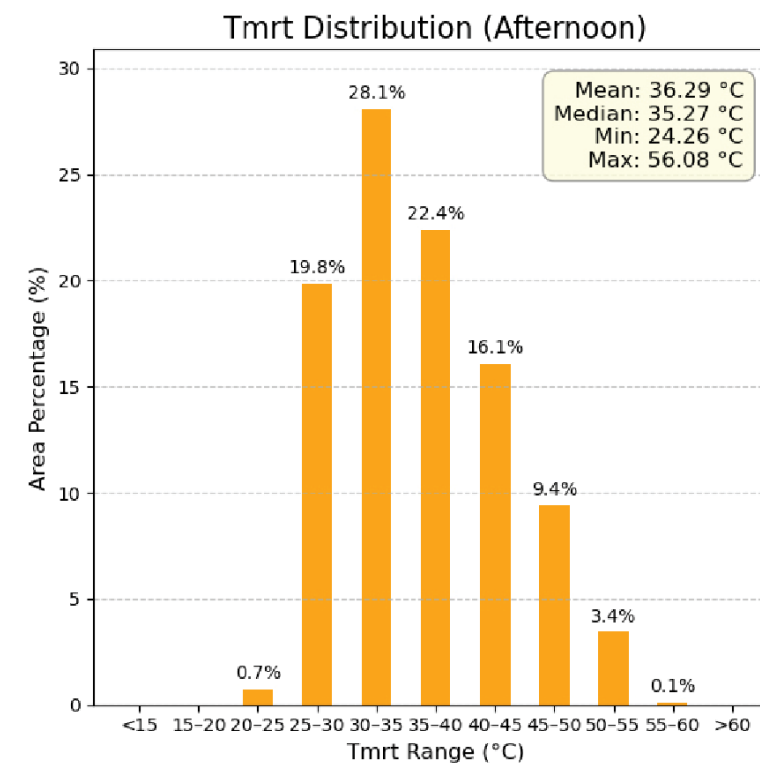
SOLFD automatically
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location data

SOLFD allows input
designs and changing
the urban scene

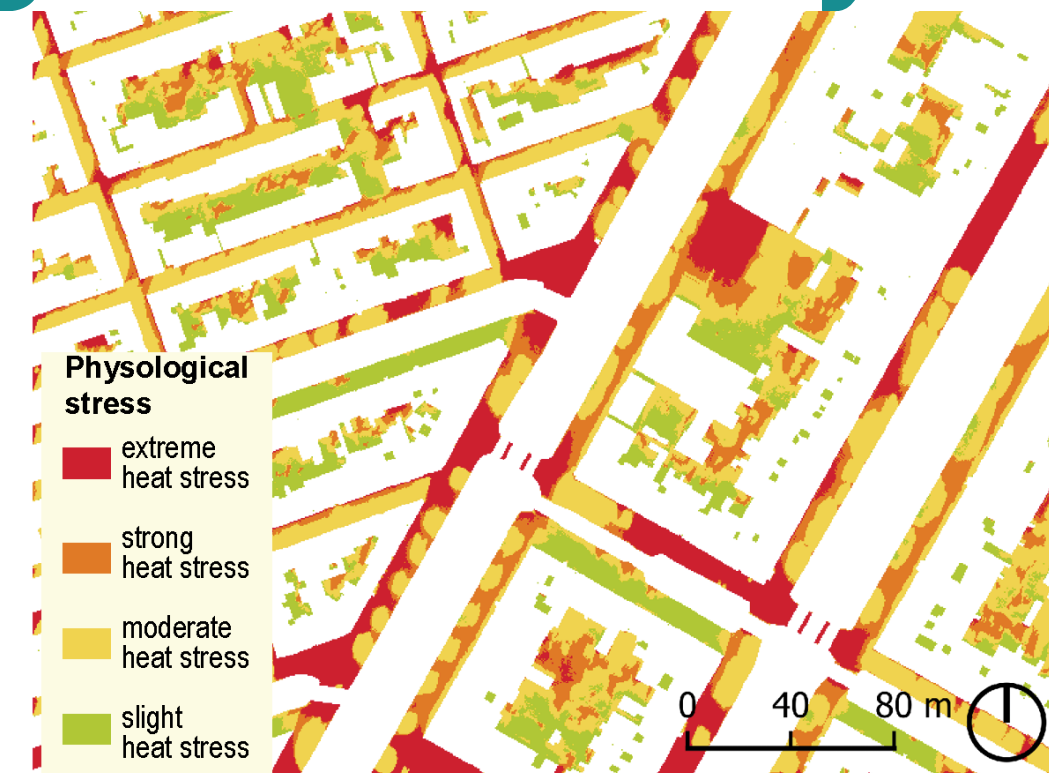
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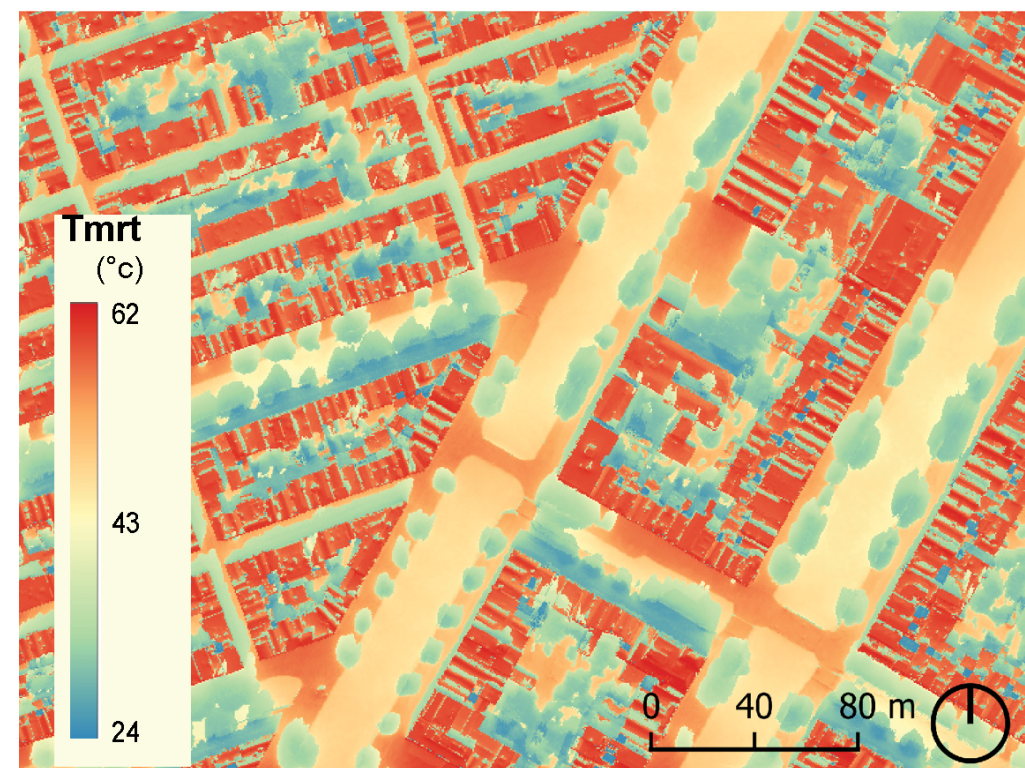
Outputs for Design and Analysis



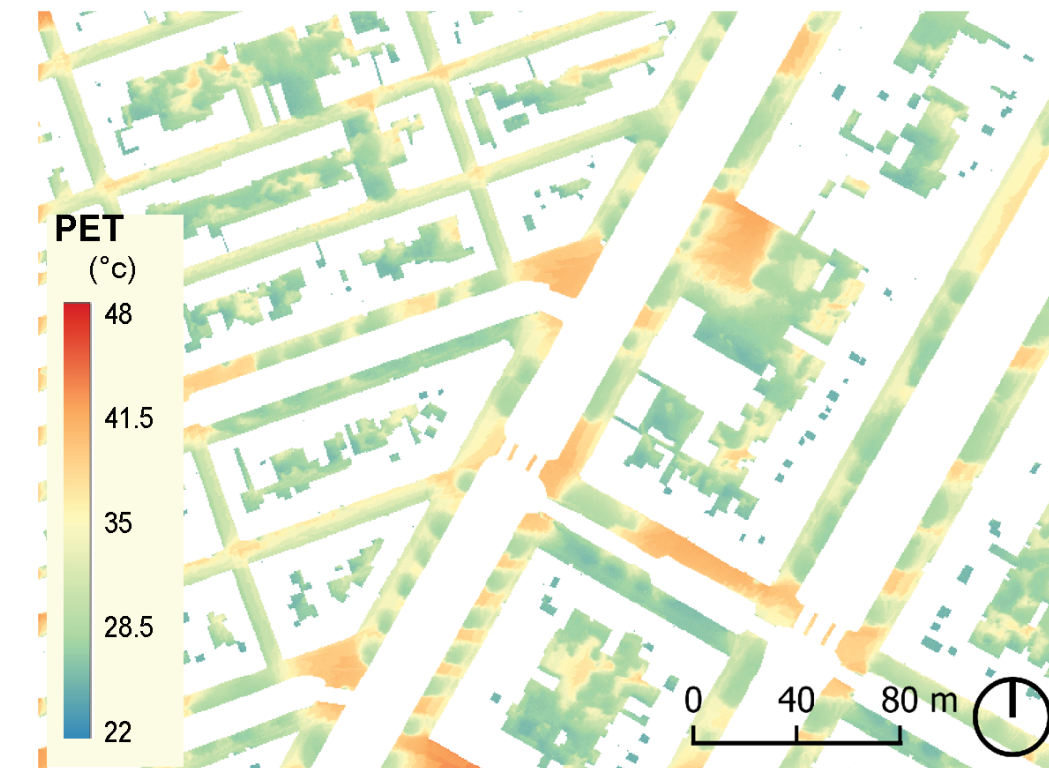
Statistics



Classified PET



Hourly Tmrt



PET aggregated over afternoon

Output Overview

Computation Time Optimization

*SOLFD allows
3D designs*

*SOLFD automatically
collects required
location data*

*SOLFD allows input
designs and changing
the urban scene*

*SOLFD allows
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**SOLFD operates
within an acceptable
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SOLFD allows
3D designs

