High-resolution, large-scale, and fast calculation of solar irradiance with 3D City Models

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Delegate: Azarakhsh Rafiee

Content

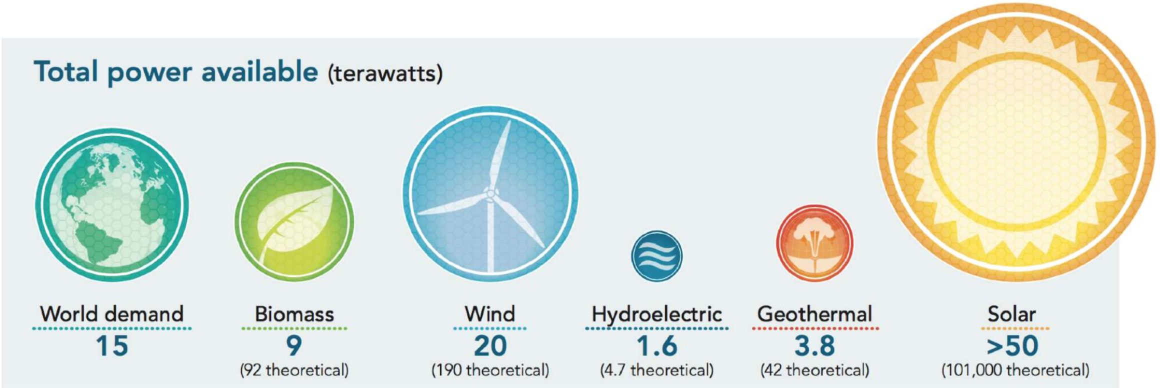
- Research background & Objective
- Related Work
- Methodology
- Results & Discussion
- Conclusions

Research background & Objective

Research background & Objective

Why predicting solar irradiance is important?

Global Energy Contribution

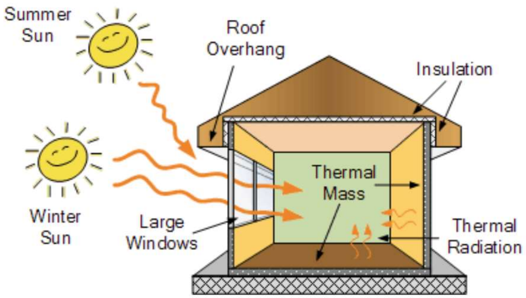


Adrian C. (2010)

Urban Flexibility

https://rmi.org/insight/page/28/

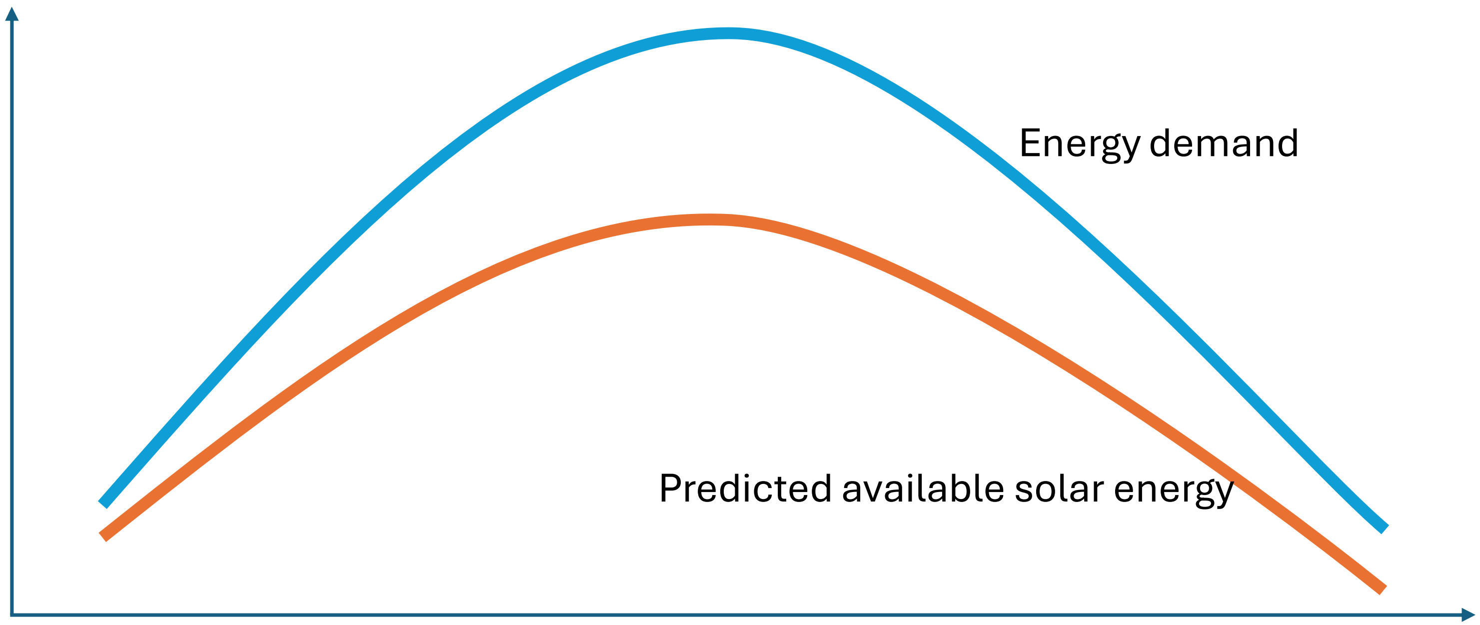
Impact on Urban Climate and Human Behavior



https://au.pinterest.com/pin/passive-solar-building-design-360-building-solutions--718394578055713790/

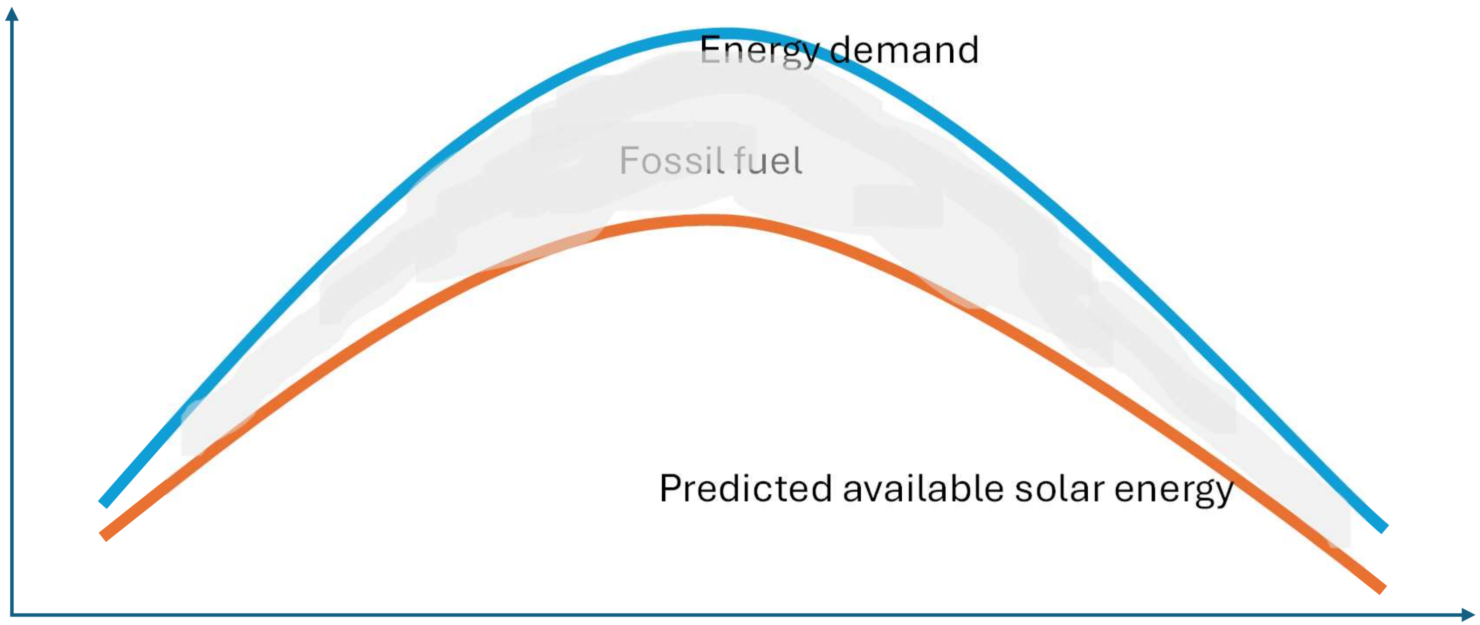
Research background & Objective

Why predicting solar irradiance is important?



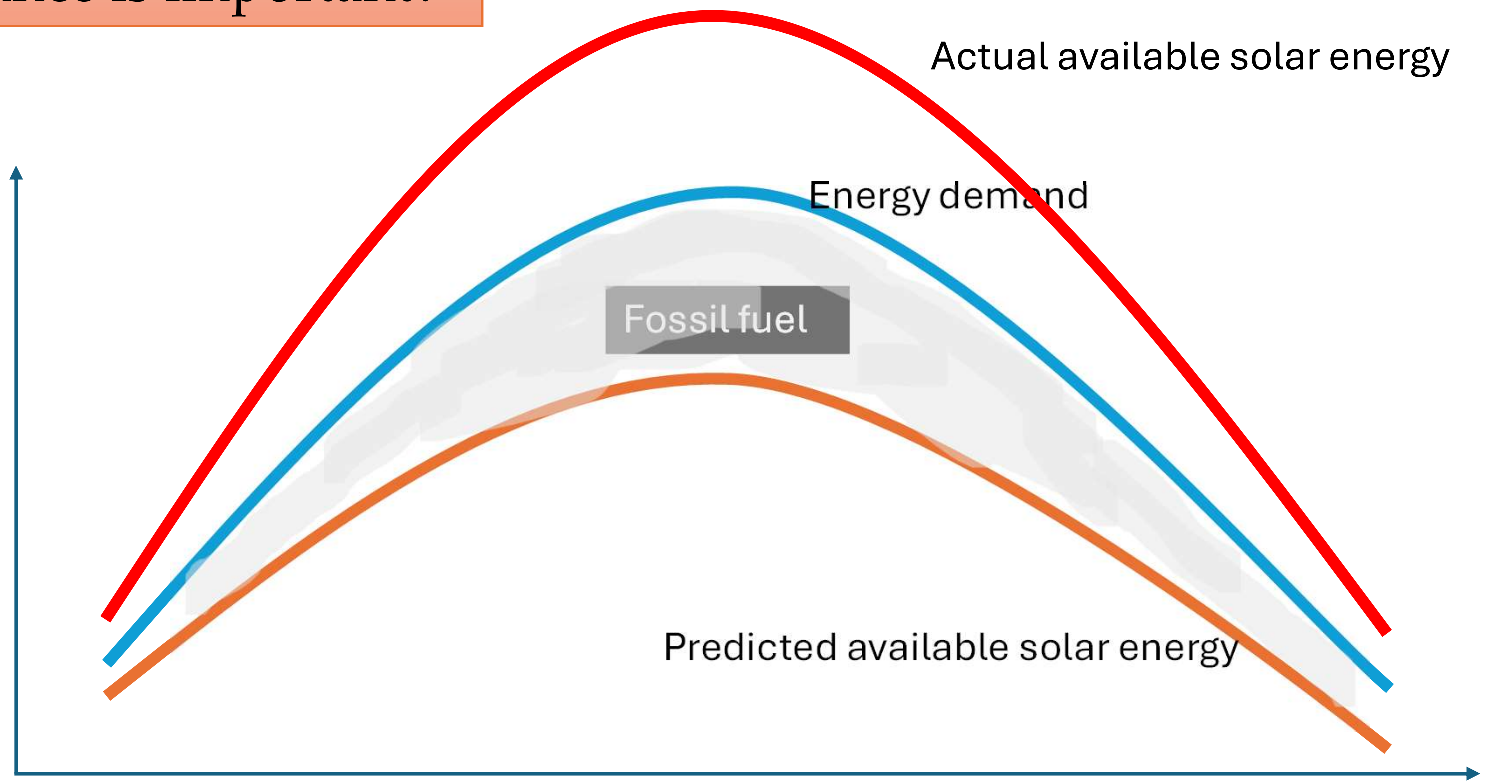
Research background & Objective

Why predicting solar irradiance is important?



Research background & Objective

Why predicting solar irradiance is important?

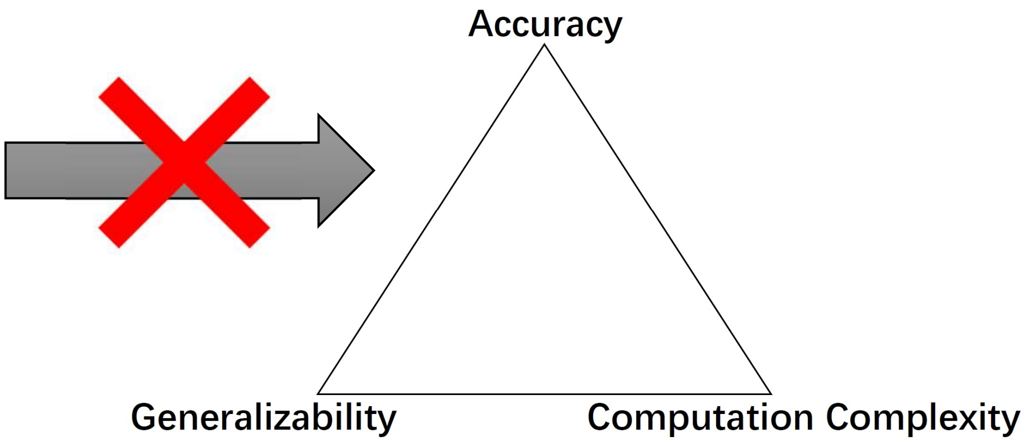


Research background & Objective

What is the research gap?

Total Irradiance = Direct Beam + Diffuse + Reflected

Shadowing effect   Visible sky patches   Ray tracing



Research background & Objective

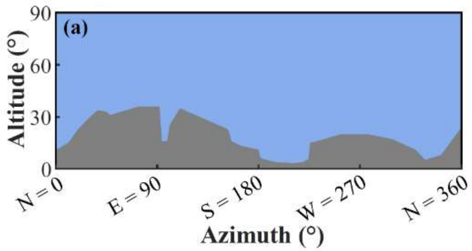
How can a solar irradiance simulation method be developed to balance accuracy and computational efficiency for city-scale simulations while utilizing semantic information from 3D city models?

- In what ways can semantic data derived from 3D city models refine the precision of solar irradiance simulations by considering the direct, diffuse and reflected solar components?
- What are the potential trade-offs between accuracy and computation simplification when utilizing 3D city models for estimating solar irradiance at an urban scale?

Related Work

Related Work: Viewshed-based methods

(a) The scene

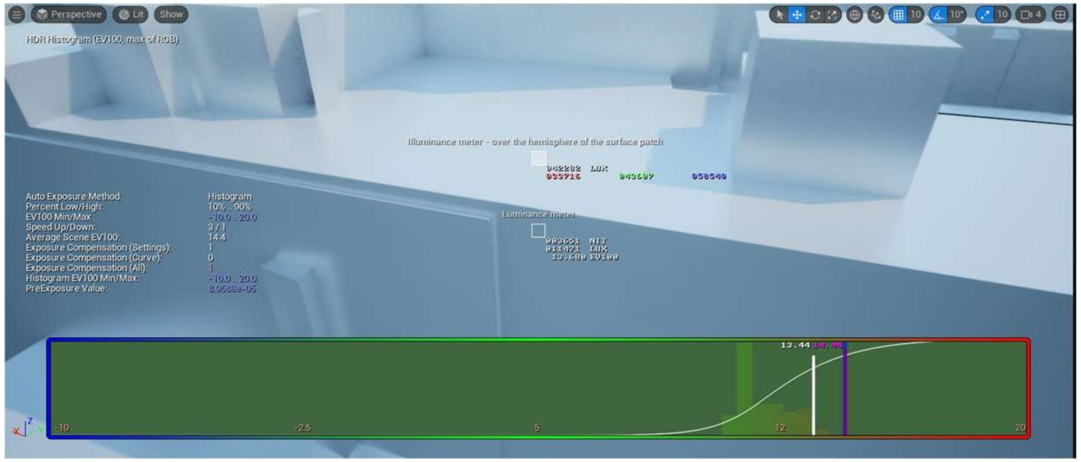


(b) The resulting viewshed

Calcabrini, A. (2023)

- Simplified surroundings
- Inaccurate shadowing effect
- Lack of support for 3D data

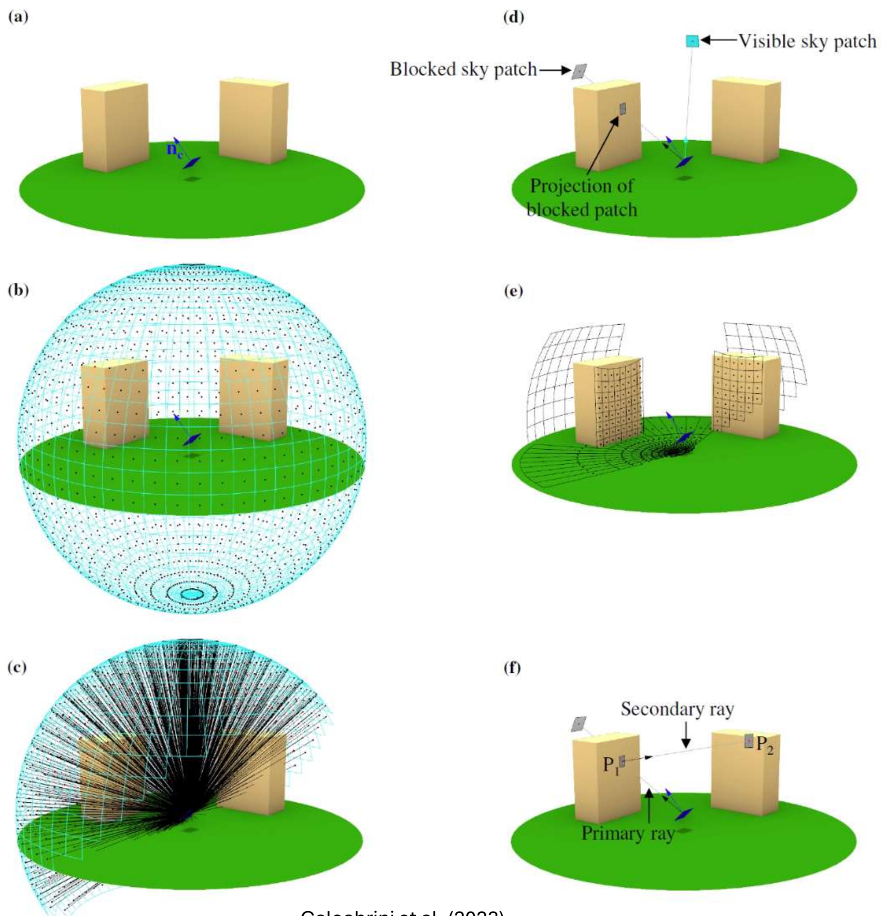
Related Work: Pixel counting methods



Meines, S. (2023)