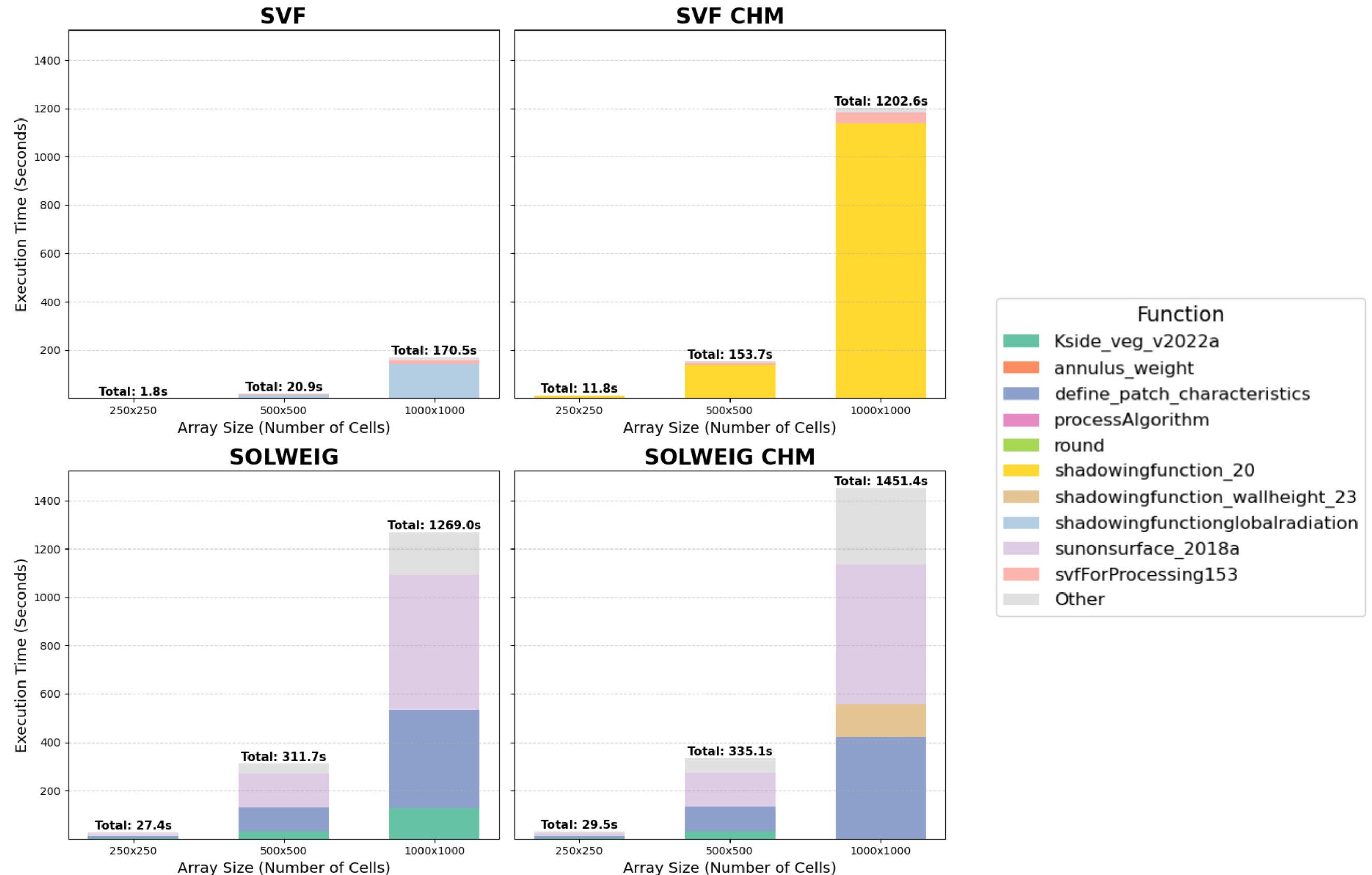
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Computation Time Optimization



SOLFD allows
3D designs

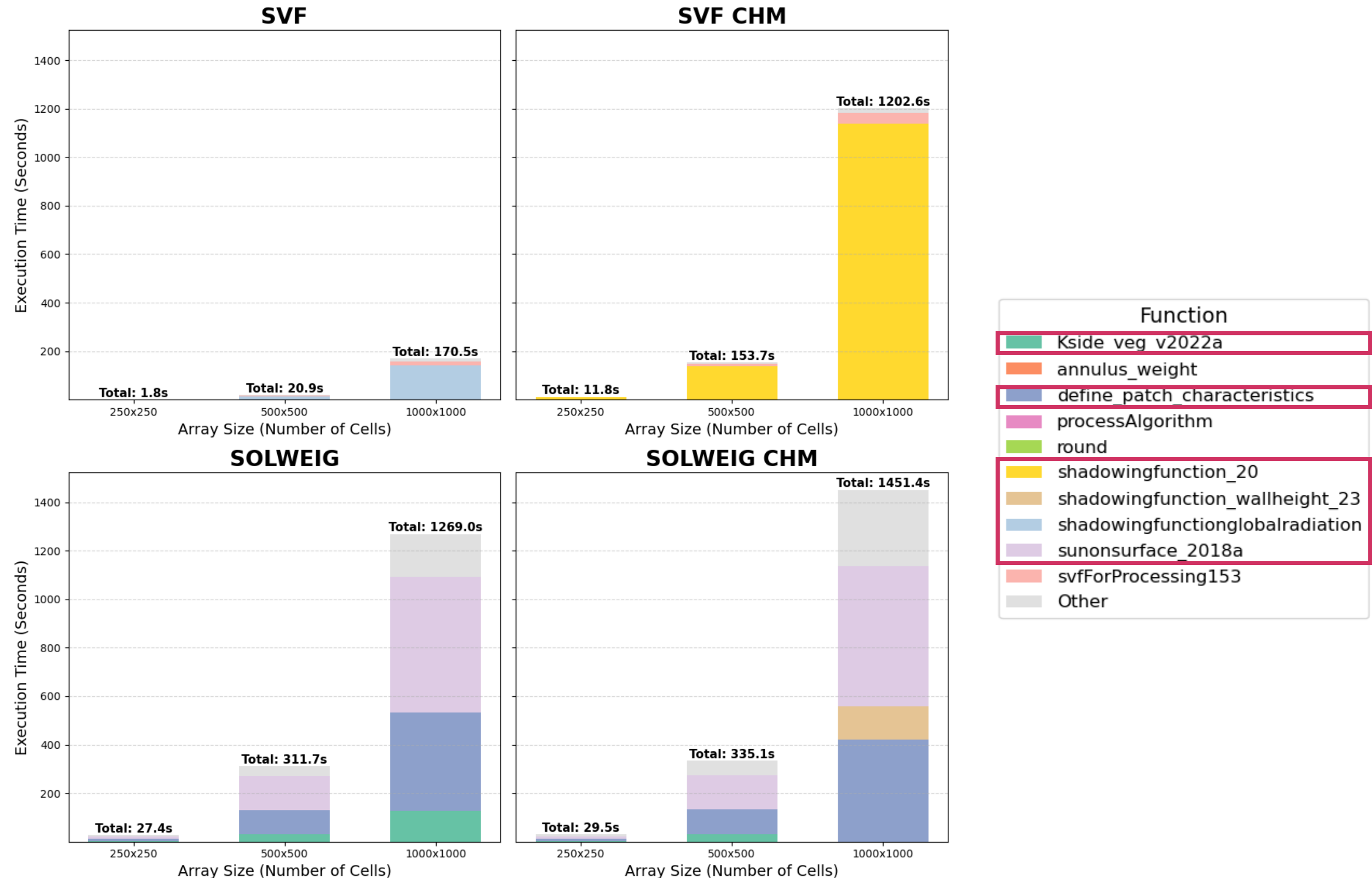
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Computation Time Optimization

- **CPU -> GPU**

SOLFD allows
3D designs

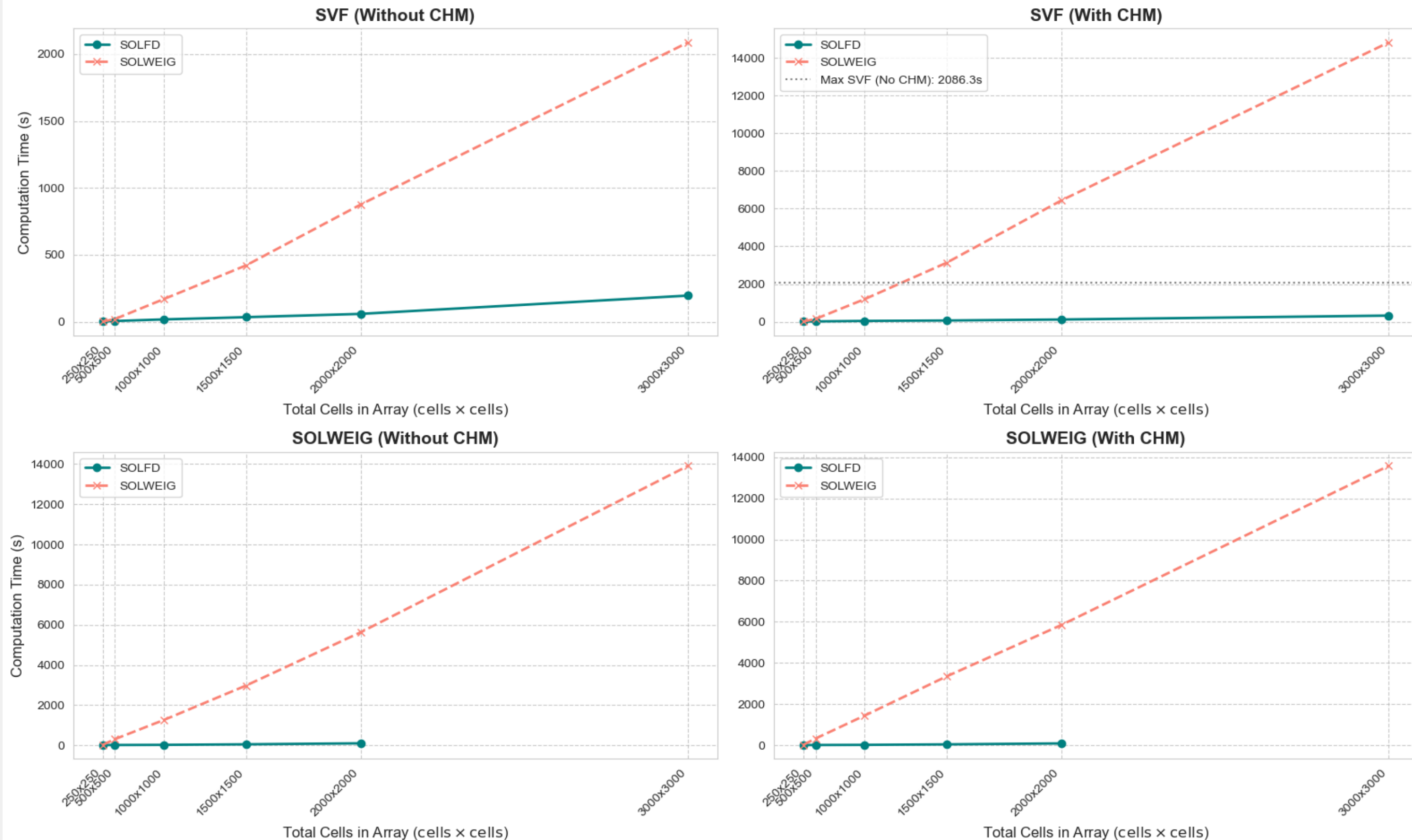
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Computation Time Optimization