- Black/Grey box mechanism
- Low generalizability

Related Work: Ray Tracing based methods



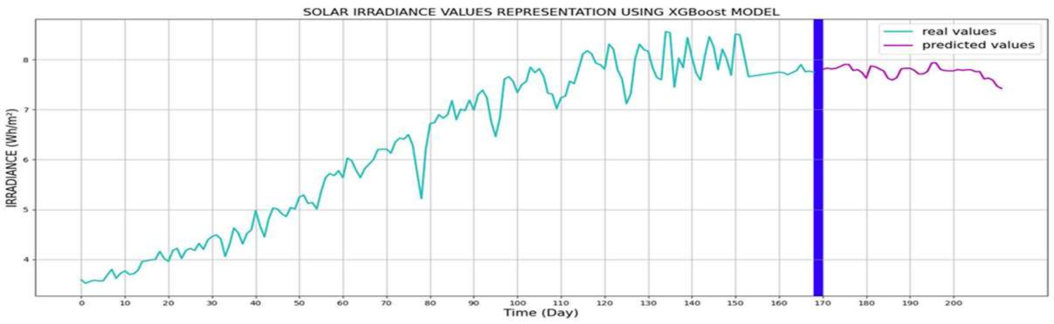
Calcabrini et al. (2023)

- Computational expensive

Related Work: Empirical methods

$$I_T = I_{h,b}R_b + I_{h,d}\left[(1 - F_1)\left(\frac{1+\cos\beta}{2}\right) + F_1\frac{a}{b} + F_2\sin\beta\right] + I_h\rho\left(\frac{1-\cos\beta}{2}\right)$$

Perez, R. (1987)

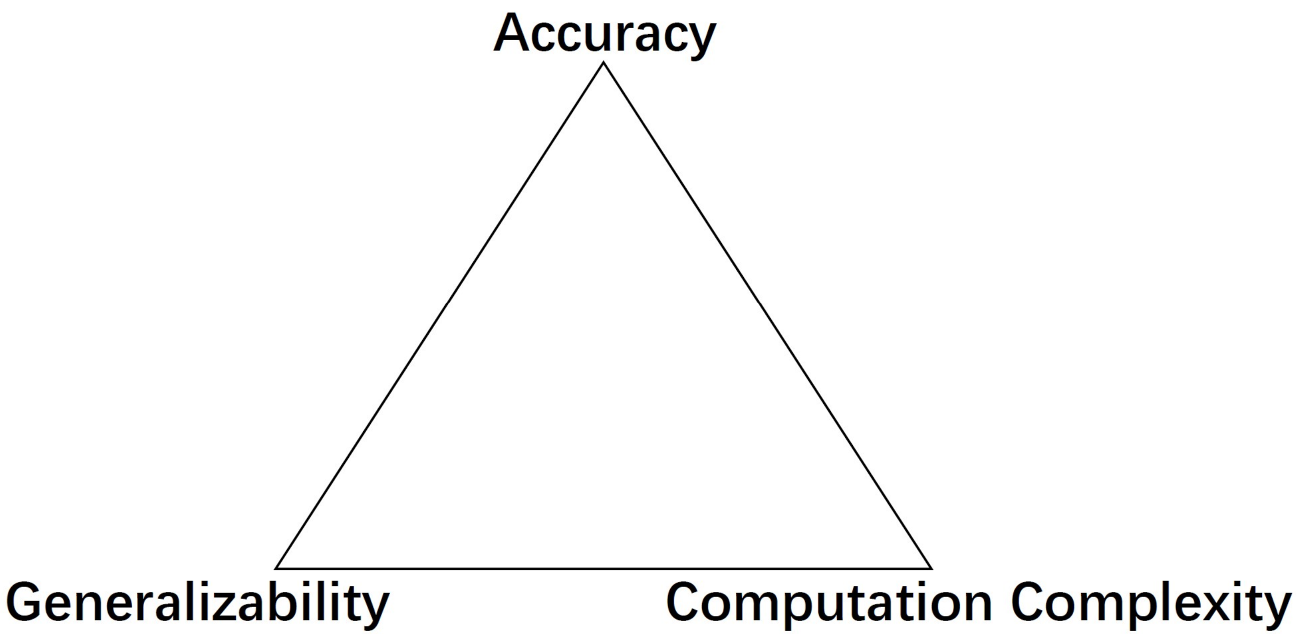


Tercha et al. (2024)

- Low accuracy
- Low generalizability

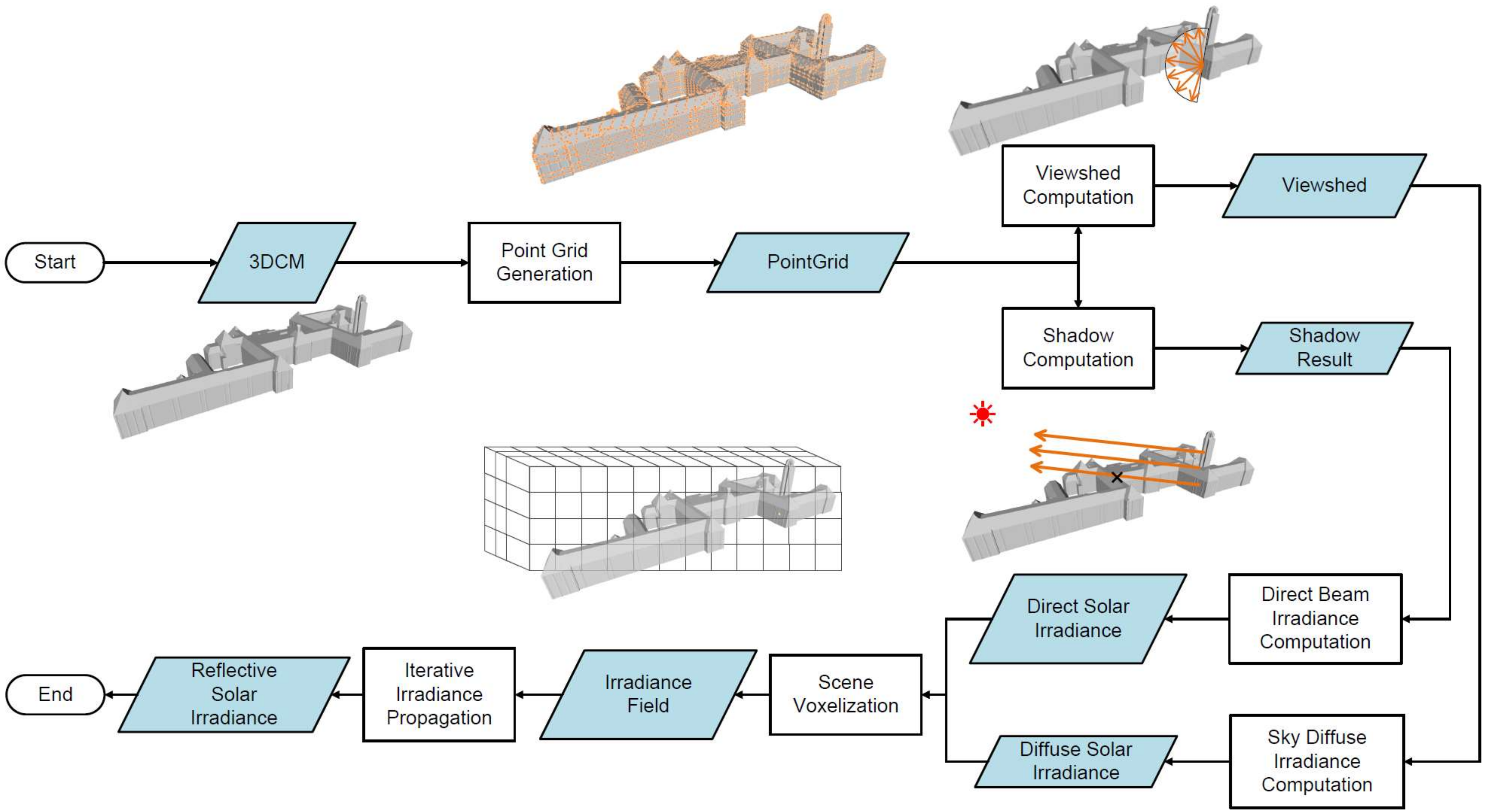
Related Work: Summary

The “impossible” triangle

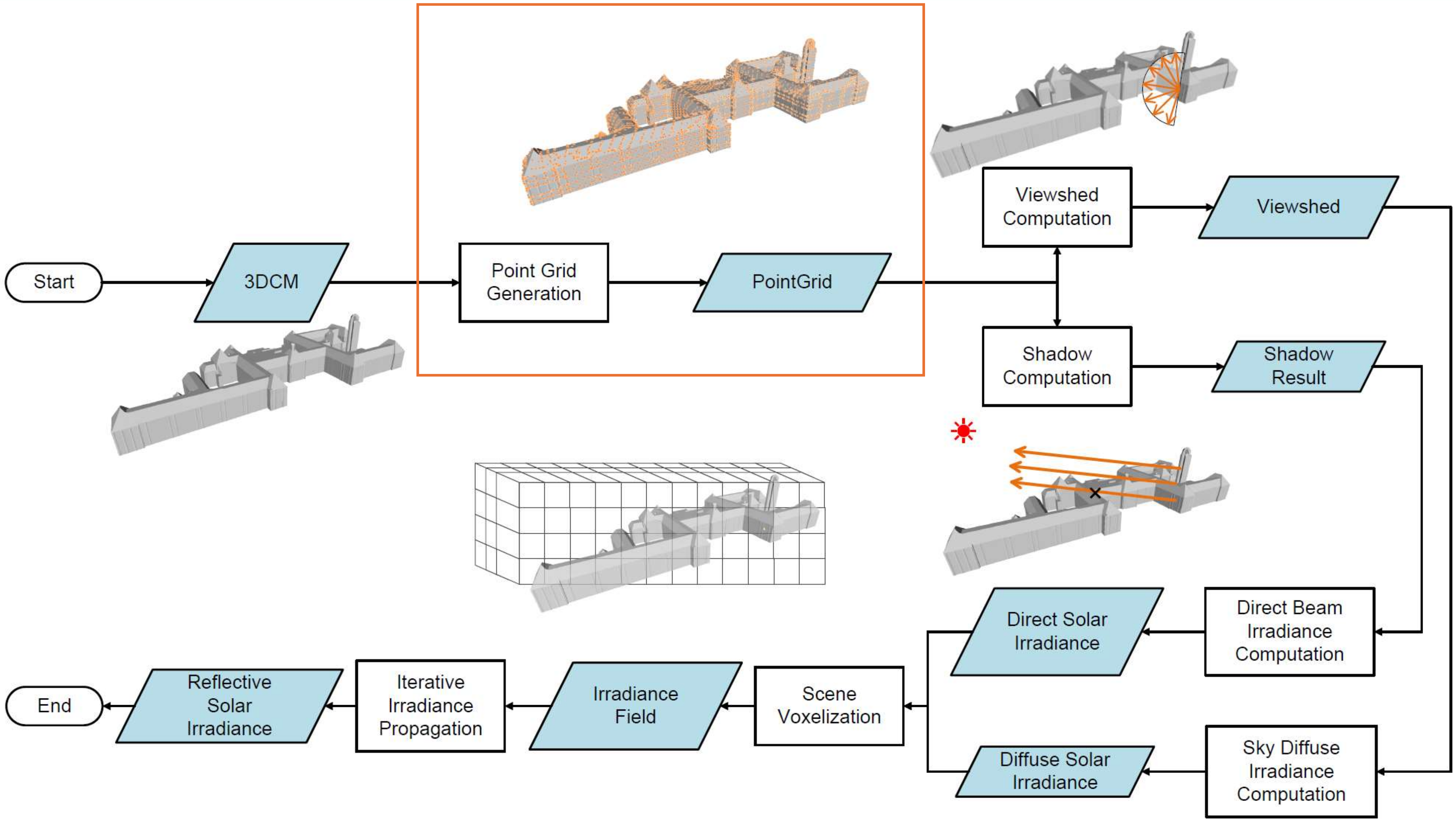


Methodology

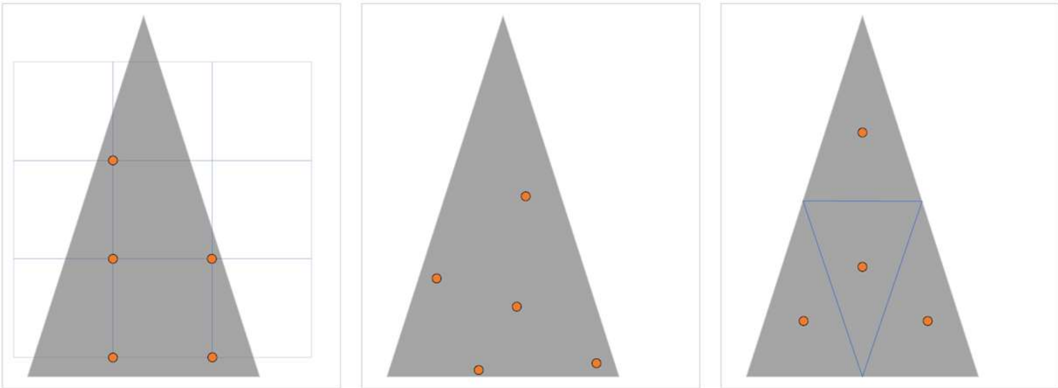
Methodology



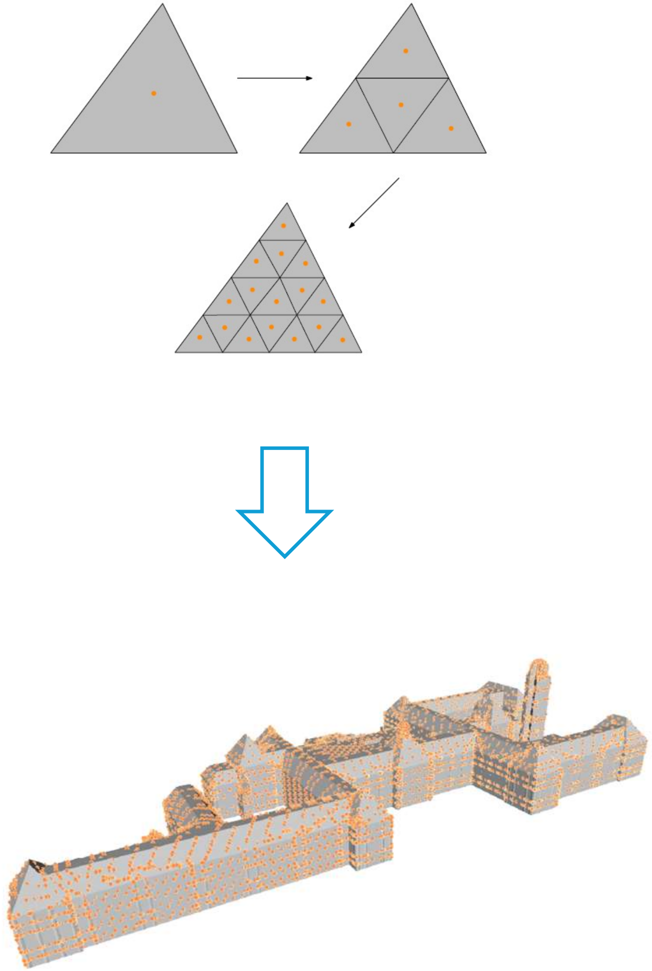
Methodology: Point Grid Generation

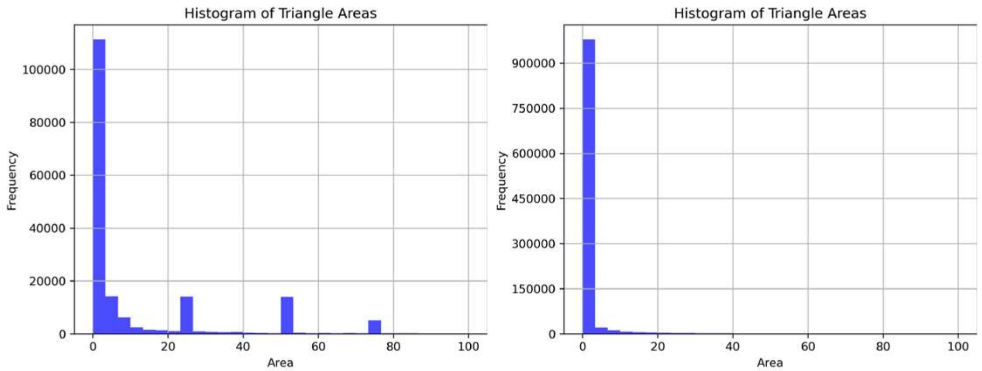


Methodology: Point Grid Generation



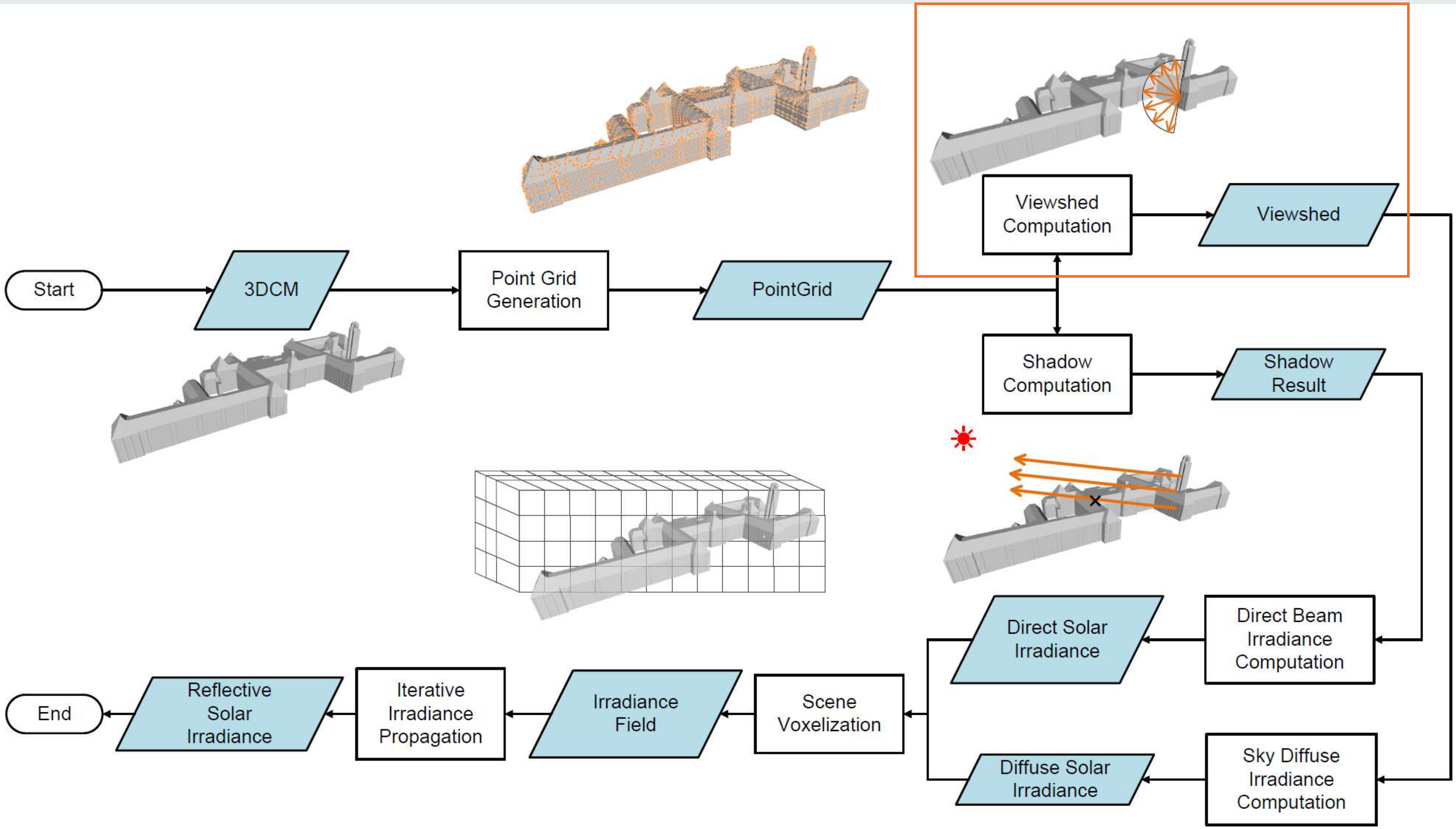
(a) Grid sampling (b) PDF sampling (c) Split sampling





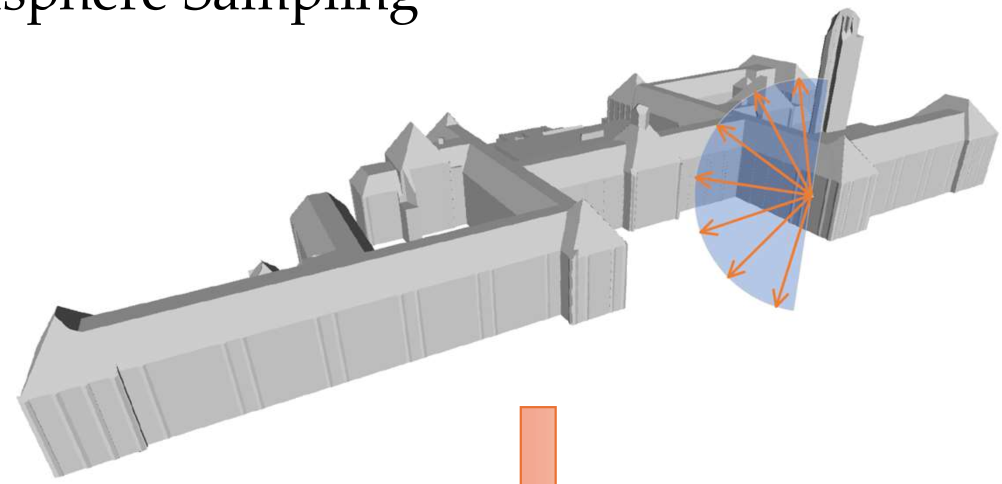
(a) Heino weather station dataset (b) TU Delft dataset

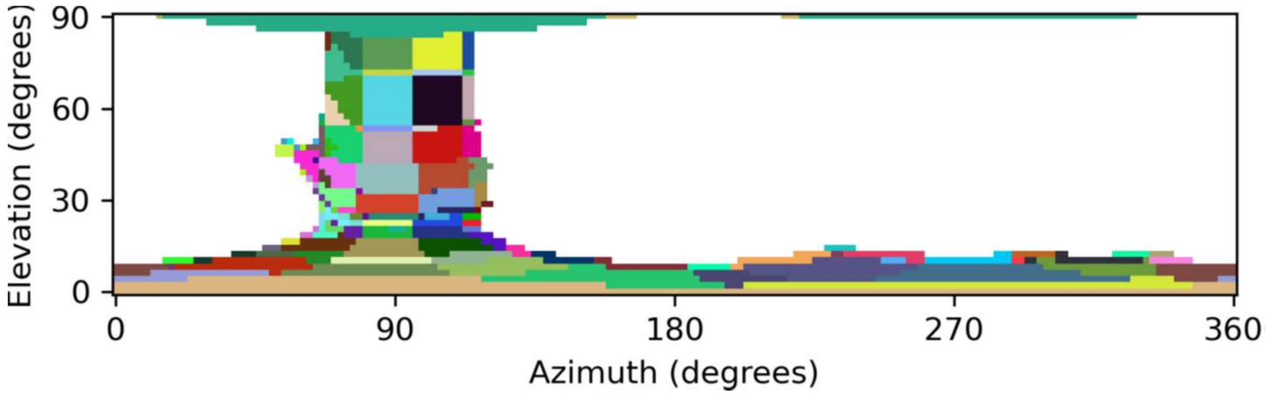
Methodology: Viewshed Computation



Methodology: Viewshed Computation

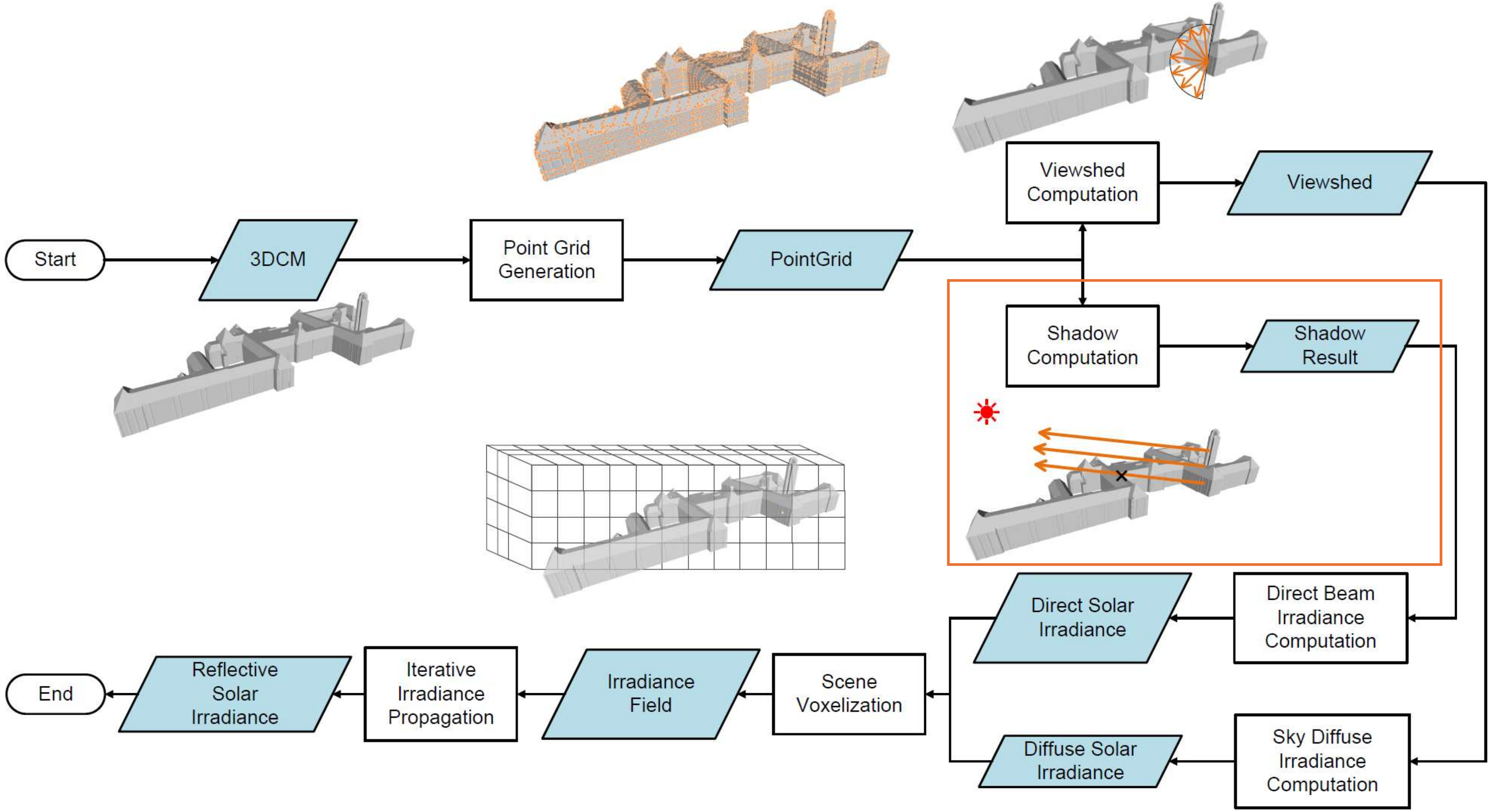
Hemisphere Sampling





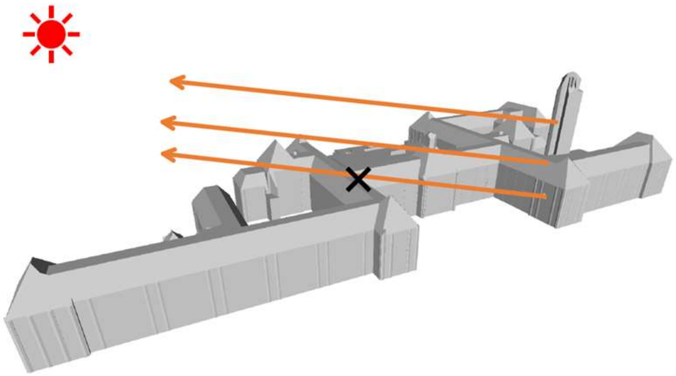
- Object ID
- Surface ID
- Object type
- Surface type
- Sky View Factor
- Ground View Factor
- …

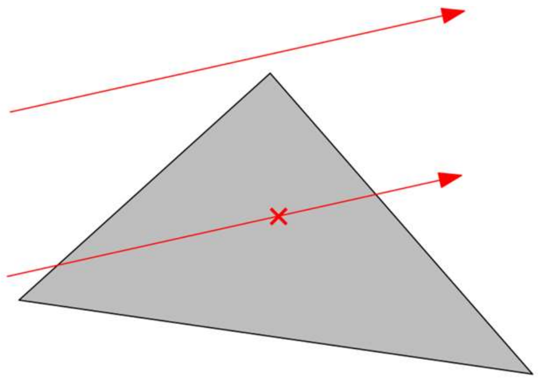
Methodology: Viewshed Computation



Methodology: Shadow Computation

Determine shadowing effect: **Ray-Object Intersection Test**





For 3DCM with 500,000 surfaces and 1,000,000 sample points:

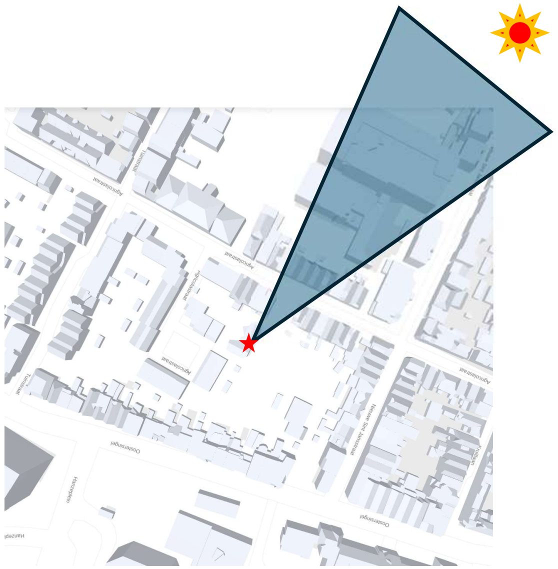
500,000,000,000 (500 billion) intersection tests

Optimization required for city-scale computation

Methodology: Shadow Computation

Existing methods:

Radius Culling



View frustrum culling

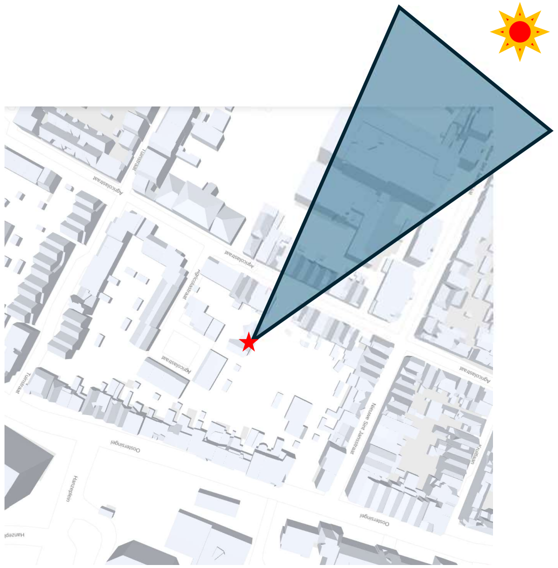
Problem remains:

- Radius setting
- Computation complexity

Methodology: Shadow Computation

Existing methods:

Radius Culling



View frustrum culling

Problem remains:

- Radius setting
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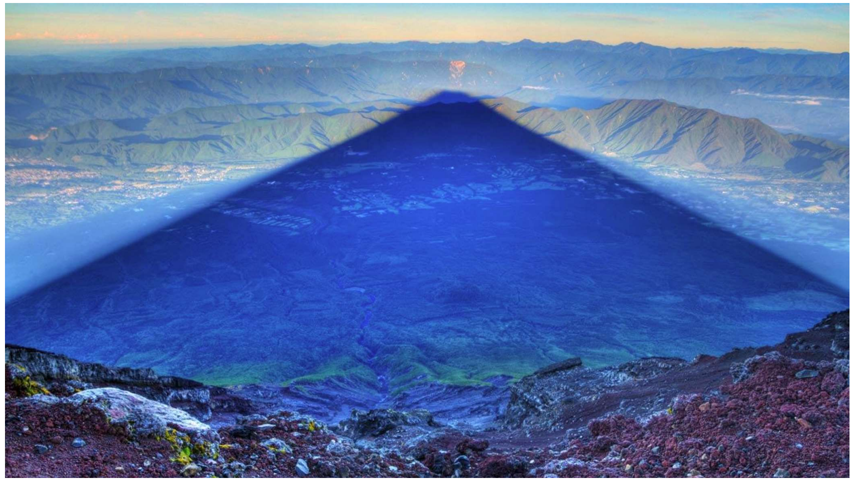
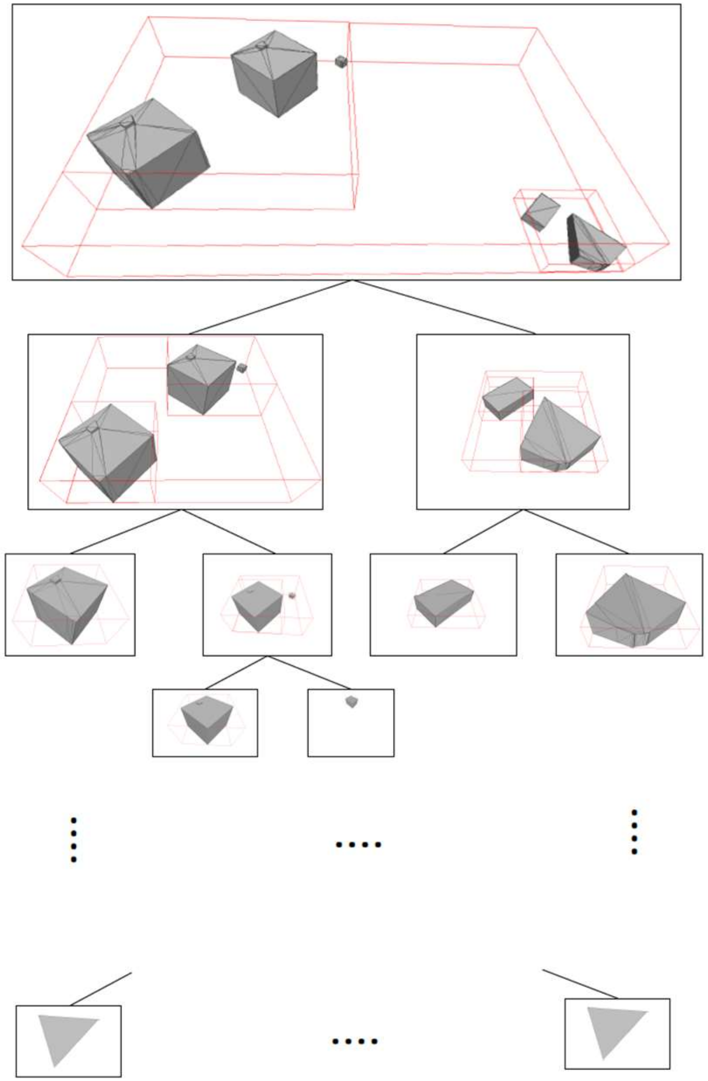


https://www.pinterest.com/pin/275352964692412846/

Methodology: Shadow Computation



Bounding Volume Hierarchy

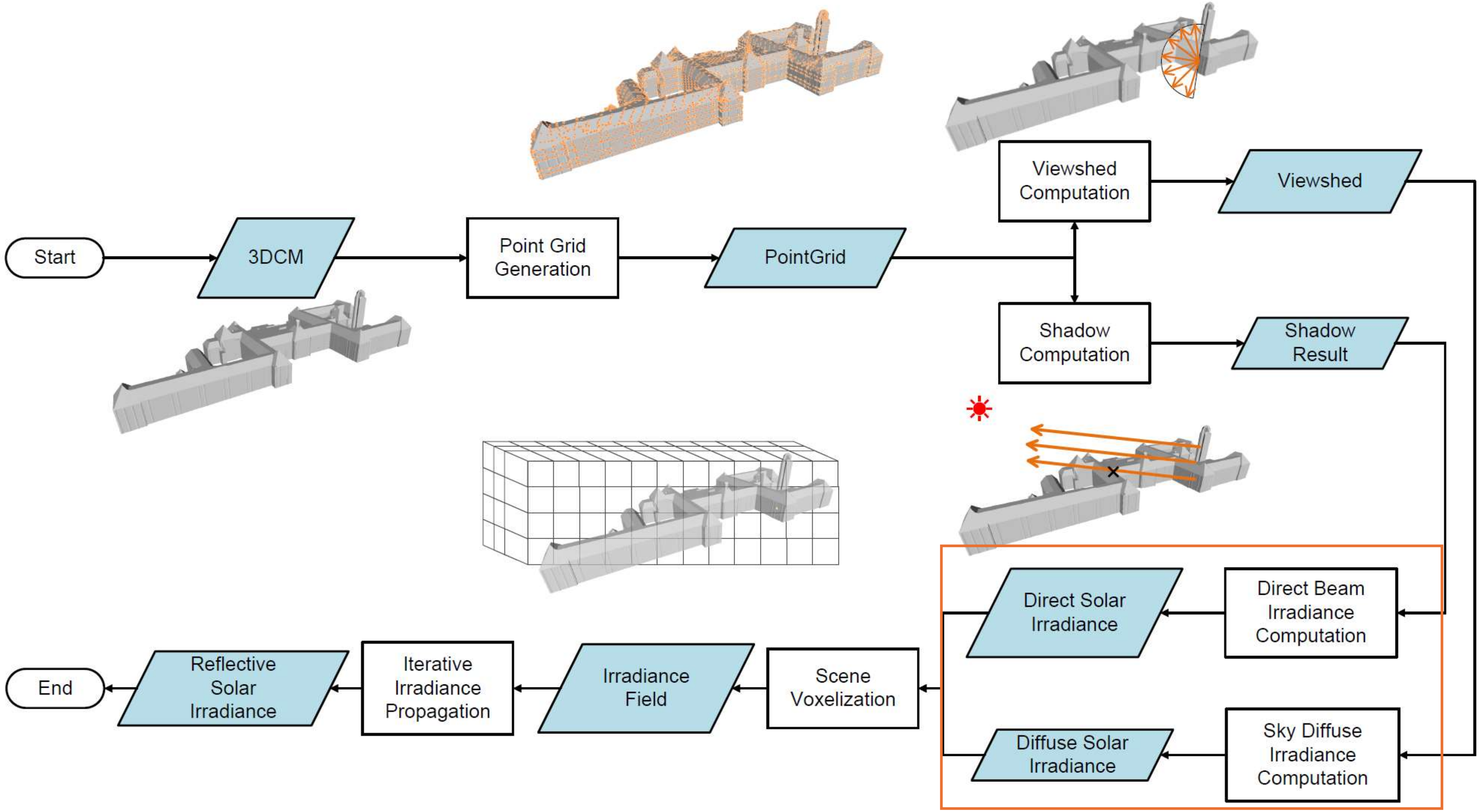
Reduce computation complexity from O(NM) to O(NlogM)