SOLFD allows
3D designs

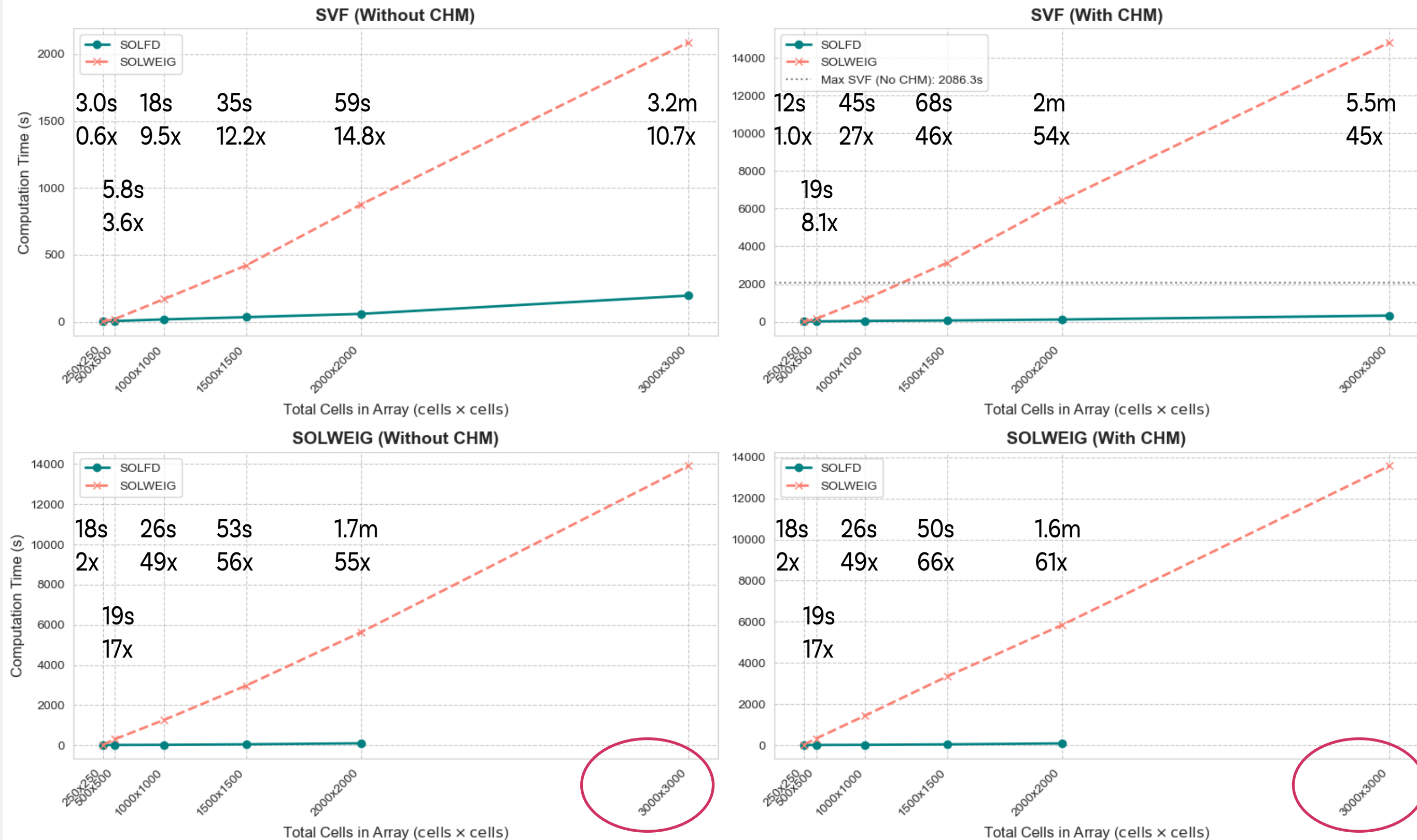
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SOLFD allows
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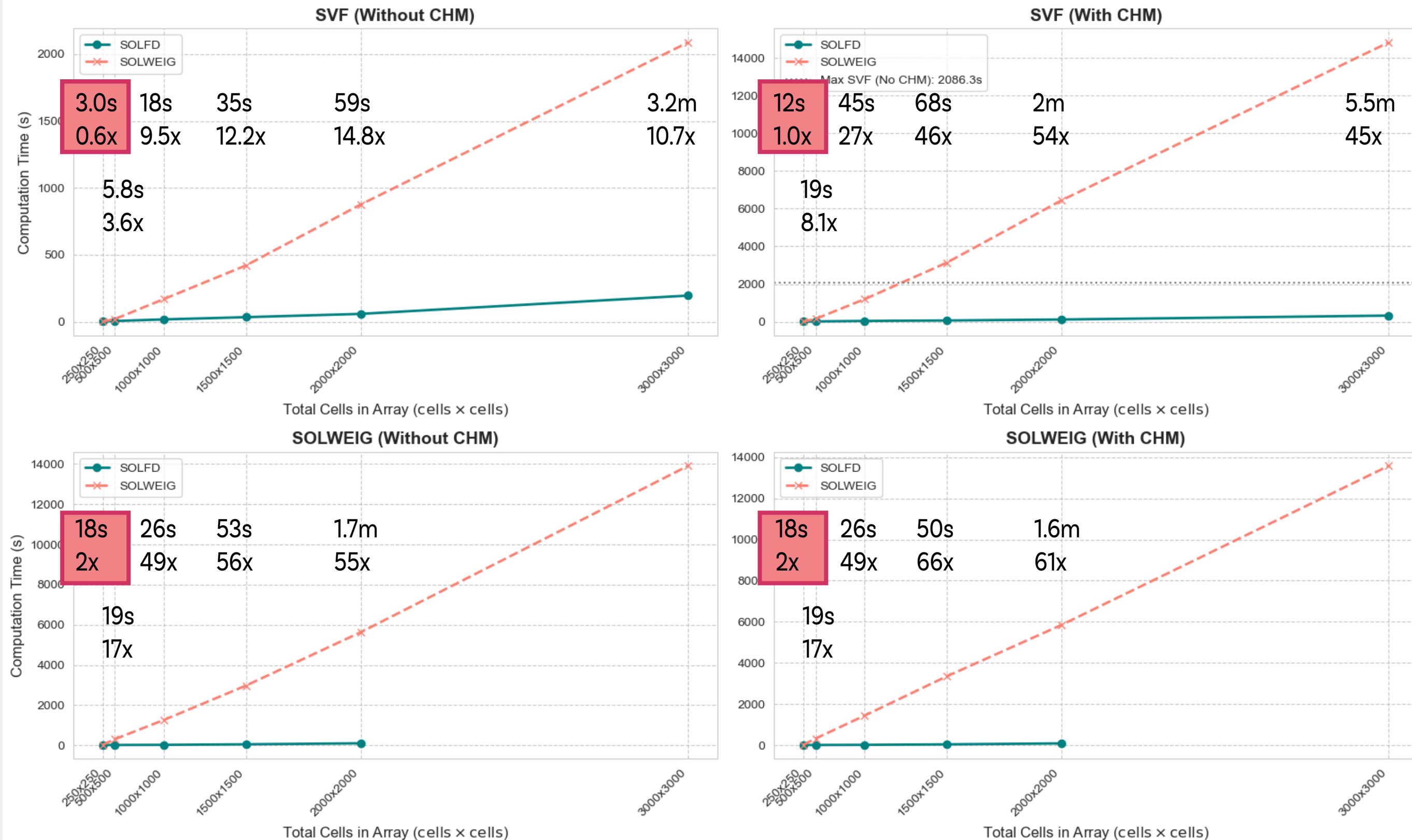
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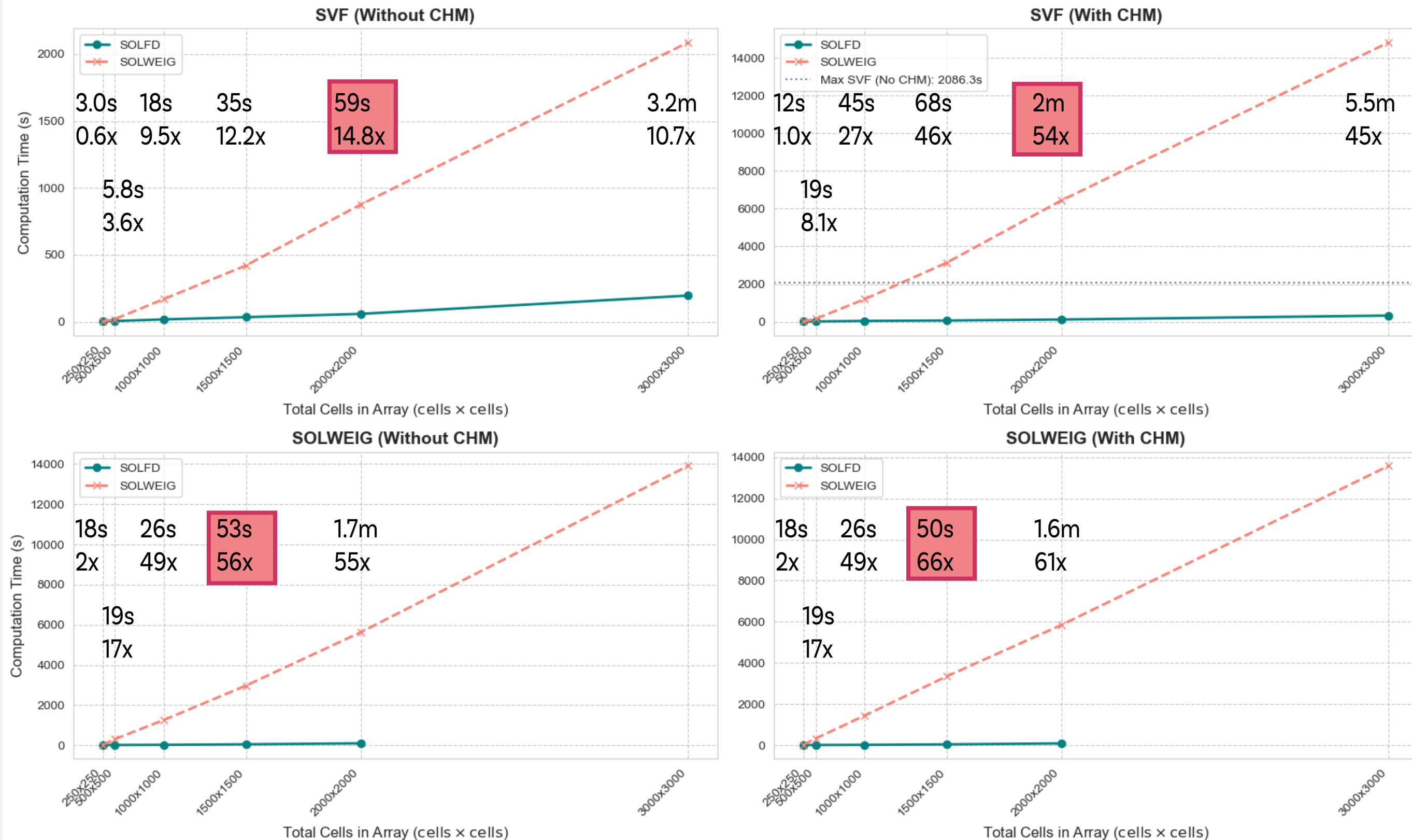
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Accuracy Assessment

RQ2: What does existing research report about the accuracy of SOLWEIG, and how well do the newly implemented 3D modifications perform when validated against sensor data?

Accuracy Assessment

- **SOLWEIG**

- Literature review; strengths, limitations & accuracy metrics
- Divided into:
 - (1) validation studies conducted by the model developers themselves
 - (2) independent research by external groups.