For 3DCM with 500,000 surfaces and 1,000,000 sample points:

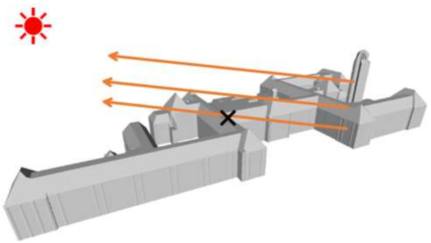
A tree depth of 19 is enough

38,000,000 <<< 500 billion

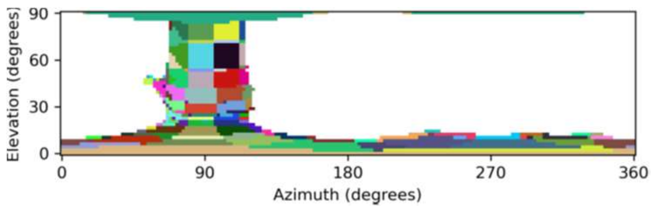
Methodology: Direct and Diffuse Computation



Methodology: Direct and Diffuse Computation

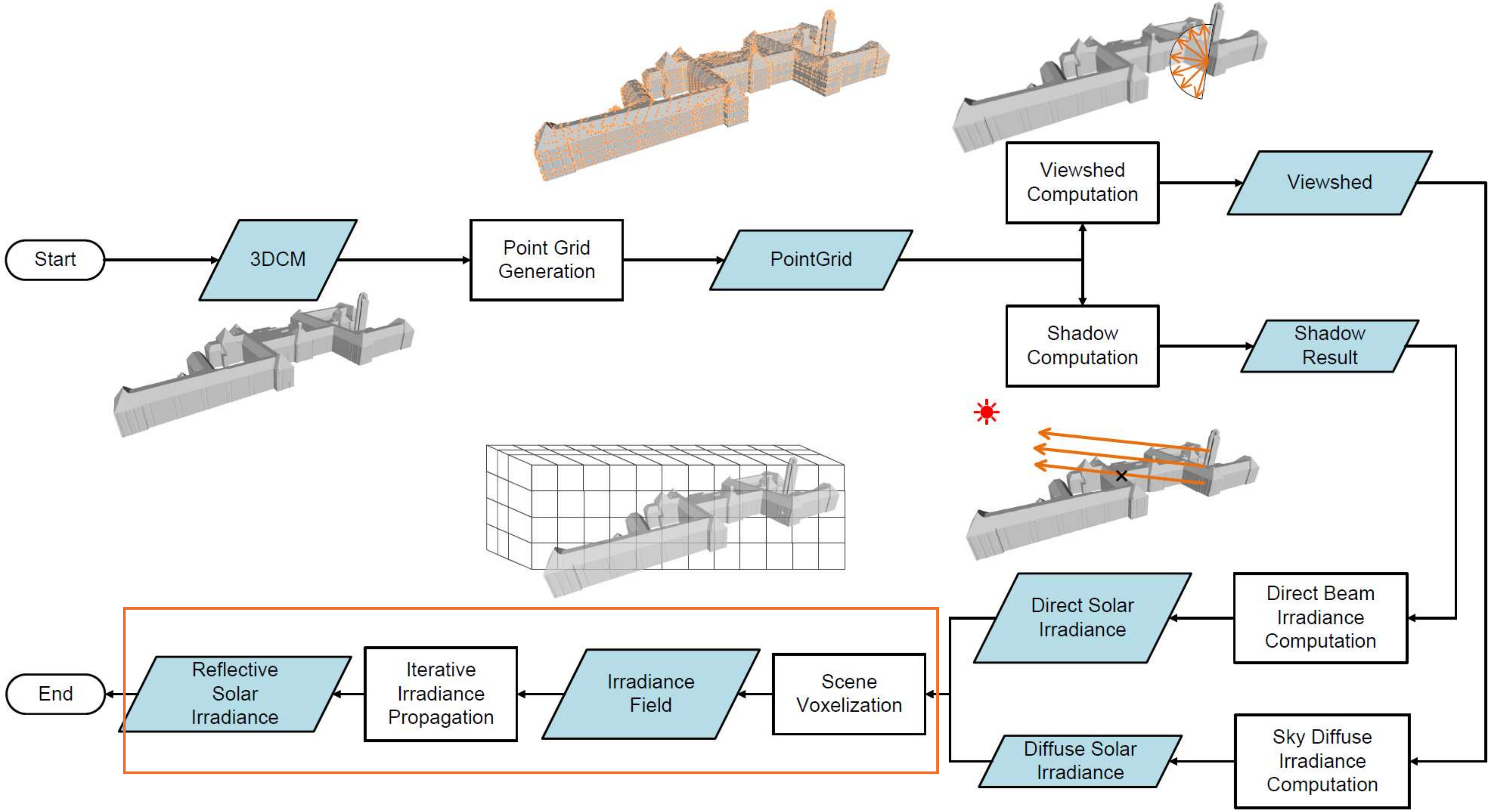


$$I_{S,dir,\beta} = M_{shadow} \cdot DNI \cdot \cos\delta$$

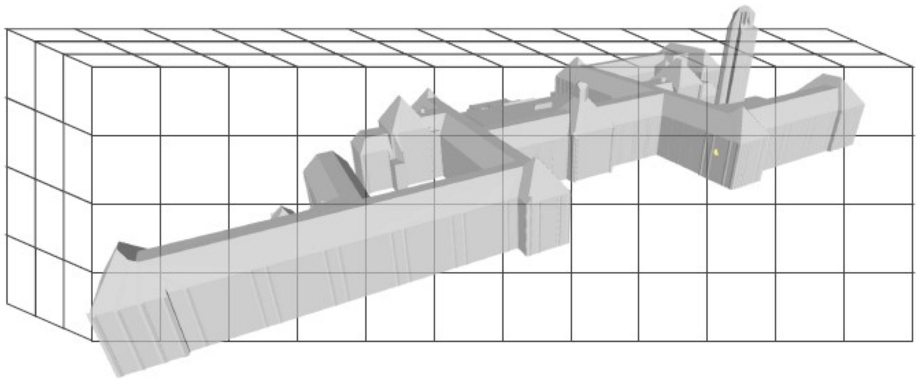


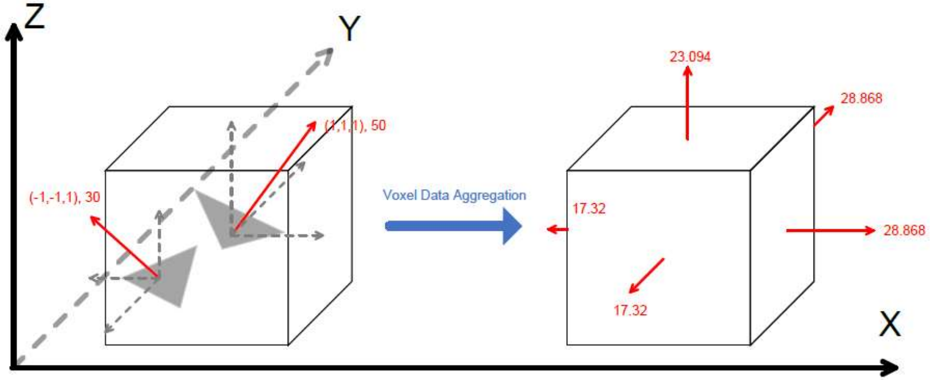
$$I_{S,diff,\beta} = DHI \cdot SVF$$

Methodology: Direct and Diffuse Computation



Methodology: Reflective Irradiance Computation



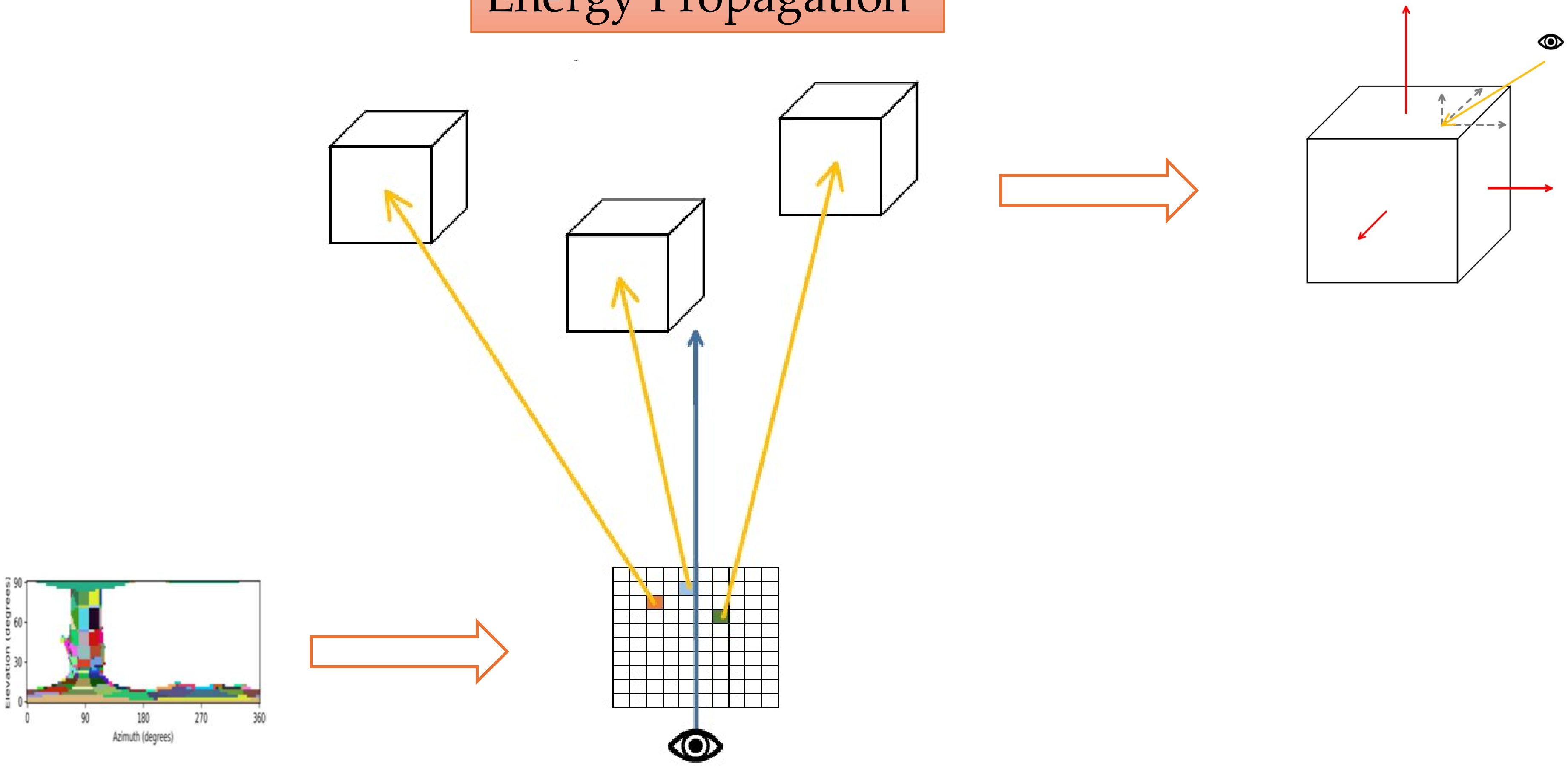


Aggregate the sample points within voxels

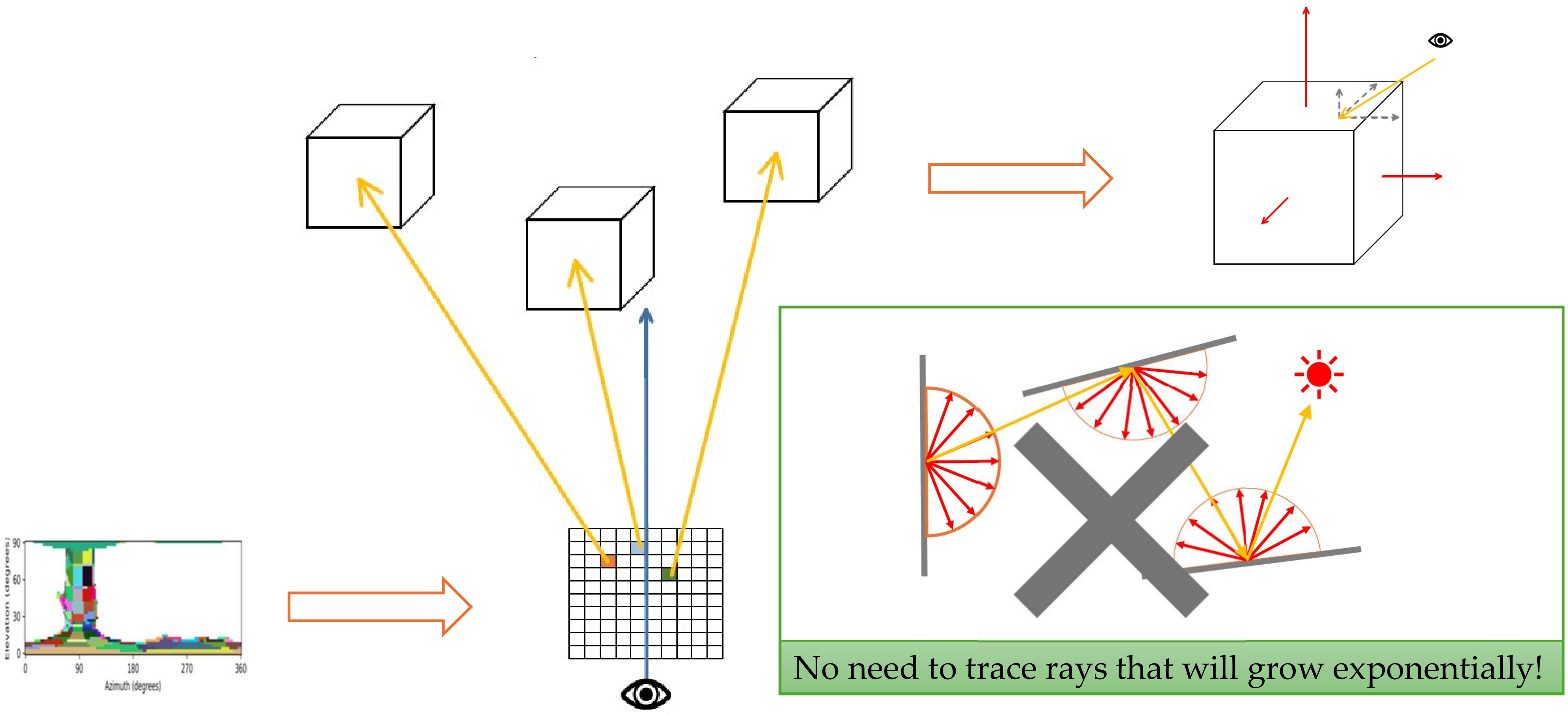
Light field

Methodology: Reflective Irradiance Computation

Energy Propagation

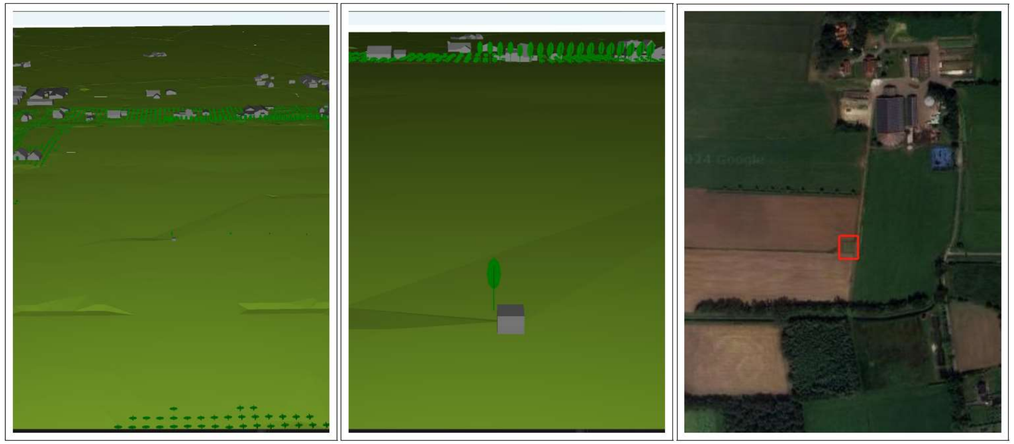


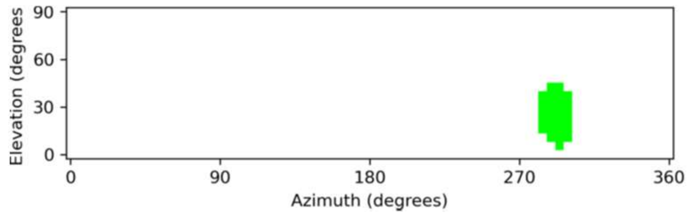
Methodology: Reflective Irradiance Computation