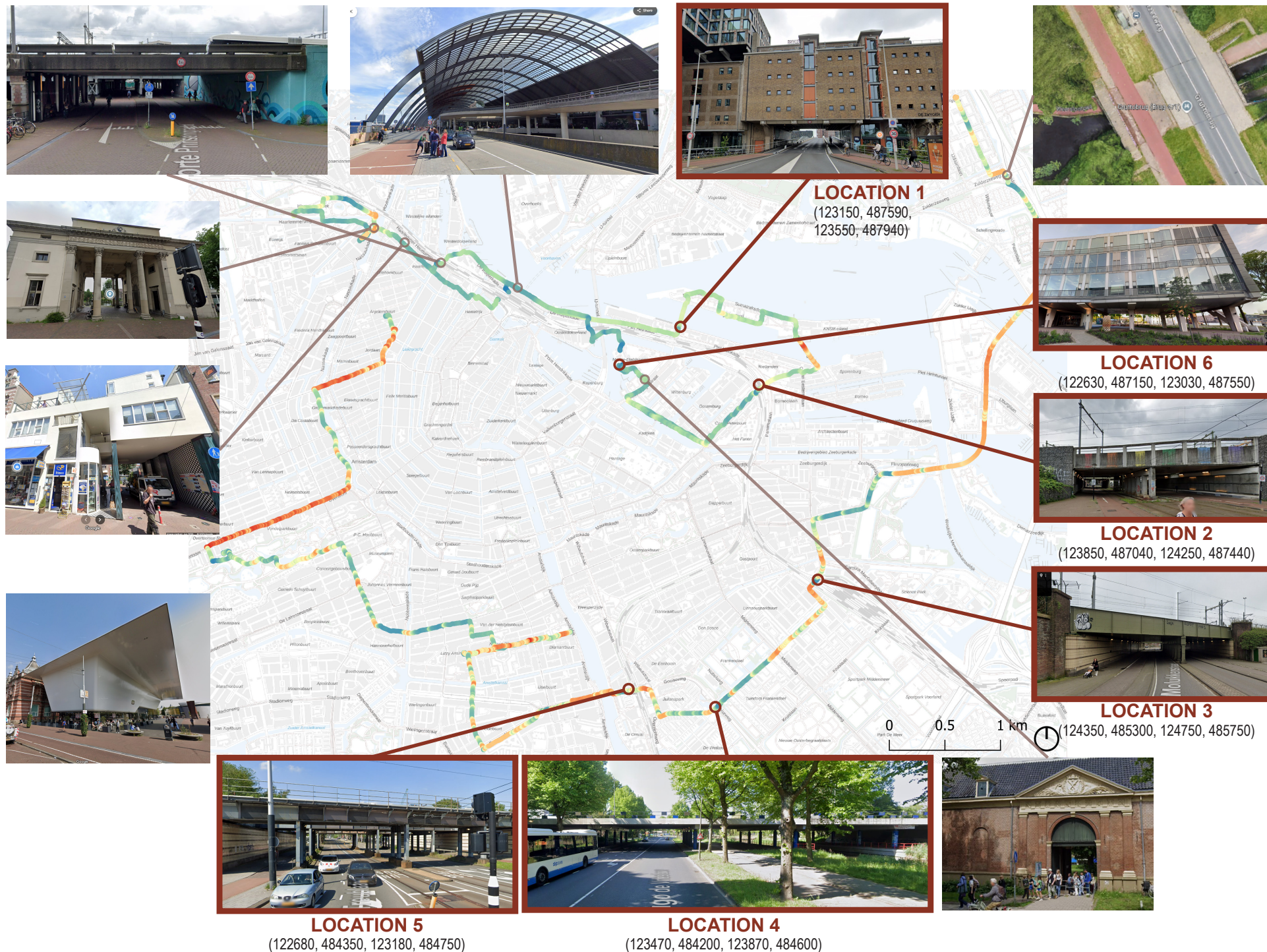
- **SOLFD**

- Climate Bike sensor data
 - six directions of short- & longwave radiation
 - two cycling routes Amsterdam



Accuracy Assessment

- **SOLFD data preperation**
 1. Find locations underneath structures

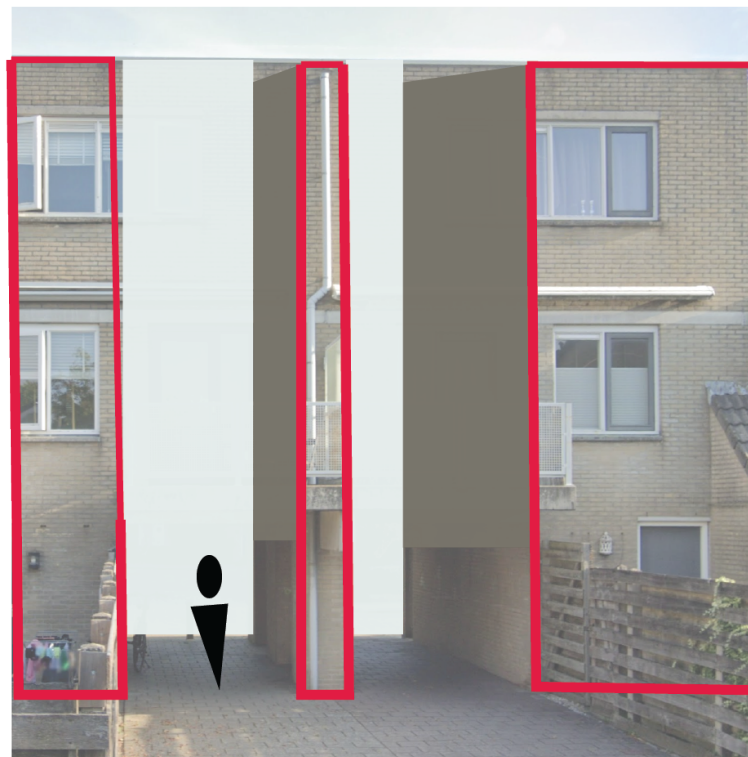


Accuracy Assessment

- **SOLFD data preperation**
 1. Find locations underneath structures
 2. Prepare inputs for three different cases



3D case



Gap case



On-top case

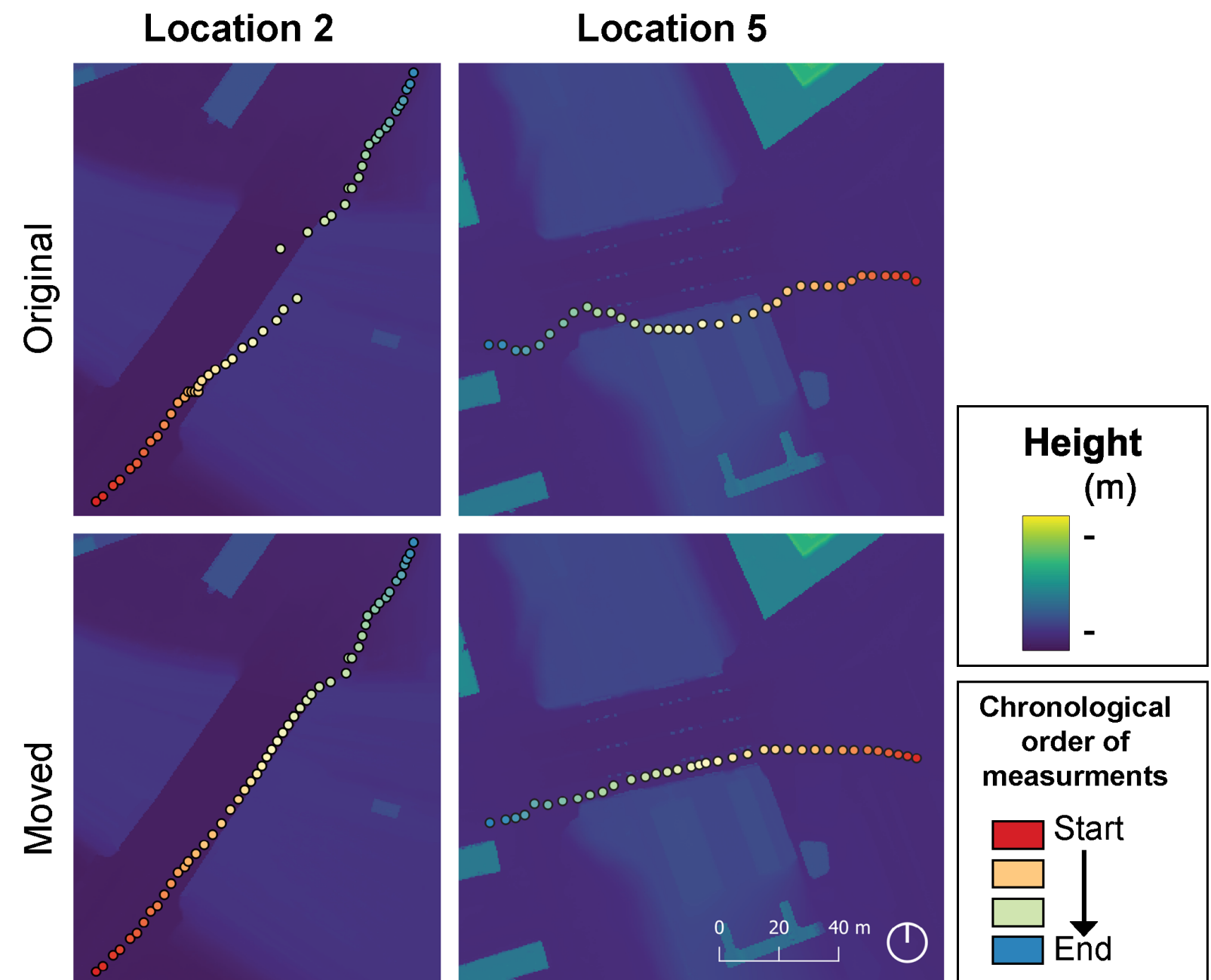
Accuracy Assessment

- **SOLFD data preperation**
 1. Find locations underneath structures
 2. Prepare inputs for three different cases
 3. Prepare the meteorological input data
 - Taken from climate bike, KNMI and AAMS

Accuracy Assessment

- **SOLFD data preperation**

1. Find locations underneath structures
2. Prepare inputs for three different cases
3. Prepare the meteorological input data
4. Prepare the climate bike data



Accuracy Assessment

- SOLWEIG**

Accuracy from Developers

Study / Version	n	R ²	RMSE
Lindberg and S. Grimmond (2011) v2.0	205	0.93 / 0.91	6.79 / 3.1
Lindberg et al. (2016), v2015a	200	0.92 / 0.86	4.42 / 4.68
Wallenberg et al. (2023) v2022a	-	0.9	4.6

Accuracy from Others

Study / Version	n	R ²	RMSE
Thom et al. (2016) v2014a	975	0.93 / 0.91	5.06
Gál and Kántor (2020) v2019a	98	0.92	5.02
Buo et al. (2023) v2021a	763	0.83	5.59