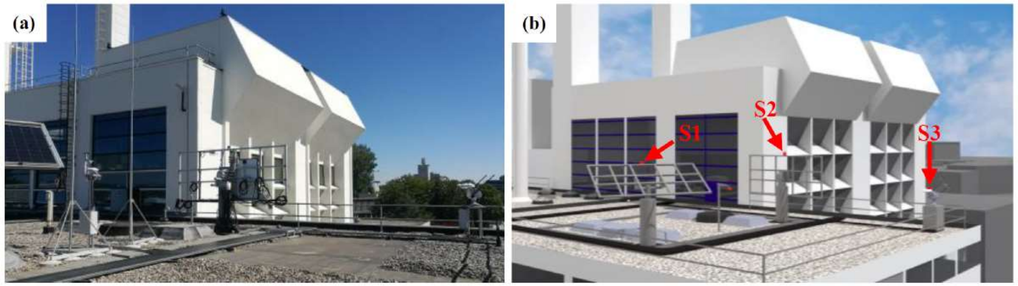
Results & Discussion

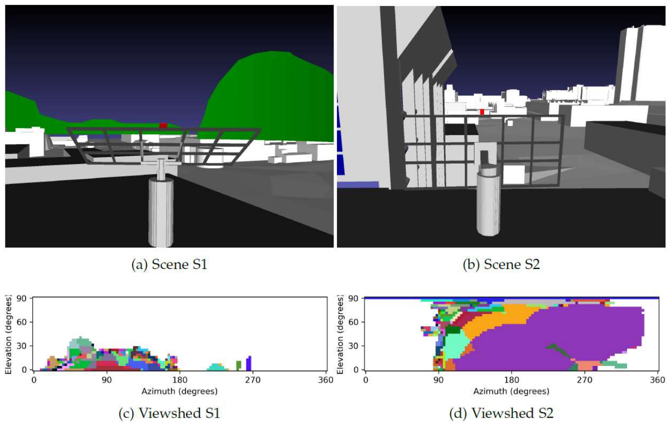
Results & Discussion: Validation





Heino KNMI weather station



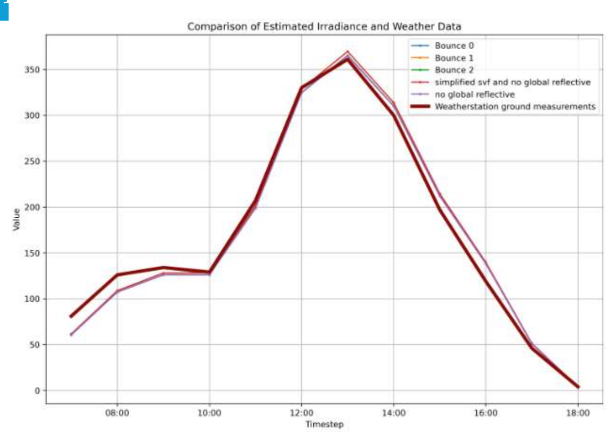


TU Delft (PVMD group data)

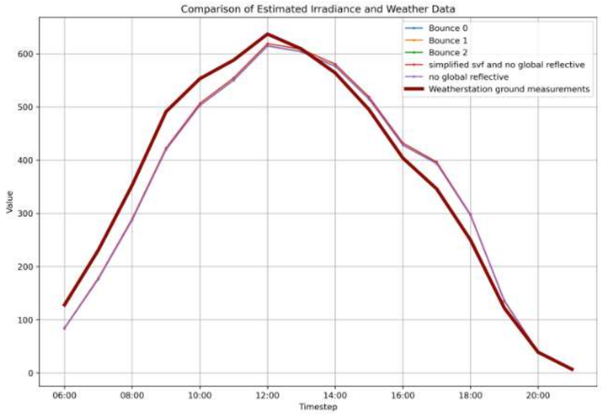
Calcabrini et al. (2023)

Results & Discussion: Validation

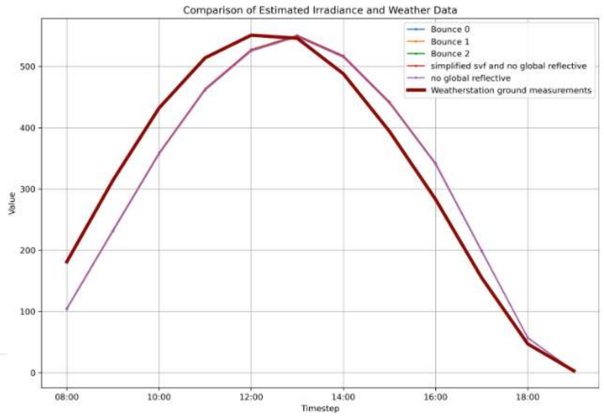
Heino KNMI weather statio



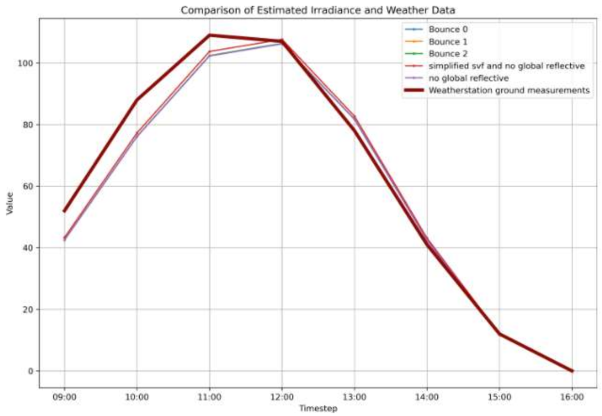
(a) Heino March 21



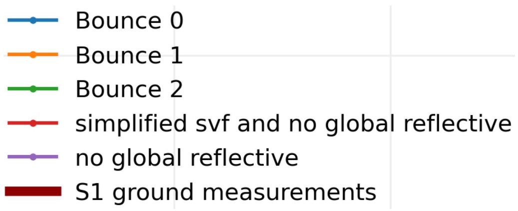
(b) Heino June 21



(c) Heino Sept 22

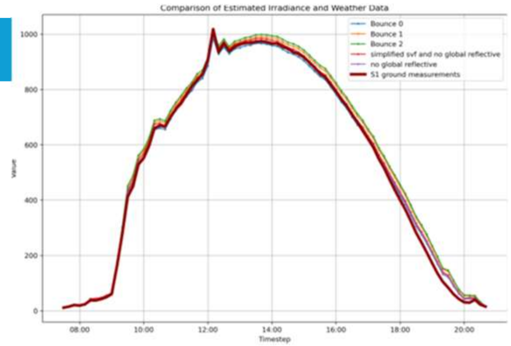


(d) Heino Dec 22

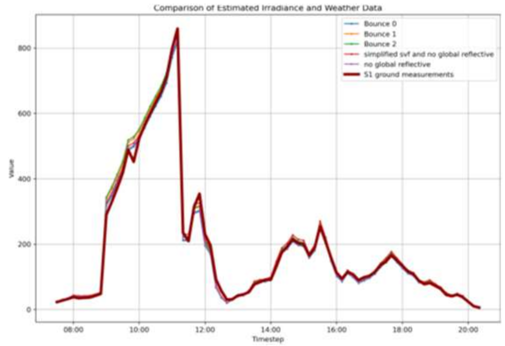


Results & Discussion: Validation

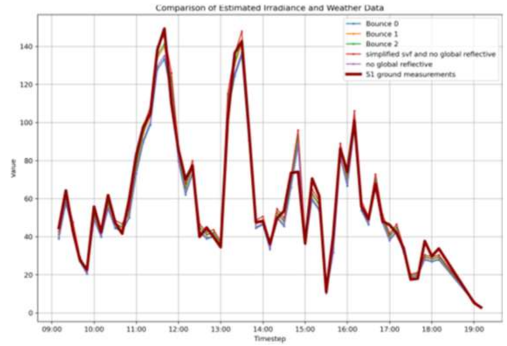
Sensor S1



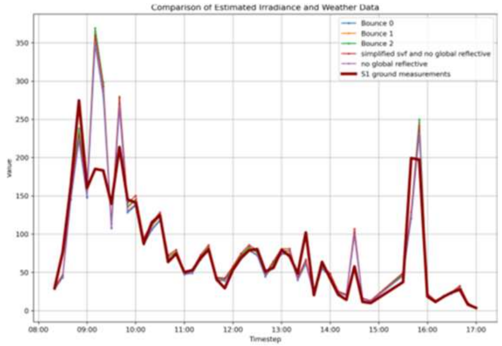
2020/8/20



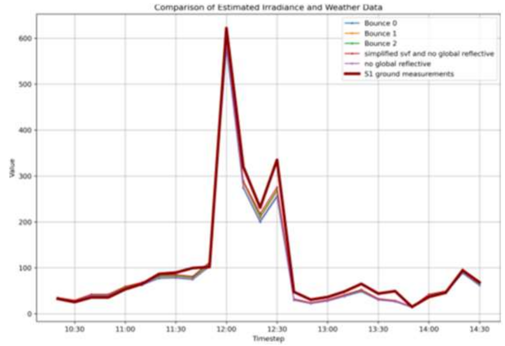
2020/9/1



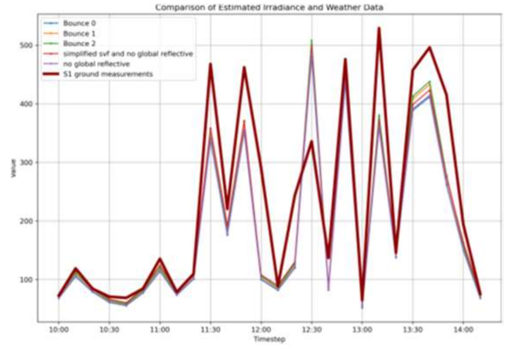
2020/10/1



2020/11/1

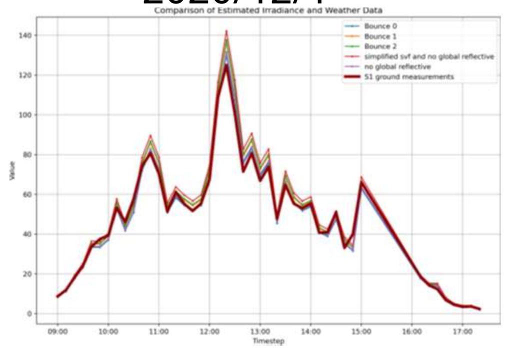


2020/12/1



2021/1/1

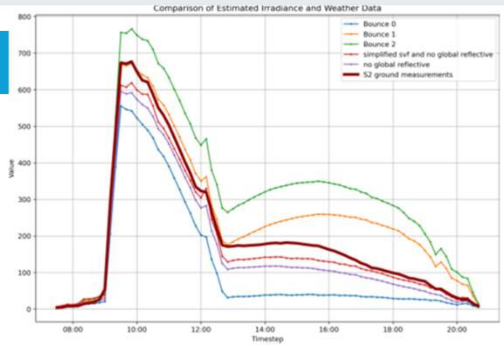
- Bounce 0
- Bounce 1
- Bounce 2
- simplified svf and no global reflective
- no global reflective
- S1 ground measurements



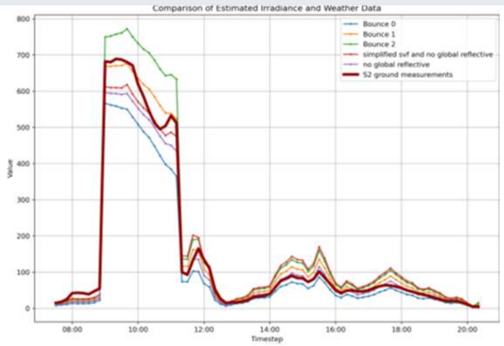
2021/2/1

Results & Discussion: Validation

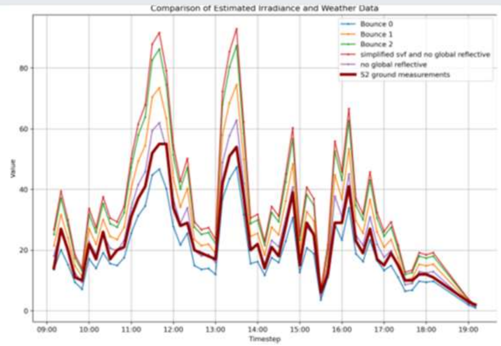
Sensor S2



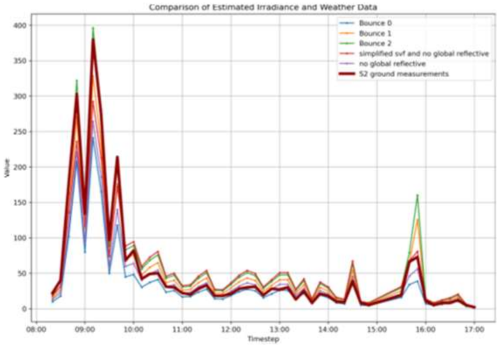
2020/8/20



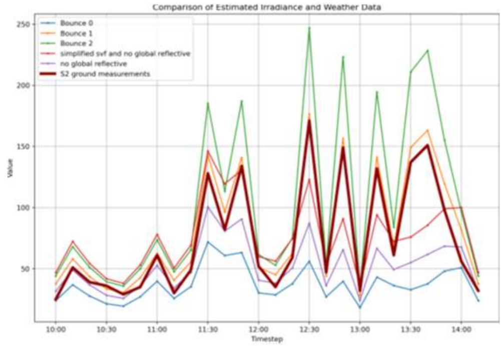
2020/9/1



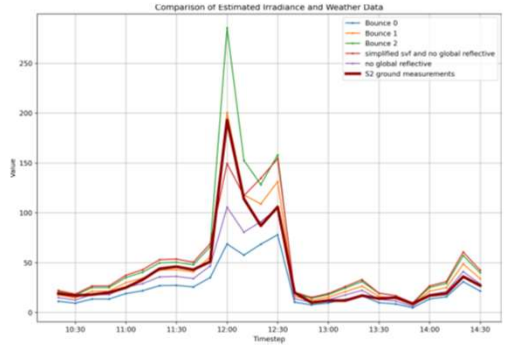
2020/10/1



2020/11/1



2020/12/1



2021/1/1

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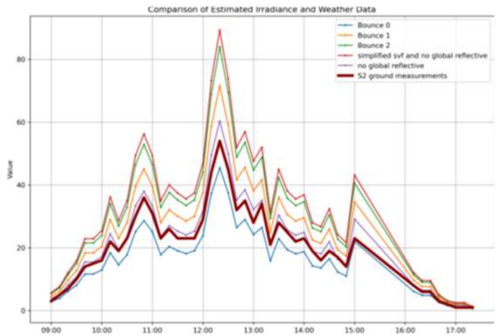


2021/2/1

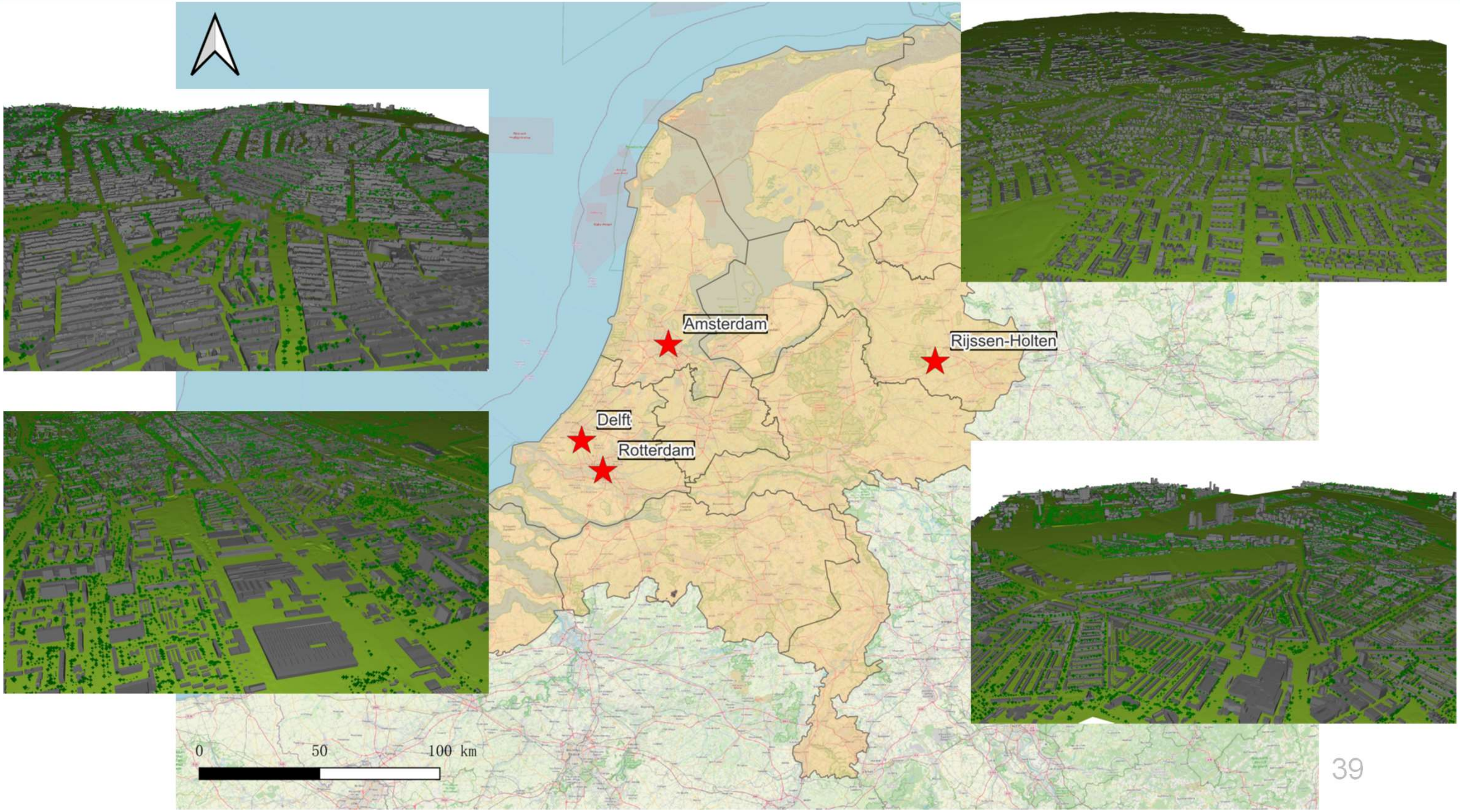
Results & Discussion: Validation

Sensor S2

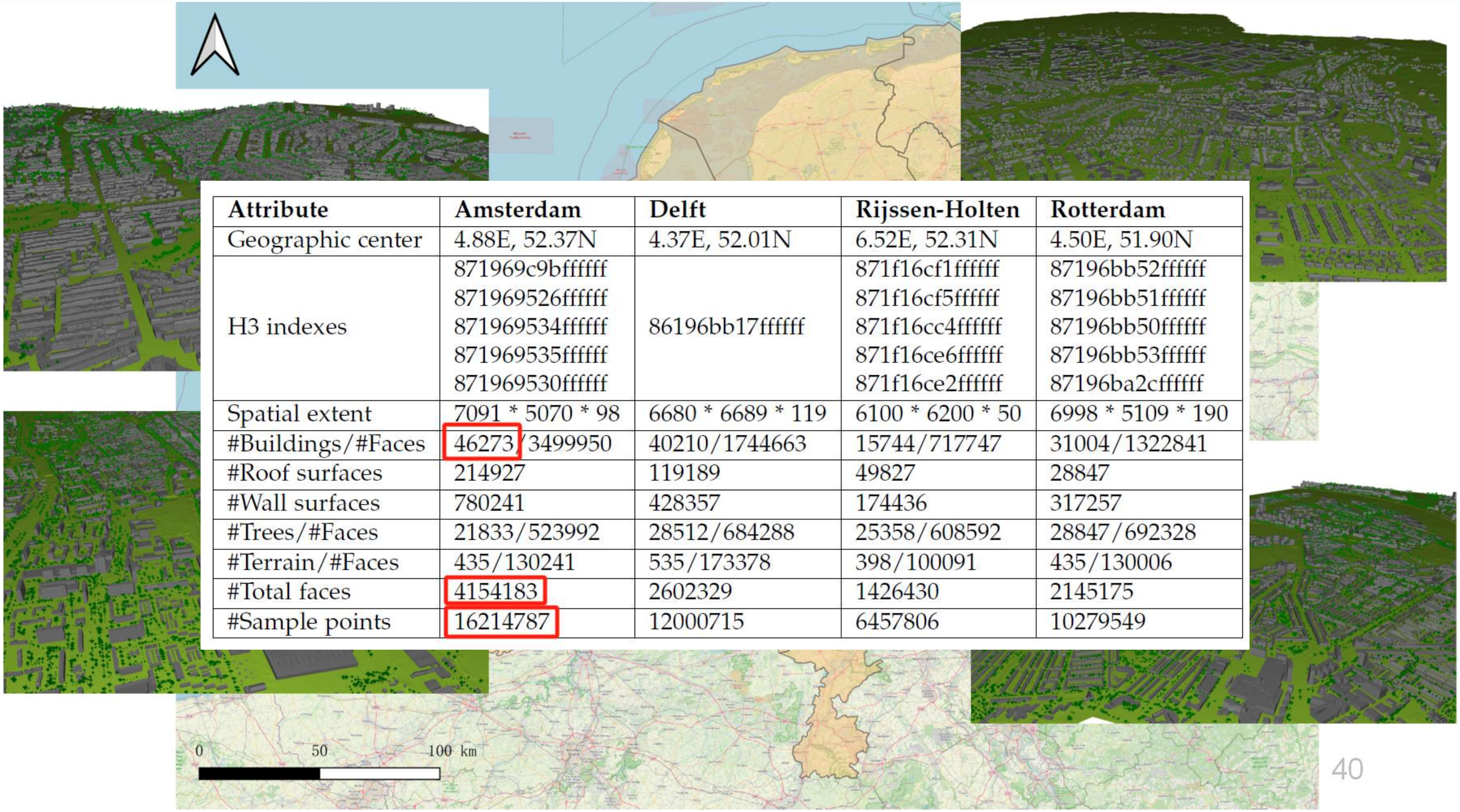
Metrics	Setting	2020/8/20	2020/9/1	2020/10/1	2020/11/1	2020/12/1	2021/1/1	2021/2/1	Average
Correlation	b=0	0.9695	0.9972	0.9897	0.9929	0.6786	0.9036	0.9966	0.9326
	b=1	0.9735	0.9964	0.9897	0.9872	0.9907	0.9903	0.9966	0.9892
	b=2	0.9558	0.9949	0.9897	0.9856	0.9932	0.9941	0.9966	0.9871
	setting 1	0.9968	0.9928	0.9897	0.9825	0.7749	0.9256	0.9966	0.9513
	setting 2	0.9949	0.9972	0.9897	0.9929	0.8111	0.9346	0.9966	0.9596
nMBE	b=0	-0.4327	-0.2205	**-0.1831**†	-0.3358	-0.4966	-0.3751	**-0.1822**†	-0.3180
	b=1	0.2435	**0.0487***	0.2865	**0.0050***	**0.1035**†	**0.1123***	0.2880	**0.1554**†
	b=2	0.5738	0.2183	0.5091	0.1988	0.4224	0.3729	0.5108	0.4009
	setting 1	**-0.1065***	**0.0513**†	0.6040	**0.0649**†	**0.0293***	0.2467	0.6059	0.2137
	setting 2	**-0.2009**†	-0.0995	**0.0842***	-0.1906	-0.2910	**-0.1509**†	**0.0854***	**-0.1090***
nMAE	b=0	0.4327	0.2205	**0.1831**†	0.3365	0.4966	0.3776	**0.1835**†	0.3186
	b=1	0.2554	**0.0999***	0.2878	**0.2071***	**0.1142***	**0.1436***	0.2880	**0.1994**†
	b=2	0.5770	0.2410	0.5094	**0.2241**†	0.4224	0.3746	0.5108	0.4085
	setting 1	**0.1180***	0.1787	0.6041	0.3220	**0.3162**†	0.3318	0.6059	0.3538
	setting 2	**0.2024**†	**0.1221**†	**0.1024***	0.2491	0.3186	**0.2021**†	**0.0874***	**0.1834***
nRMSE	b=0	0.4968	0.3493	**0.2119**†	0.6674	0.7139	0.7306	**0.2150**†	0.4836
	b=1	0.3234	**0.1330***	0.3535	**0.3141***	**0.1395***	**0.2083***	0.3498	**0.2602***
	b=2	0.6471	0.3613	0.6051	**0.3212**†	0.5451	0.6336	0.6109	0.5320
	setting 1	**0.1427***	0.2271	0.7133	0.4467	**0.4023**†	**0.4745**†	0.7227	0.4470
	setting 2	**0.2340**†	**0.2163**†	**0.1382***	0.5347	0.5158	0.4785	**0.1190***	**0.3195**†

Table 6.6.: Sensor S2. Table showing various metrics across different settings and dates. Numbers marked with * represent the best entry, while the numbers marked with † represent the worst entry

Results & Discussion: Testing on larger areas



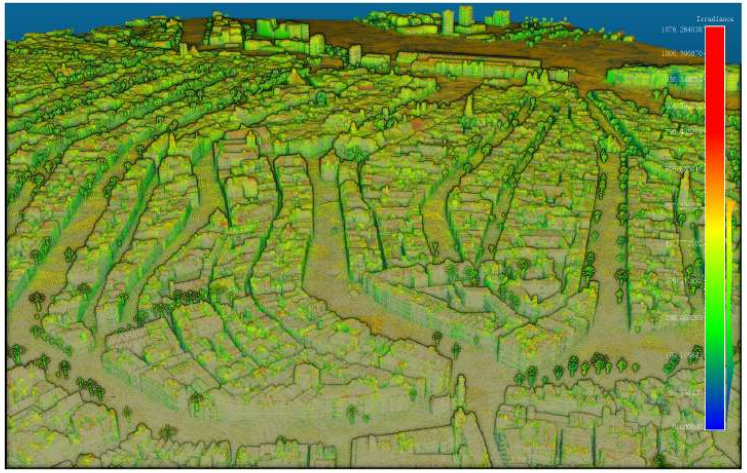
Results & Discussion: Testing on larger areas



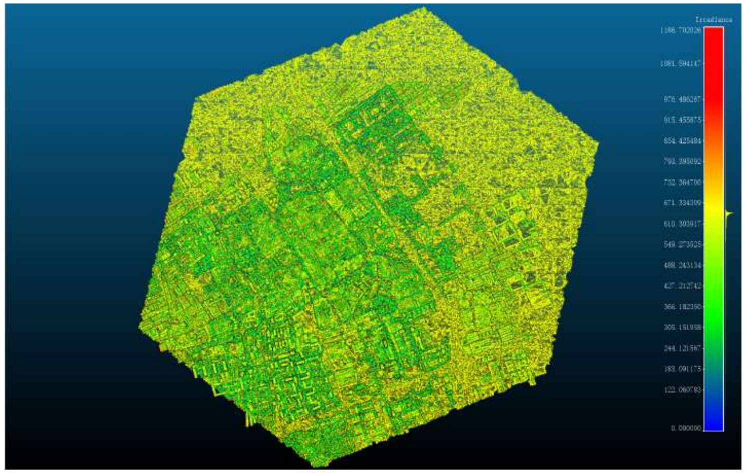
Attribute	Amsterdam	Delft	Rijssen-Holten	Rotterdam
Geographic center	4.88E, 52.37N	4.37E, 52.01N	6.52E, 52.31N	4.50E, 51.90N
H3 indexes	871969c9bffffff 871969526ffffff 871969534ffffff 871969535ffffff 871969530ffffff	86196bb17ffffff	871f16cf1ffffff 871f16cf5ffffff 871f16cc4ffffff 871f16ce6ffffff 871f16ce2ffffff	87196bb52ffffff 87196bb51ffffff 87196bb50ffffff 87196bb53ffffff 87196ba2cffffff
Spatial extent	7091 * 5070 * 98	6680 * 6689 * 119	6100 * 6200 * 50	6998 * 5109 * 190
#Buildings/#Faces	46273/3499950	40210/1744663	15744/717747	31004/1322841
#Roof surfaces	214927	119189	49827	28847
#Wall surfaces	780241	428357	174436	317257
#Trees/#Faces	21833/523992	28512/684288	25358/608592	28847/692328
#Terrain/#Faces	435/130241	535/173378	398/100091	435/130006
#Total faces	4154183	2602329	1426430	2145175
#Sample points	16214787	12000715	6457806	10279549

Results & Discussion: Testing on larger areas

(a) Amsterdam - overview



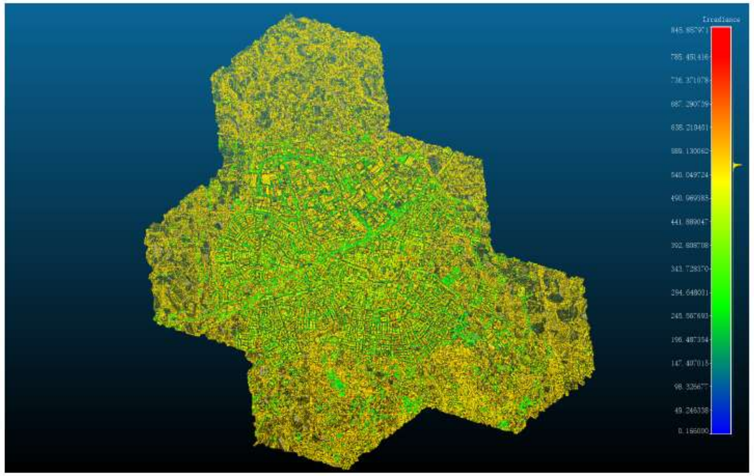
(b) Amsterdam - zoomed in



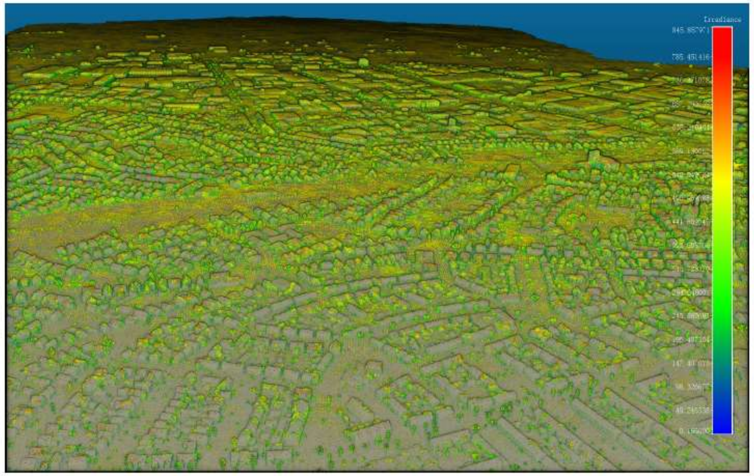
(c) Delft - overview

(d) Delft - zoomed in

Results & Discussion: Testing on larger areas

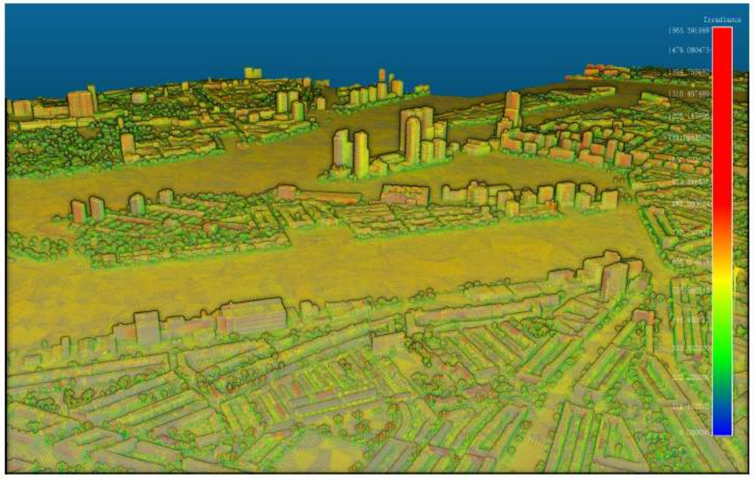


(e) Rijssen-Holten - overview



(f) Rijssen-Holten - zoomed in

(g) Rotterdam - overview



(h) Rotterdam - zoomed in

Results & Discussion: Testing on larger areas

Simulation for 2021 Feb 1 with 10 minutes time interval

Within several minutes!

27 hours

City	#Timestep	Shadow computation	SVF computation	Direct+Diffuse	Reflective	Total	Reflective ratio
Amsterdam	54	2.33	406.48	27.06	98302.20	98738.07	99.56
Delft	54	1.57	301.10	16.21	79782.55	80101.43	99.60
Rijssen-Holten	54	1.02	151.44	5.97	42941.12	43093.58	99.65
Rotterdam	54	1.58	240.70	14.39	80424.76	80681.43	99.68

12 hours

Attribute	Amsterdam	Delft	Rijssen-Holten	Rotterdam
Geographic center	4.88E, 52.37N	4.37E, 52.01N	6.52E, 52.31N	4.50E, 51.90N
H3 indexes	871969c9bffffff 871969526ffffff 871969534ffffff 871969535ffffff 871969530ffffff	86196bb17ffffff	871f16cf1ffffff 871f16cf5ffffff 871f16cc4ffffff 871f16ce6ffffff 871f16ce2ffffff	87196bb52ffffff 87196bb51ffffff 87196bb50ffffff 87196bb53ffffff 87196ba2cffffff
Spatial extent	7091 * 5070 * 98	6680 * 6689 * 119	6100 * 6200 * 50	6998 * 5109 * 190
#Buildings/#Faces	46273/3499950	40210/1744663	15744/717747	31004/1322841
#Roof surfaces	214927	119189	49827	28847
#Wall surfaces	780241	428357	174436	317257
#Trees/#Faces	21833/523992	28512/684288	25358/608592	28847/692328
#Terrain/#Faces	435/130241	535/173378	398/100091	435/130006
#Total faces	4154183	2602329	1426430	2145175
#Sample points	16214787	12000715	6457806	10279549

Results & Discussion: Testing on larger areas

Orientation	Amsterdam	Delft	Rijssen-Holten	Rotterdam
east	301.90	**390.17-**	**361.43-**	**349.95-**
north	**267.16-**	435.10	424.53	400.49
northeast	293.52	414.16	451.07	405.99
northwest	303.21	408.25	446.68	398.53
south	**457.67***	**615.00***	484.40	**611.62***
southeast	440.36	549.69	492.35	516.33
southwest	379.14	587.55	**494.79***	592.71
west	302.90	546.36	443.82	499.84

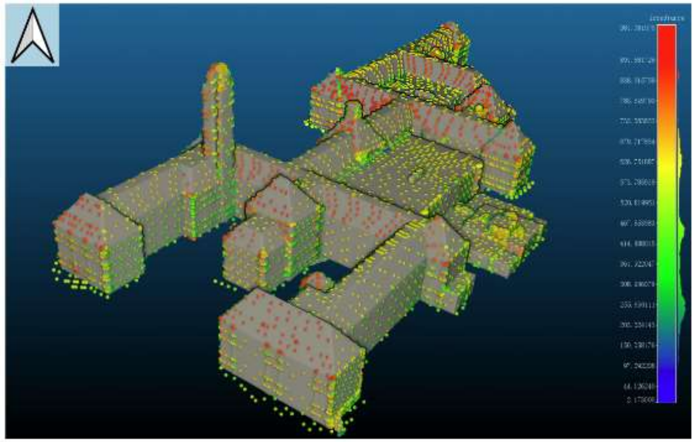
City	Orientation	Inclination	Irradiance
Amsterdam	south	45°	634.20
Delft	south	30°	791.49
Rijssen-Holten	south	45°	636.74
Rotterdam	south	30°	812.10

Inclination	Amsterdam	Delft	Rijssen-Holten	Rotterdam
-0°	**135.98-**	**168.86-**	**116.81-**	**195.08-**
-75°	304.13	453.66	329.67	442.60
-60°	265.97	368.49	220.01	328.79
-45°	214.57	276.47	209.53	237.93
-30°	163.63	277.59	135.32	165.47
-15°	131.12	144.04	128.71	155.22
0°	494.71	575.38	502.79	581.44
15°	440.42	553.81	506.38	540.40
30°	502.76	**597.69***	**518.69***	581.93
45°	**504.07***	594.85	503.19	**595.61***
60°	457.81	575.24	480.62	580.60
75°	428.53	543.52	426.92	545.44
90°	273.96	411.45	300.83	405.19

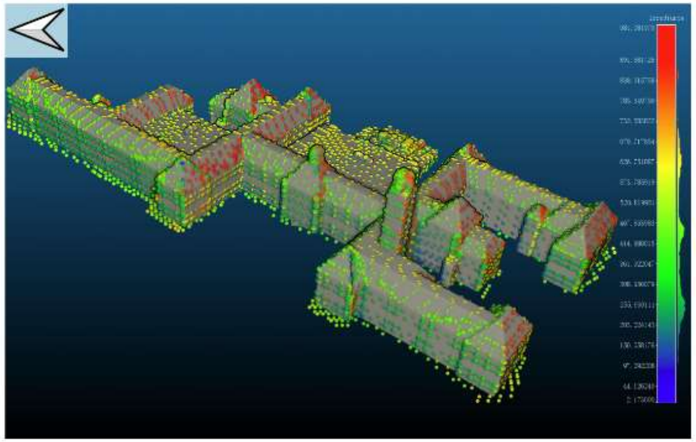
City	Orientation	Inclination	Irradiance
Amsterdam	north	-15°	39.08
Delft	north	-15°	56.83
Rijssen-Holten	southwest	-30°	62.83
Rotterdam	northwest	-15°	78.83