Accuracy Assessment

- SOLWEIG**

Accuracy from Developers

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RMSE

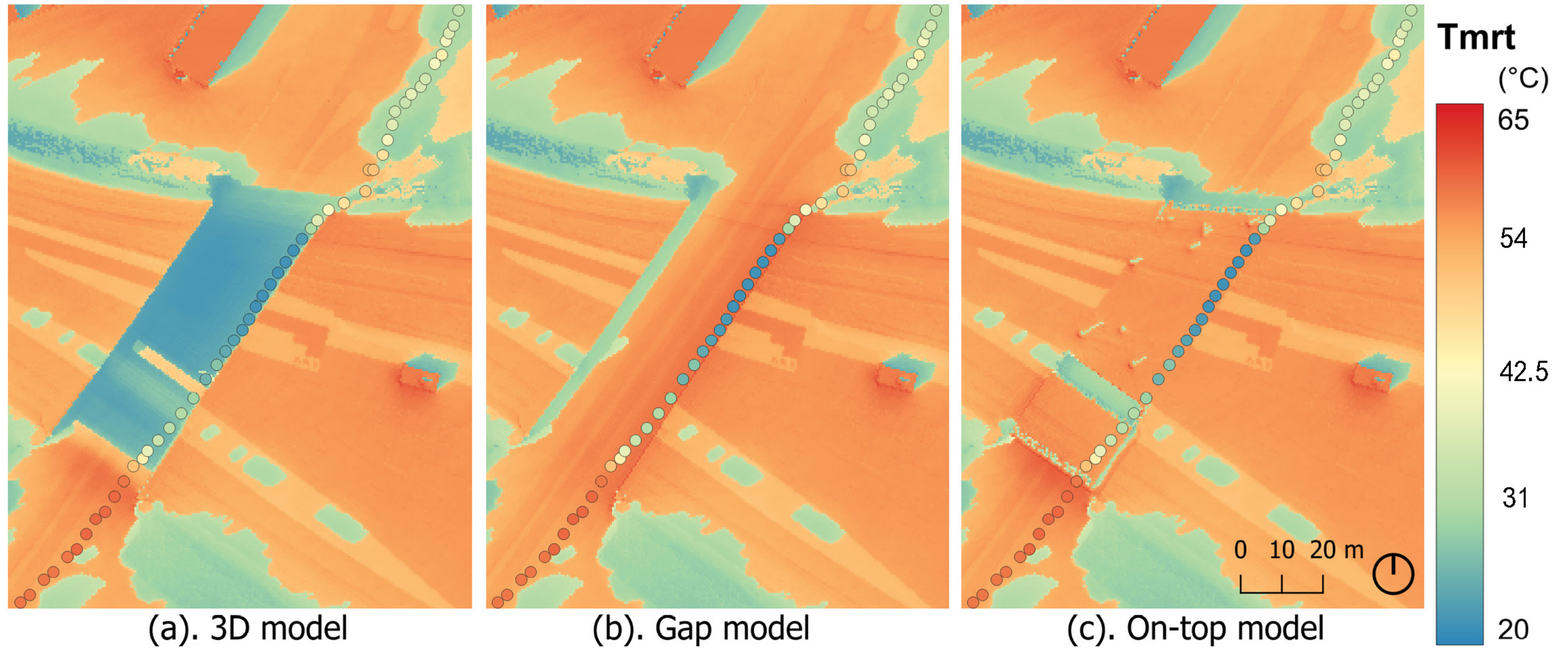
3.1 °C - 6.79 °C

R²

0.83 - 0.93

Accuracy Assessment

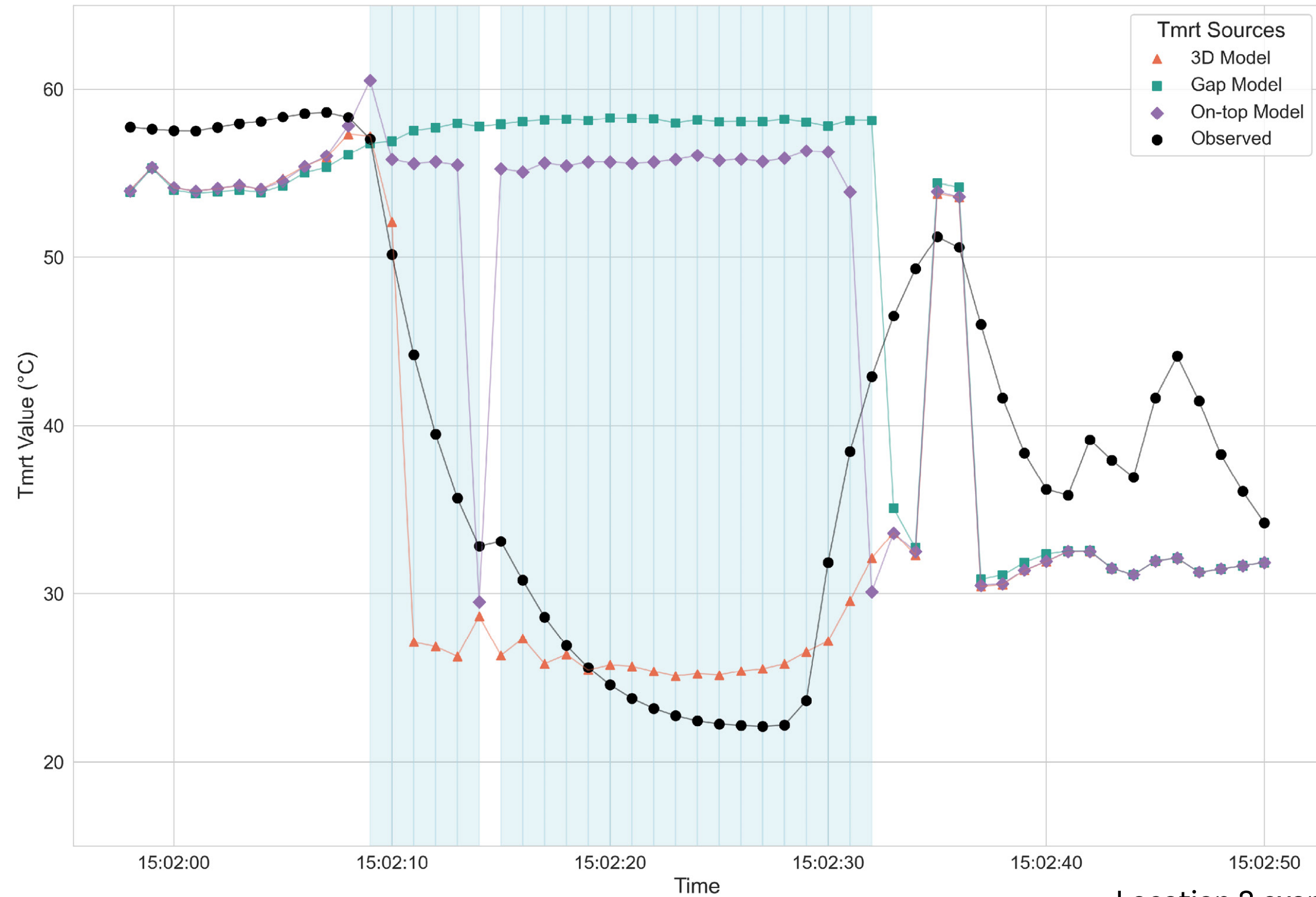
- SOLFD**



Location 3 example

Accuracy Assessment

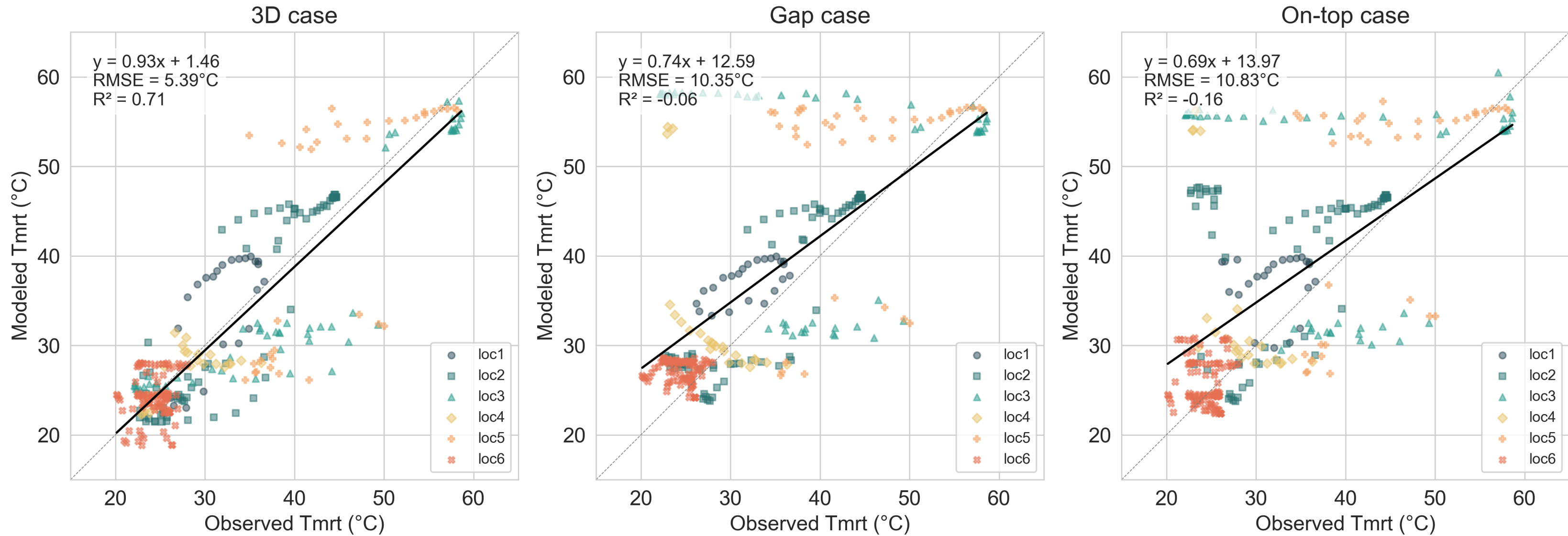
- SOLFD**



Location 3 example

Accuracy Assessment

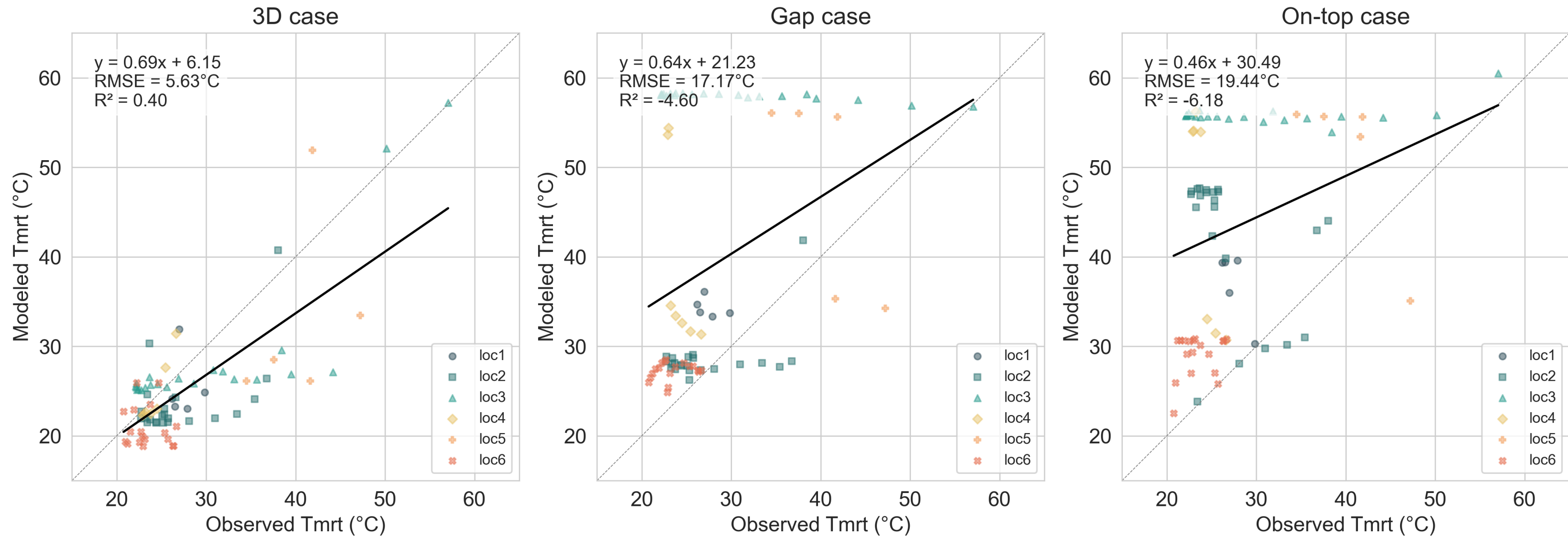
- SOLFD**



Tmrt Modeled vs observed for all three cases
n= 312

Accuracy Assessment

- SOLFD**



Tmrt Modeled vs observed for all three cases underneath structures

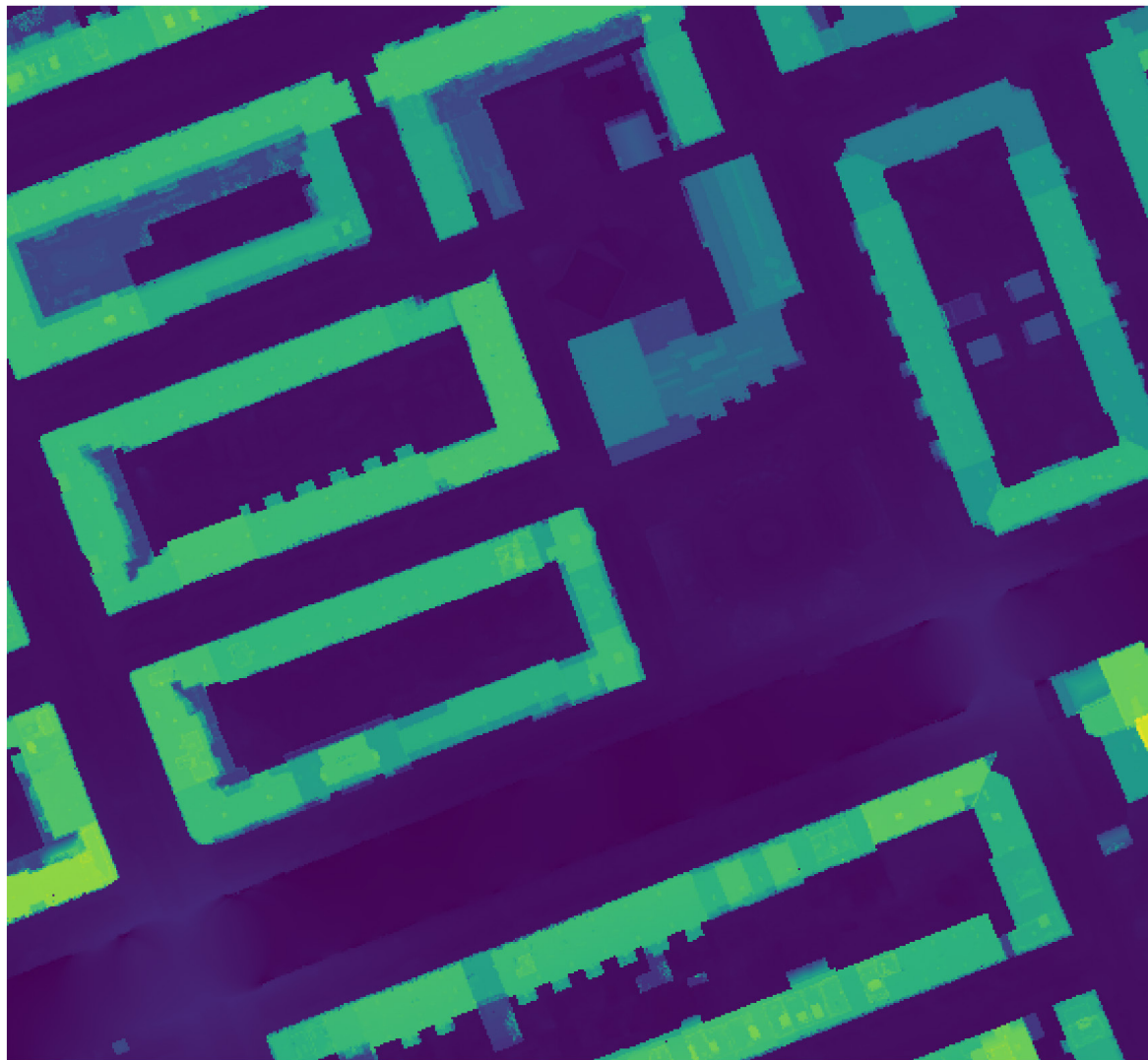
n= 79

SOLFD Case study