Surface type	Amsterdam	Delft	Rijssen-Holten	Rotterdam
Wall surface	**260.65-**	**393.17-**	**288.28-**	**390.05-**
Roof surface	**497.54***	**592.64***	**509.72***	**587.60***
Terrain surface	406.78	547.52	504.82	532.83
Vegetation surface	363.20	456.67	325.88	441.15

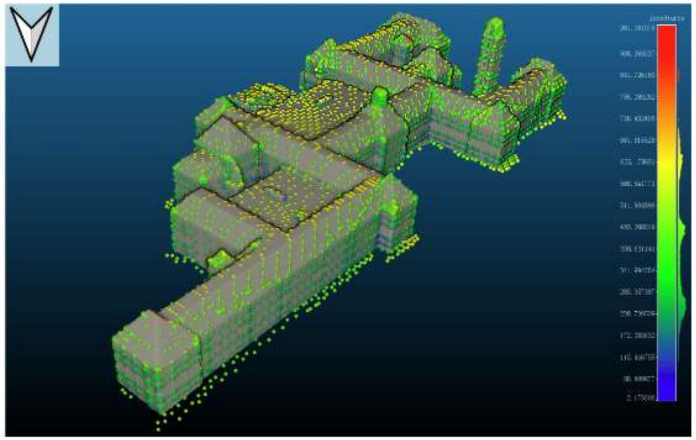
Results & Discussion: Testing on specific buildings



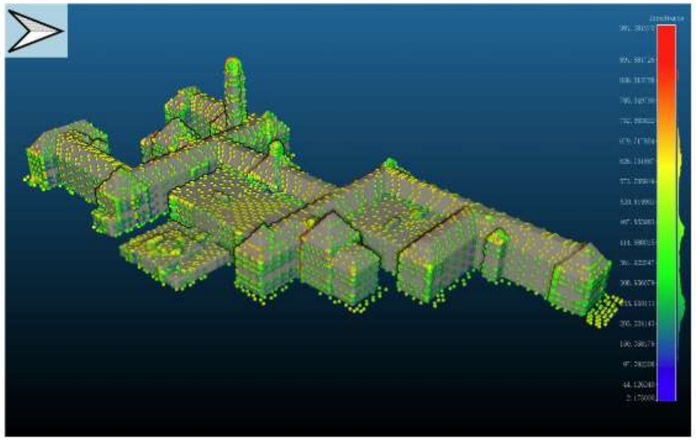
(a) Looking at the north direction



(b) Looking at the east direction

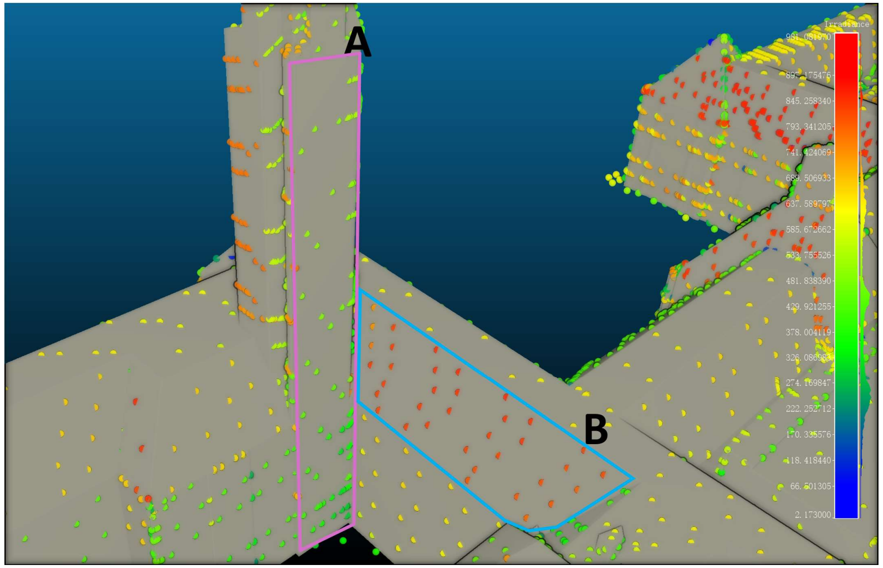


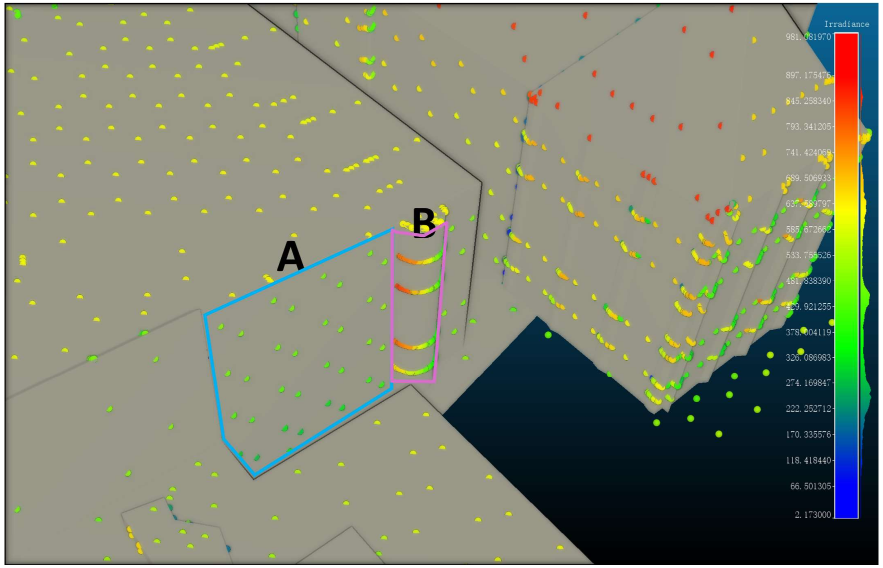
(c) Looking at the south direction



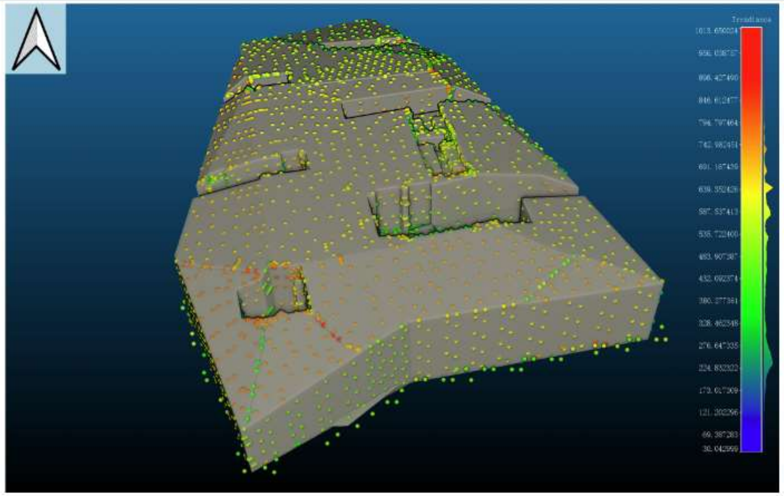
(d) Looking at the west direction

Results & Discussion: Testing on specific buildings

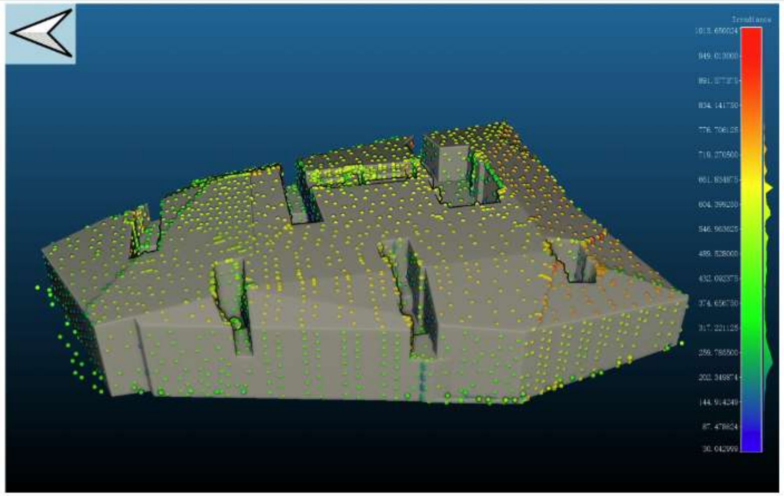




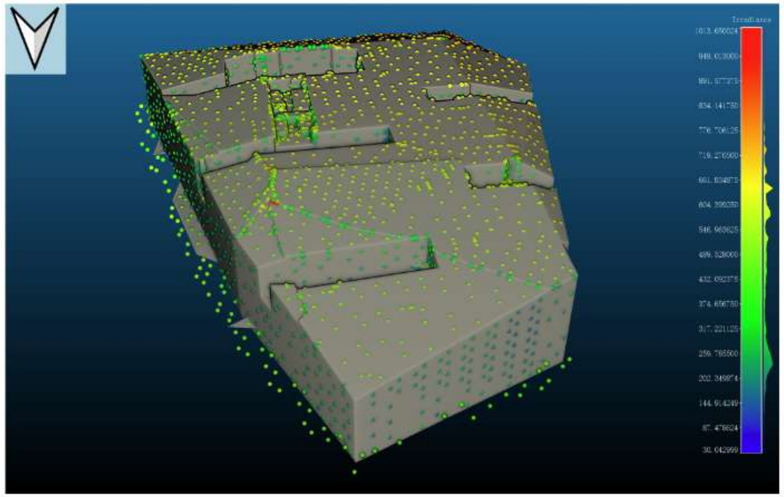
Results & Discussion: Testing on specific buildings

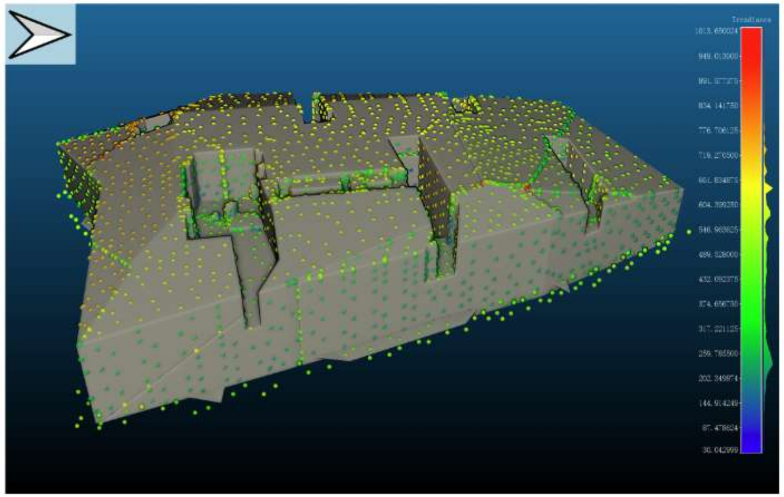


(a) Looking at the north direction

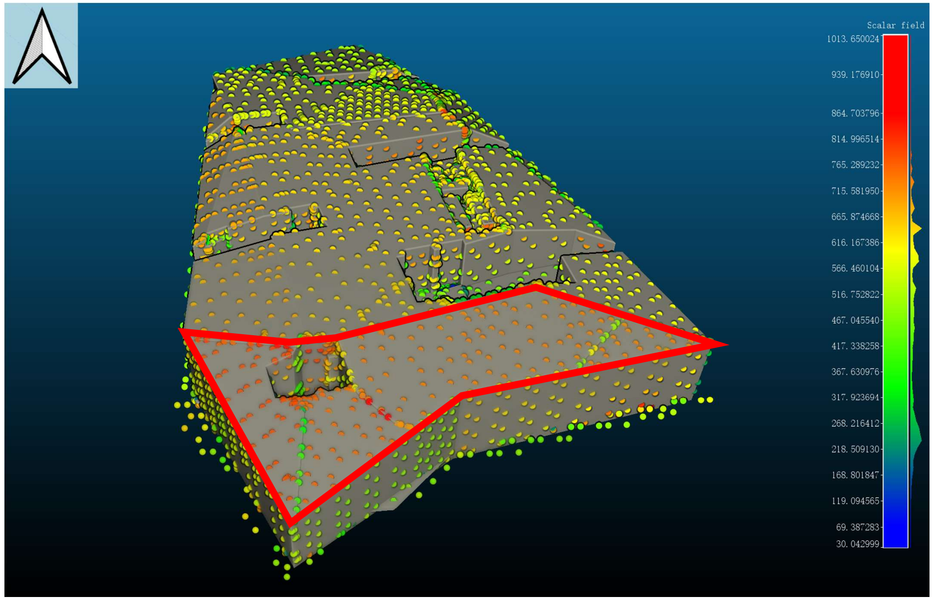


(b) Looking at the east direction





Results & Discussion: Testing on specific buildings



Results & Discussion: Testing on specific buildings

Orientation	BK	Delft Station
east	343.83	380.12
north	**268.48**$^-$	**340.37**$^-$
northeast	298.51	350.99
northwest	293.43	340.57
south	526.48	**632.45***
southeast	465.82	545.03
southwest	**676.35***	504.08
west	427.11	434.49

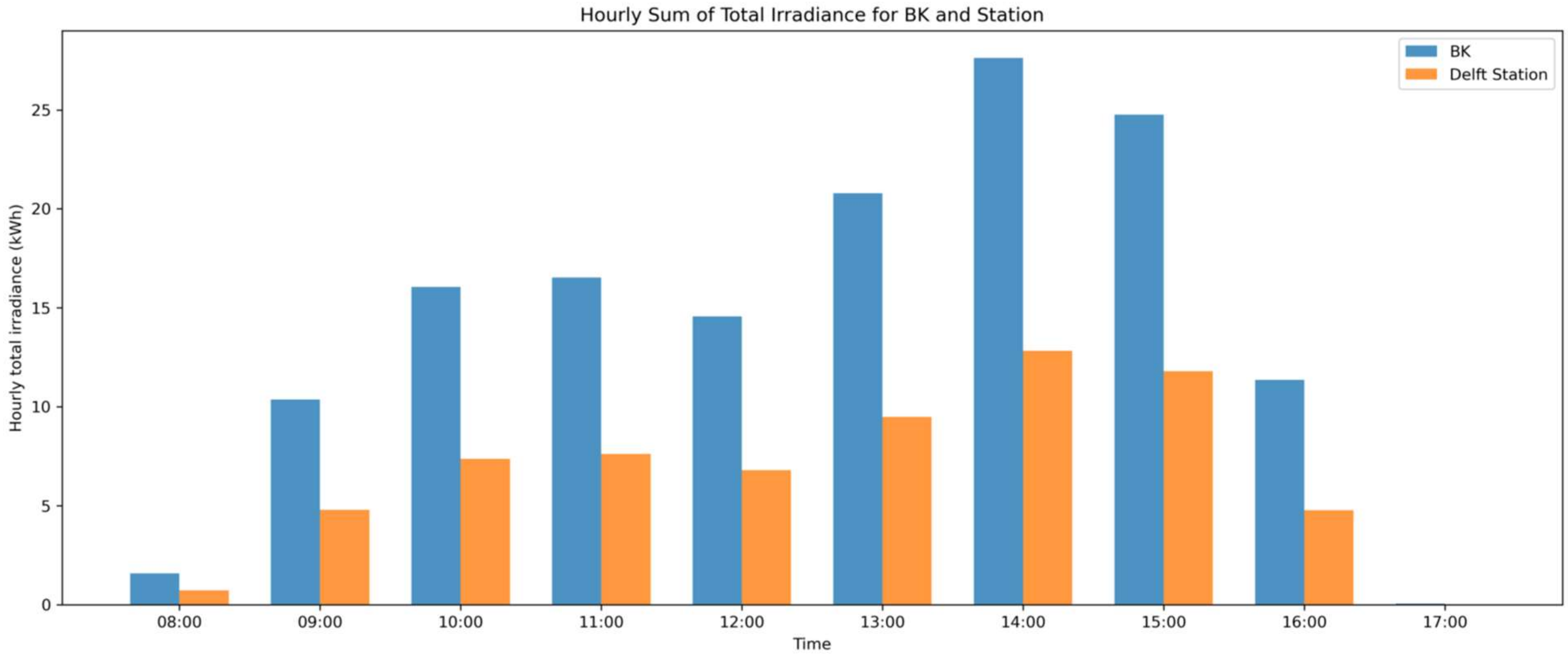
Inclination	BK	Delft Station
-75°	368.65	394.72
-30°	**274.00**$^-$	Nan
0°	409.29	**383.80**$^-$
15°	424.01	582.82
30°	**640.90***	**670.40***
45°	609.10	602.24
60°	570.48	Nan
75°	471.85	Nan
90°	380.09	428.60

Building	Orientation	Inclination	Irradiance
BK	southwest	75°	867.58
Delft Station	southwest	30°	779.85

Building	Orientation	Inclination	Irradiance
BK	northeast	90°	227.48
Delft Station	north	45°	103.19

Surface type	BK	Delft Station
Wall surface	**379.01**$^-$	**428.13**$^-$
Roof surface	**576.70***	**563.80***

Results & Discussion: Testing on specific buildings



Daily total:

- BK: 143.70 kWh
- Delft Station: 66.24 kWh

20 Days of electricity use for an average NL households

Results & Discussion: Findings

- **More detailed usage of 3DCM information can provide high accuracy**
  - With more detailed modelling of reflective irradiance, the accuracy is higher under clear-sky conditions