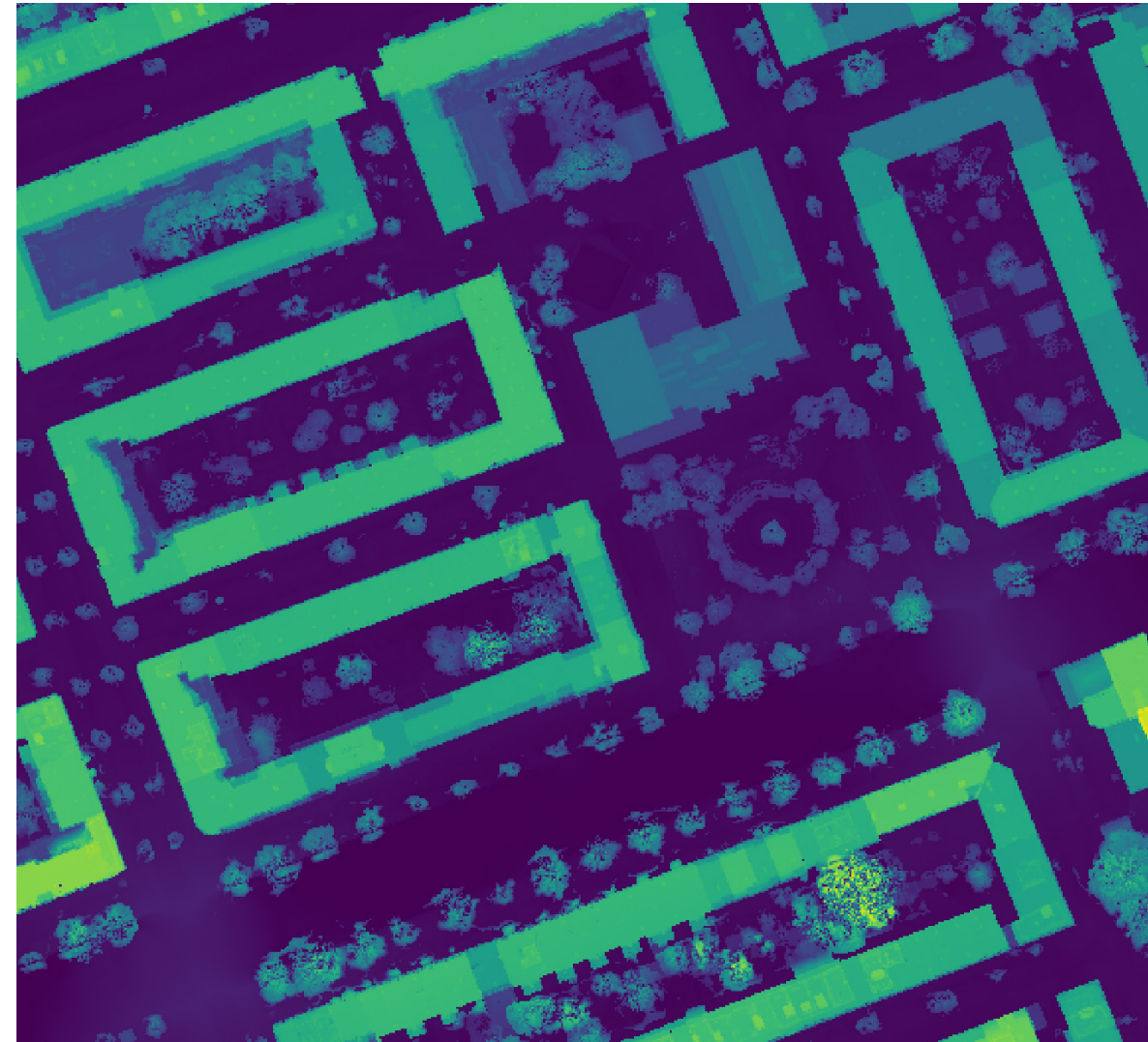
RQ3: How can the tool be used to analyze the effects of urban design proposals on microclimatic conditions and outdoor thermal comfort in various Dutch urban typologies?

SOLFD Case study

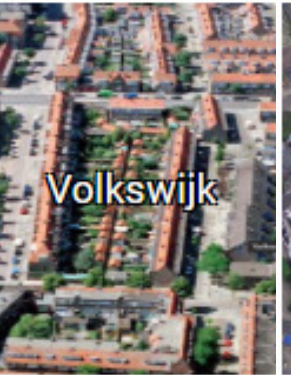
1. Current Situation Without Trees



2. Current Situation With Trees



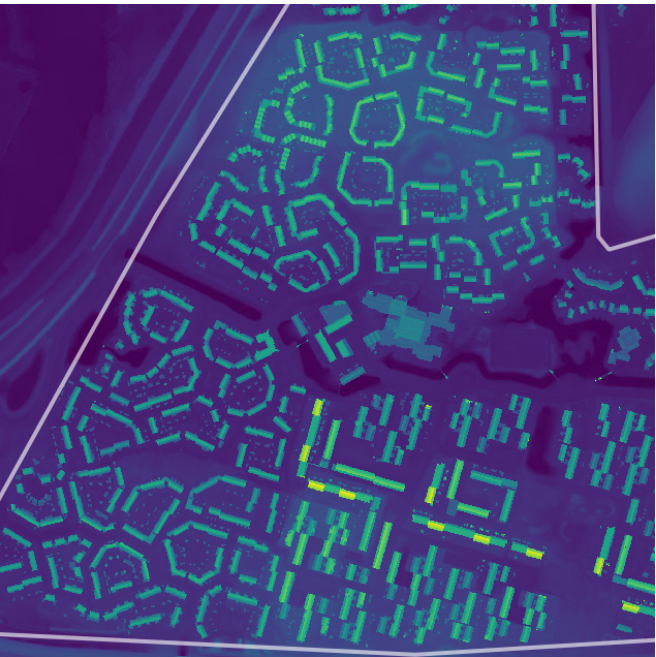
SOLFD Case study

						
 Bouwjaar	 Voor 1910	 1890-1940	 1910-1940	 1910-1940	 1970-1990	 1990-2010
 Hoogte	 3 tot 5 lagen	 4 tot 6 lagen	 2 tot 3 lagen	 2 tot 3 lagen	 3 tot 5 lagen	 3 tot 10 lagen
 Groen	 10-22%	 18-26%	 20-35%	 14-26%	 28-42%	 17-35%
 Hitte	 Hoog	 Hoog	 Hoog	 Hoog	 Midden	 Midden

Tuindorp



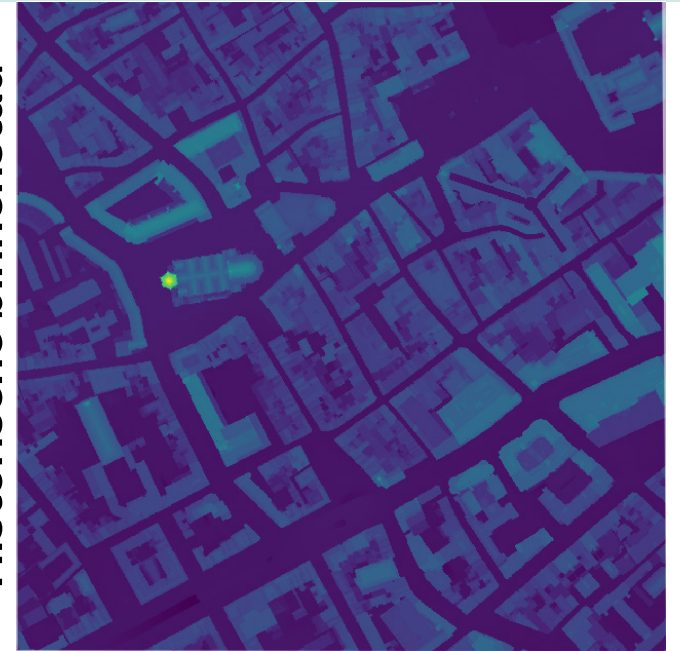
Bloemkoolwijk



Vinex-wijk



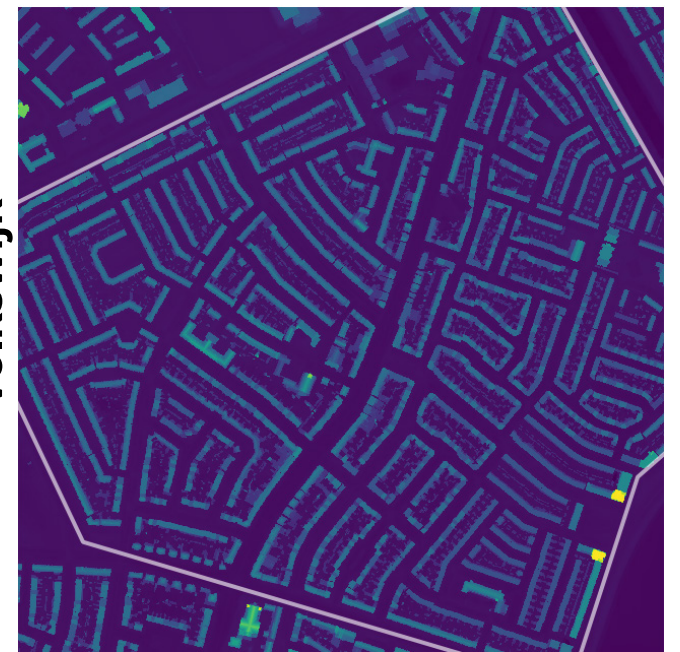
Historische binnenstad



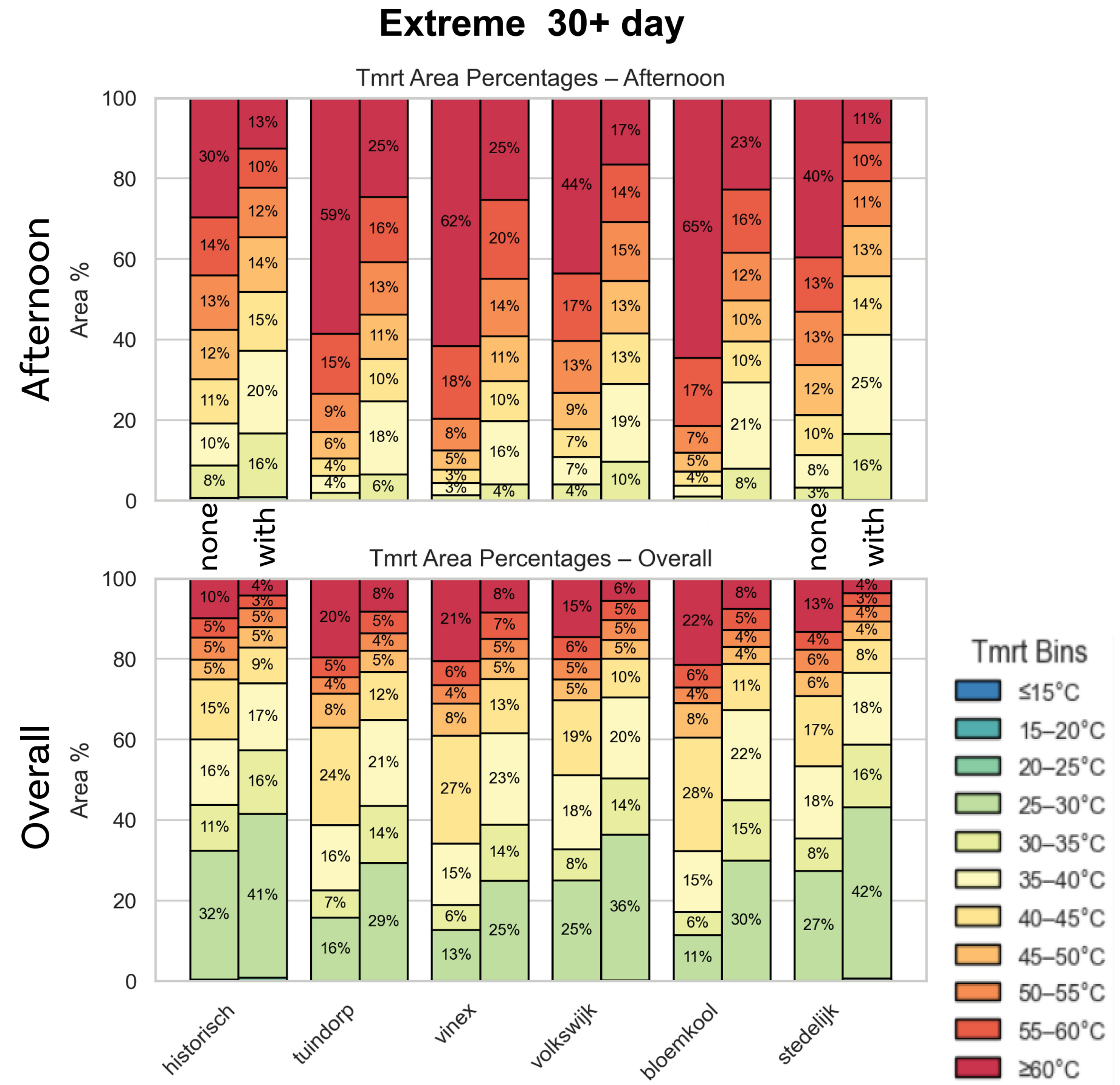
Stedelijke Bouwblok



Volkswijk



SOLFD Case study



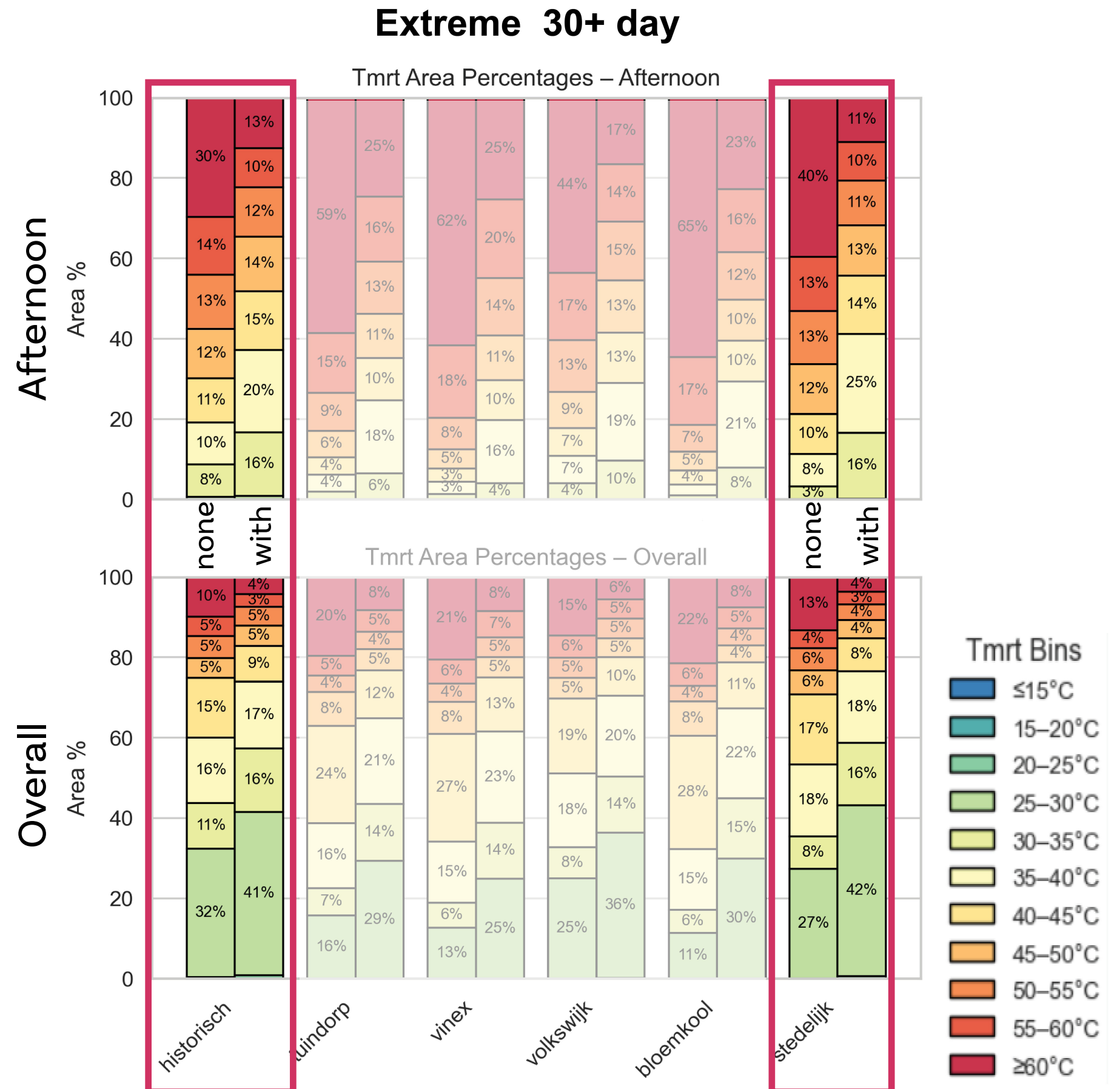
SOLFD Case study

- Historisch

- Average without trees: **51.8 °C**
- Average with trees: **45.9 °C**
-5.9 °C

- Stedelijk

- Average without trees: **54.5 °C**
- Average with trees: **45.1 °C**
-9.4 °C



SOLFD Case study

- Tuindorp

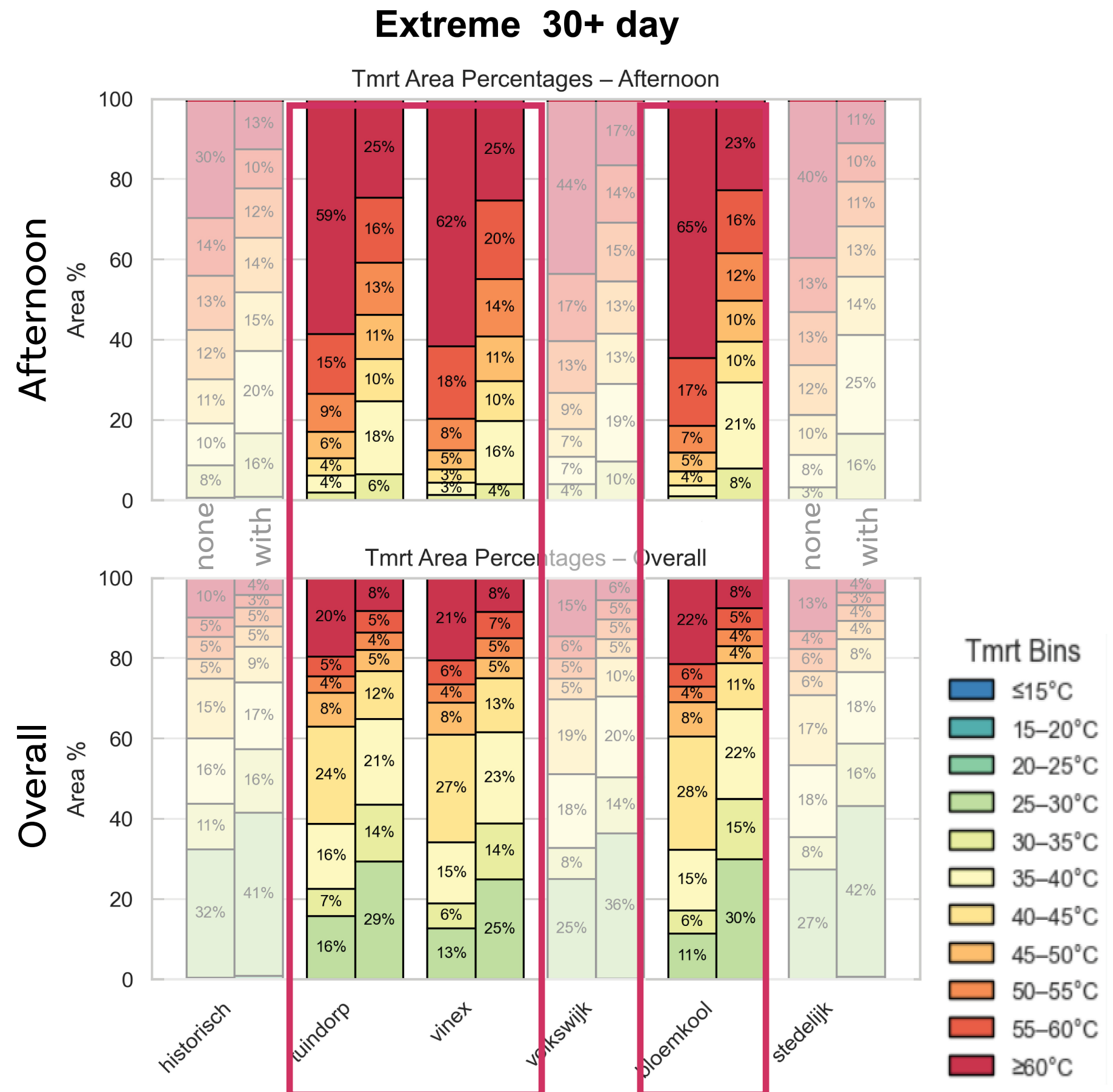
- Average without trees: **58.4 °C**
- Average with trees: **50.4 °C**
-8.0 °C

- Vinex

- Average without trees: **59.0 °C**
- Average with trees: **51.5 °C**
-7.5 °C

- Bloemkool

- Average without trees: **59.3 °C**
- Average with trees: **49.4 °C**
-9.9 °C



Objective

To develop a framework for a tool (SOLFD), based on the SOLWEIG model, that enables designers to visualize current urban climate conditions at the neighborhood scale in the Netherlands and to evaluate, visualize and compare the potential impacts of proposed designs on these conditions for the human comfort.

The created SOLFD framework allows users to:

- Simulate and assess (3D) urban designs using **automated Dutch geospatial data**
- Modify existing scenes by editing and inserting **trees, (3d) buildings**, and **materials**
- **Visualize** (in)direct solar radiation effects via MRT and PET
- Evaluate design proposals with **MRT** maps, **PET** maps and comparison **statistics**
- Run simulations in **2–5 minutes** using GPU acceleration
- Achieve 3D accuracy with RMSE of **5.39–5.63 °C**

Contributions

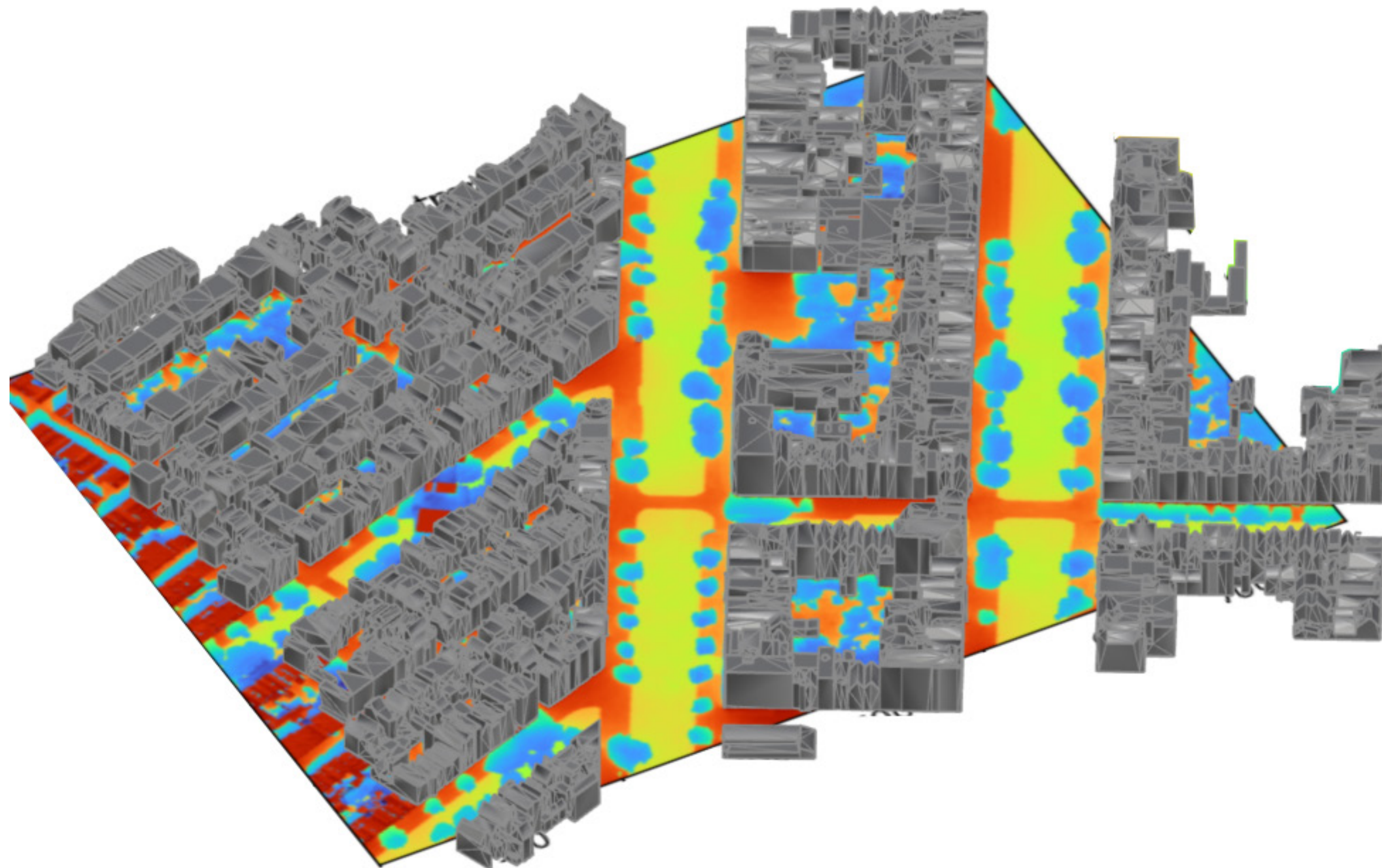
- Progress towards a truly 3D implementation of SOLWEIG
- Substantial acceleration of SOLWEIG through GPU integration
- Automated pipeline for Dutch geospatial datasets
- SOLWEIG support for modified and new urban scenarios
- Bringing SOLWEIG closer to practical use in urban design

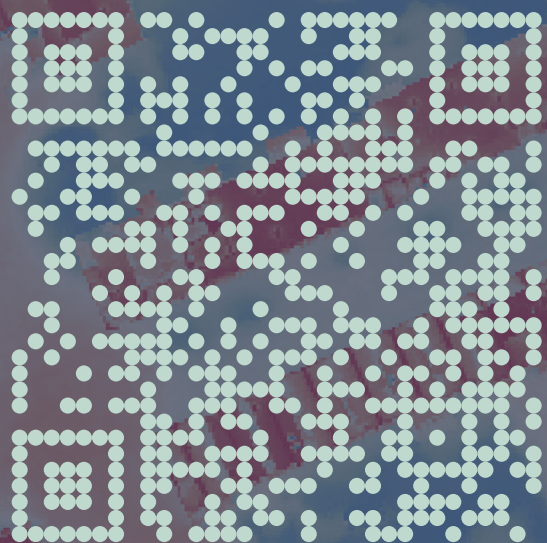
Limitations

- No validation with design practitioners
- Exclusion of localized wind data
- Limited support for design guidance
- Model input limitations; trees, materials & only the Netherlands
- Missing radiative effects of above-head surfaces

Future Work

- No validation with design practitioners
 - > Discuss, test and evaluate with design practitioners
 - Exclusion of localized wind data
 - > Include fast wind model
 - Limited support for design guidance