Metrics	Setting	2020/8/20	2020/9/1	2020/10/1	2020/11/1	2020/12/1	2021/1/1	2021/2/1	Average
Correlation	b=0	0.9695	0.9972	0.9897	0.9929	0.6786	0.9036	0.9966	0.9326
	b=1	0.9735	0.9964	0.9897	0.9872	0.9907	0.9903	0.9966	0.9892
	b=2	0.9558	0.9949	0.9897	0.9856	0.9932	0.9941	0.9966	0.9871
	setting 1	0.9968	0.9928	0.9897	0.9825	0.7749	0.9256	0.9966	0.9513
	setting 2	0.9949	0.9972	0.9897	0.9929	0.8111	0.9346	0.9966	0.9596
nMBE	b=0	-0.4327	-0.2205	**-0.1831**†	-0.3358	-0.4966	-0.3751	**-0.1822**†	-0.3180
	b=1	0.2435	**0.0487***	0.2865	**0.0050***	**0.1035**†	**0.1123***	0.2880	**0.1554**†
	b=2	0.5738	0.2183	0.5091	0.1988	0.4224	0.3729	0.5108	0.4009
	setting 1	**-0.1065***	**0.0513**†	0.6040	**0.0649**†	**0.0293***	0.2467	0.6059	0.2137
	setting 2	**-0.2009**†	-0.0995	**0.0842***	-0.1906	-0.2910	**-0.1509**†	**0.0854***	**-0.1090***
nMAE	b=0	0.4327	0.2205	**0.1831**†	0.3365	0.4966	0.3776	**0.1835**†	0.3186
	b=1	0.2554	**0.0999***	0.2878	**0.2071***	**0.1142***	**0.1436***	0.2880	**0.1994**†
	b=2	0.5770	0.2410	0.5094	**0.2241**†	0.4224	0.3746	0.5108	0.4085
	setting 1	**0.1180***	0.1787	0.6041	0.3220	**0.3162**†	0.3318	0.6059	0.3538
	setting 2	**0.2024**†	**0.1221**†	**0.1024***	0.2491	0.3186	**0.2021**†	**0.0874***	**0.1834***
nRMSE	b=0	0.4968	0.3493	**0.2119**†	0.6674	0.7139	0.7306	**0.2150**†	0.4836
	b=1	0.3234	**0.1330***	0.3535	**0.3141***	**0.1395***	**0.2083***	0.3498	**0.2602***
	b=2	0.6471	0.3613	0.6051	**0.3212**†	0.5451	0.6336	0.6109	0.5320
	setting 1	**0.1427***	0.2271	0.7133	0.4467	**0.4023**†	**0.4745**†	0.7227	0.4470
	setting 2	**0.2340**†	**0.2163**†	**0.1382***	0.5347	0.5158	0.4785	**0.1190***	**0.3195**†

Table 6.6.: Sensor S2. Table showing various metrics across different settings and dates. Numbers marked with * represent the best entry, while the numbers marked with † represent the worst entry

Results & Discussion: Findings

- **Accurate modelling of direct beam irradiance and sky diffuse solar** irradiance provide good results
  - But performance not stable

Metrics	Setting	2020/8/20	2020/9/1	2020/10/1	2020/11/1	2020/12/1	2021/1/1	2021/2/1	Average
Correlation	b=0	0.9695	0.9972	0.9897	0.9929	0.6786	0.9036	0.9966	0.9326
	b=1	0.9735	0.9964	0.9897	0.9872	0.9907	0.9903	0.9966	0.9892
	b=2	0.9558	0.9949	0.9897	0.9856	0.9932	0.9941	0.9966	0.9871
	setting 1	0.9968	0.9928	0.9897	0.9825	0.7749	0.9256	0.9966	0.9513
	setting 2	0.9949	0.9972	0.9897	0.9929	0.8111	0.9346	0.9966	0.9596
nMBE	b=0	-0.4327	-0.2205	**-0.1831**†	-0.3358	-0.4966	-0.3751	**-0.1822**†	-0.3180
	b=1	0.2435	**0.0487***	0.2865	**0.0050***	**0.1035**†	**0.1123***	0.2880	**0.1554**†
	b=2	0.5738	0.2183	0.5091	0.1988	0.4224	0.3729	0.5108	0.4009
	setting 1	**-0.1065***	**0.0513**†	0.6040	**0.0649**†	**0.0293***	0.2467	0.6059	0.2137
	setting 2	**-0.2009**†	-0.0995	**0.0842***	-0.1906	-0.2910	**-0.1509**†	**0.0854***	**-0.1090***
nMAE	b=0	0.4327	0.2205	**0.1831**†	0.3365	0.4966	0.3776	**0.1835**†	0.3186
	b=1	0.2554	**0.0999***	0.2878	**0.2071***	**0.1142***	**0.1436***	0.2880	**0.1994**†
	b=2	0.5770	0.2410	0.5094	**0.2241**†	0.4224	0.3746	0.5108	0.4085
	setting 1	**0.1180***	0.1787	0.6041	0.3220	**0.3162**†	0.3318	0.6059	0.3538
	setting 2	**0.2024**†	**0.1221**†	**0.1024***	0.2491	0.3186	**0.2021**†	**0.0874***	**0.1834***
nRMSE	b=0	0.4968	0.3493	**0.2119**†	0.6674	0.7139	0.7306	**0.2150**†	0.4836
	b=1	0.3234	**0.1330***	0.3535	**0.3141***	**0.1395***	**0.2083***	0.3498	**0.2602***
	b=2	0.6471	0.3613	0.6051	**0.3212**†	0.5451	0.6336	0.6109	0.5320
	setting 1	**0.1427***	0.2271	0.7133	0.4467	**0.4023**†	**0.4745**†	0.7227	0.4470
	setting 2	**0.2340**†	**0.2163**†	**0.1382***	0.5347	0.5158	0.4785	**0.1190***	**0.3195**†

Table 6.6.: Sensor S2. Table showing various metrics across different settings and dates. Numbers marked with * represent the best entry, while the numbers marked with † represent the worst entry

Results & Discussion: Findings

- **Method scalable for city-scale applications**
  - Simulation not detailed model reflective components takes within several minutes
  - 1~5 hours for simulation of 1 million sample points, one day, 10 minutes time interval)
  - 24 hours for 16 million sample points

Attribute	Value
Geographic center	52.43, 6.26
Spatial extent	2665 * 2665 * 17
#Buildings/#Faces	272/29409
#Trees/#Faces	3950/94800
#Terrain/#Faces	121/86020
#Total faces	210229
#Sample points	1539022

Attribute	Value
Geographic center	52.6, 4.23
Spatial extent	1174 * 1178 * 99
#Buildings/#Faces	1114/99738
#Trees/#Faces	3/153
#Terrain/#Faces	20/964403
#Total faces	1064294
#Sample points	889500

Date	#Timestep	Shadow computation	SVF computation	Direct+Diffuse	Reflective	Total	Reflective ratio
2024/3/21	12	0.13	37.37	0.29	3232.19	3269.98	98.84
2024/6/21	16	0.20	46.61	0.37	5271.96	5319.14	99.11
2024/9/22	12	0.22	44.67	0.29	4675.88	4721.06	99.04
2024/12/22	8	0.20	41.60	0.26	4022.49	4064.55	98.97

Table 6.7.: Computation time Heino with proposed method

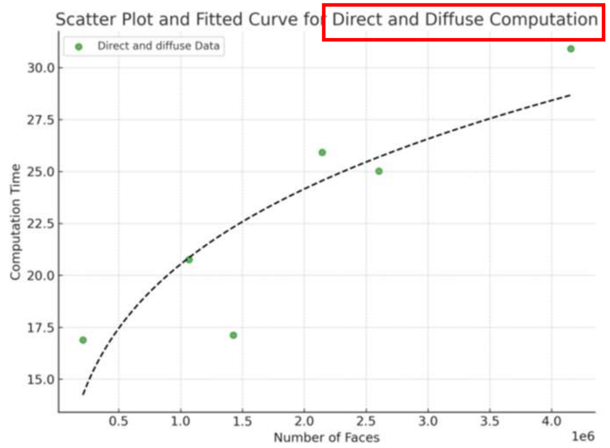
Date	#Timestep	Shadow computation	SVF computation	Direct+Diffuse	Reflective	Total	Reflective ratio
2024/8/21	80	0.62	51.03	1.47	12319.02	12372.14	99.57
2024/9/1	77	0.58	49.63	1.39	15331.52	15383.12	99.66
2024/10/1	57	0.51	41.64	1.00	9093.19	9136.34	99.53
2024/11/1	50	0.44	32.25	0.99	8118.75	8152.43	99.59
2024/12/1	26	0.23	31.56	0.59	4073.14	4105.52	99.21
2024/1/1	26	0.12	23.44	0.46	3765.48	3789.50	99.37
2024/2/1	45	0.22	26.76	0.68	8017.02	8044.68	99.66

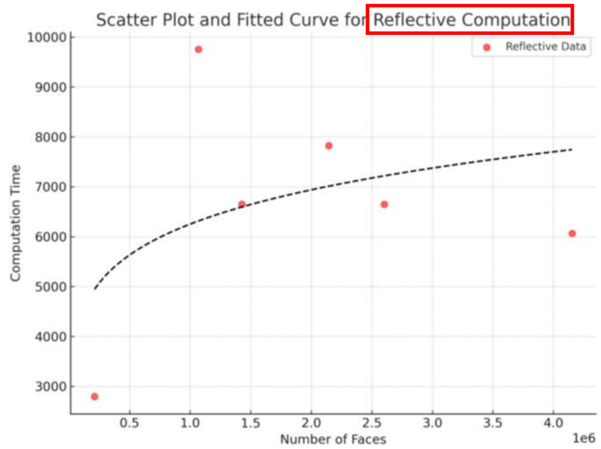
City	#Timestep	Shadow computation	SVF computation	Direct+Diffuse	Reflective	Total	Reflective ratio
Amsterdam	54	2.33	406.48	27.06	98302.20	98738.07	99.56
Delft	54	1.57	301.10	16.21	79782.55	80101.43	99.60
Rijssen-Holten	54	1.02	151.44	5.97	42941.12	43093.58	99.65
Rotterdam	54	1.58	240.70	14.39	80424.76	80681.43	99.68

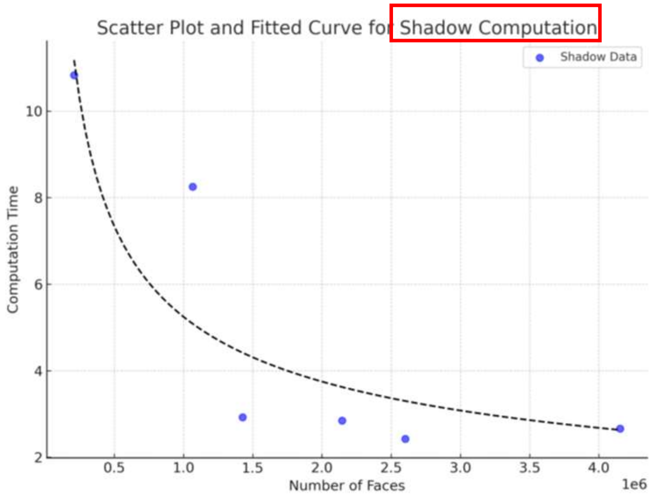
Attribute	Amsterdam	Delft	Rijssen-Holten	Rotterdam
Geographic center	4.88E, 52.37N	4.37E, 52.01N	6.52E, 52.31N	4.50E, 51.90N
H3 indexes	871969c9bffffff 871969526ffffff 871969534ffffff 871969535ffffff 871969530ffffff	86196bb17ffffff	871f16cf1ffffff 871f16cf5ffffff 871f16cc4ffffff 871f16ce6ffffff 871f16ce2ffffff	87196bb52ffffff 87196bb51ffffff 87196bb50ffffff 87196bb53ffffff 87196ba2cffffff
Spatial extent	7091 * 5070 * 98	6680 * 6689 * 119	6100 * 6200 * 50	6998 * 5109 * 190
#Buildings/#Faces	46273/3499950	40210/1744663	15744/717747	31004/1322841
#Roof surfaces	214927	119189	49827	28847
#Wall surfaces	780241	428357	174436	317257
#Trees/#Faces	21833/523992	28512/684288	25358/608592	28847/692328
#Terrain/#Faces	435/130241	535/173378	398/100091	435/130006
#Total faces	4154183	2602329	1426430	2145175
#Sample points	16214787	12000715	6457806	10279549

Results & Discussion: Findings

- **Method scalable for city-scale applications**
  - Simulation not detailed model reflective components takes within several minutes
  - 1~5 hours for simulation of 1 million sample points, one day, 10 minutes time interval)
  - 24 hours for 16 million sample points







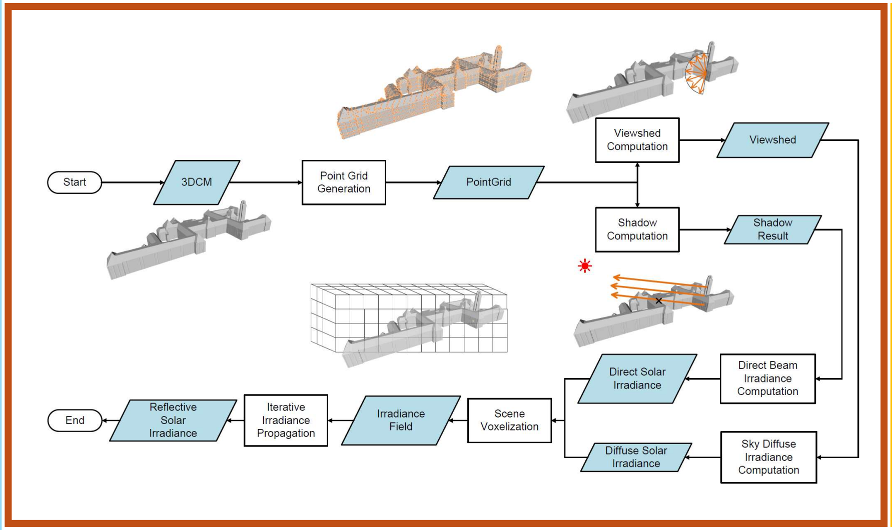
Results & Discussion: Limitations

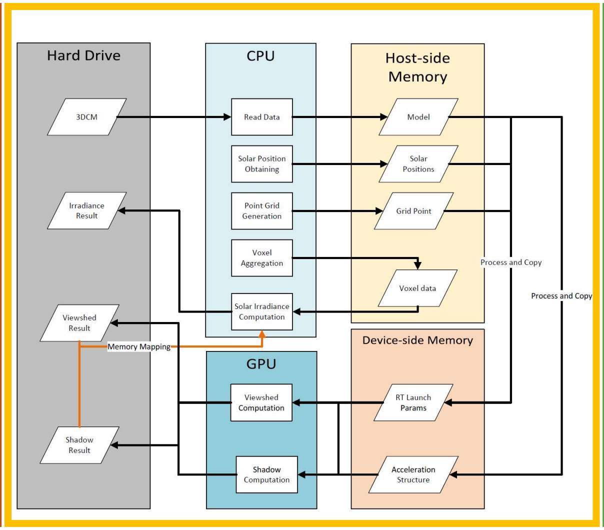
- **Accuracy**
  - Under overcast conditions the method does not show clear advantage
- **Computation Time**
  - Reflective solar irradiance computation takes up over 99% of computation time (Not optimized)
- **Ground Measurement Data Availability**
  - Only S2 has complex visibility
  - Lack of material data
- **Simplification still exist**
  - 3DCM
  - Isotropic model for sky diffuse
  - Voxelization
  - Assume all surfaces to be Lambertian surfaces

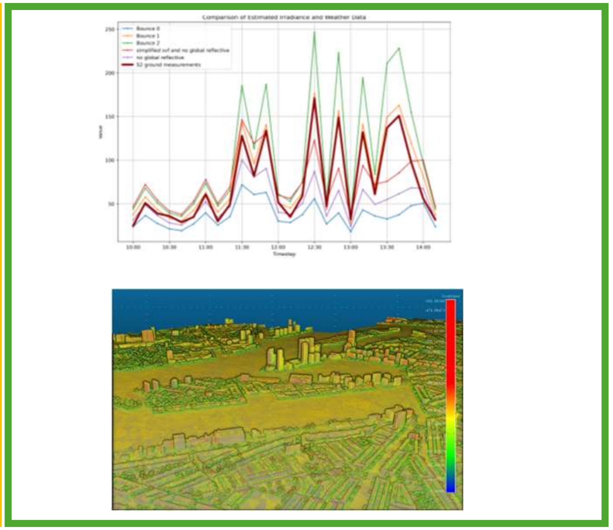
Conclusions

Conclusions

Developed, implemented, and tested a solar irradiance simulation method that is realistic and scalable.







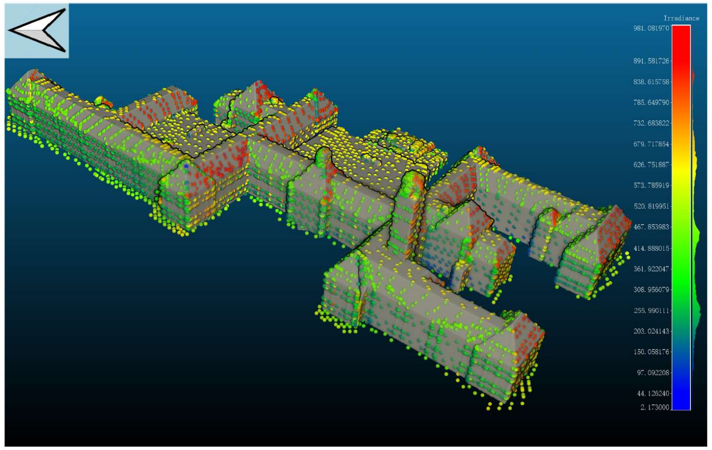
Development

Implementation

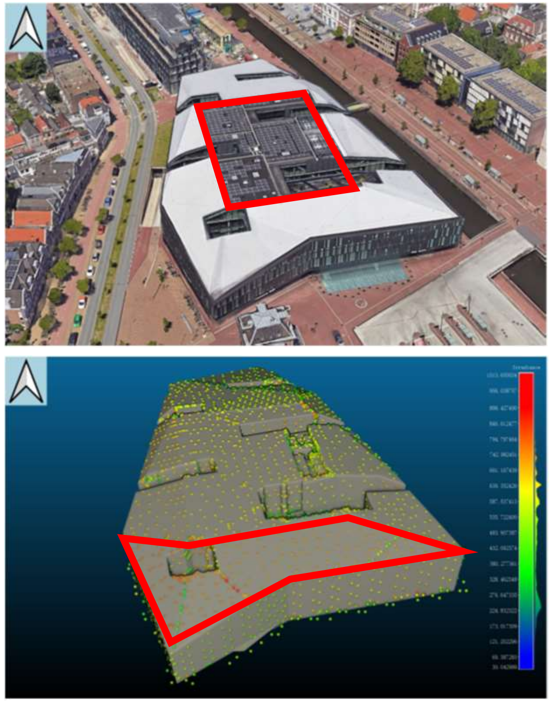
Testing

Conclusions

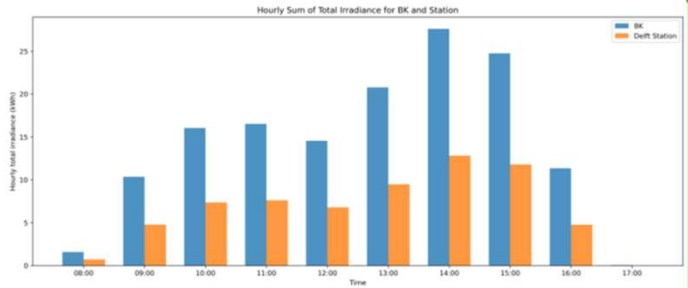
We discussed and tested the potential applications of the proposed simulation method.



Visualization



Solar panel installation



Energy potential

Conclusions: Future work

- More detailed input data
- Enhanced modeling of sky diffuse irradiance
- Improved light field representation
- Model calibration
- Database input support
- Integration with remote sensing data

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Thank you for your attention!

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