 - > Include design suggestions
 - Model input limitations; trees, materials & only the Netherlands
 - > Other CHM method, add more materials to SOLWEIG, add global datasets
 - Missing radiative effects of above-head surfaces
 - > Update radiation scheme of SOLWEIG
- + Framework -> Usable Tool





COOL BY DESIGN

SOLFD: Extending SOLWEIG for Urban Design
Decision Making on Outdoor Thermal Comfort

Jessica Monahan
4994809
19/06/2025

1st Supervisor	Dr. C. García-Sánchez
2nd Supervisor	Dr. H. Ledoux
Delegate	Ir. E. Verbree

- 1 Klimaateffectatlas. (2024). *KNMI'23-klimaatscenario's*. Retrieved January 19, 2025, from <https://www.klimaateffectatlas.nl/nl/klimaatscenarios>
- 2 Nationale Hittestresskaart. (2024). *Nationale Hittestresskaart*. Retrieved June 17, 2025, from <https://www.nationalehittestresskaart.nl>
- 3 Yang, S., Wang, L., Stathopoulos, T., & Marey, A. M. (2023). Urban microclimate and its impact on built environment – A review. *Building and Environment*, 238, 110334. <https://doi.org/10.1016/j.buildenv.2023.110334>
- 4 Orbital Stack. (2023, September 20). *Choosing the right path to comfort: Comparing UTCI and SPMV thermal comfort indexes*. Retrieved June 17, 2025, from <https://orbitalstack.com/choosing-the-right-path-to-comfort-comparing-utci-and-spmv-thermal-comfort-indexes/>
- 5 Carmona, M., Heath, T., Oc, T., and Tiesdell, S. (2010). “Part 1 - Defining Urban Design”. In: *Public Places - Urban Spaces: The Dimensions of Urban Design*. 2nd. Taylor & Francis Group, pp. 3–74.
- 6 Badino, E., Ferrara, M., Shtrepi, L., Fabrizio, E., Astolfi, A., & Serra, V. (2021). Modelling mean radiant temperature in outdoor environments: Contrasting the approaches of different simulation tools. *Journal of Physics: Conference Series*, 2069(1), 012186. <https://doi.org/10.1088/1742-6596/2069/1/012186>
- 7 Heusinkveld, B. G., Steeneveld, G.-J., Holtslag, B., Hove, B., and Jacobs, C. (2013). Spatial variability of the Rotterdam urban heat island as influenced by urban land use. *Journal of Geophysical Research*, 119, pp. 677–692. DOI: 10.1002/2012JD019399.
- 8 Brozovsky, J., Simonsen, A., & Gaitani, N. (2021). Validation of a CFD model for the evaluation of urban microclimate at high latitudes: A case study in Trondheim, Norway. *Building and Environment*, 205, 108175. <https://doi.org/10.1016/j.buildenv.2021.108175>
- 9 Klimaateffectatlas (2023). *Wijktypologie*. Retrieved January 14, 2025, from <https://www.klimaateffectatlas.nl/nl/wijktypologie>.