From GIS to 3D flow simulations in urban environments

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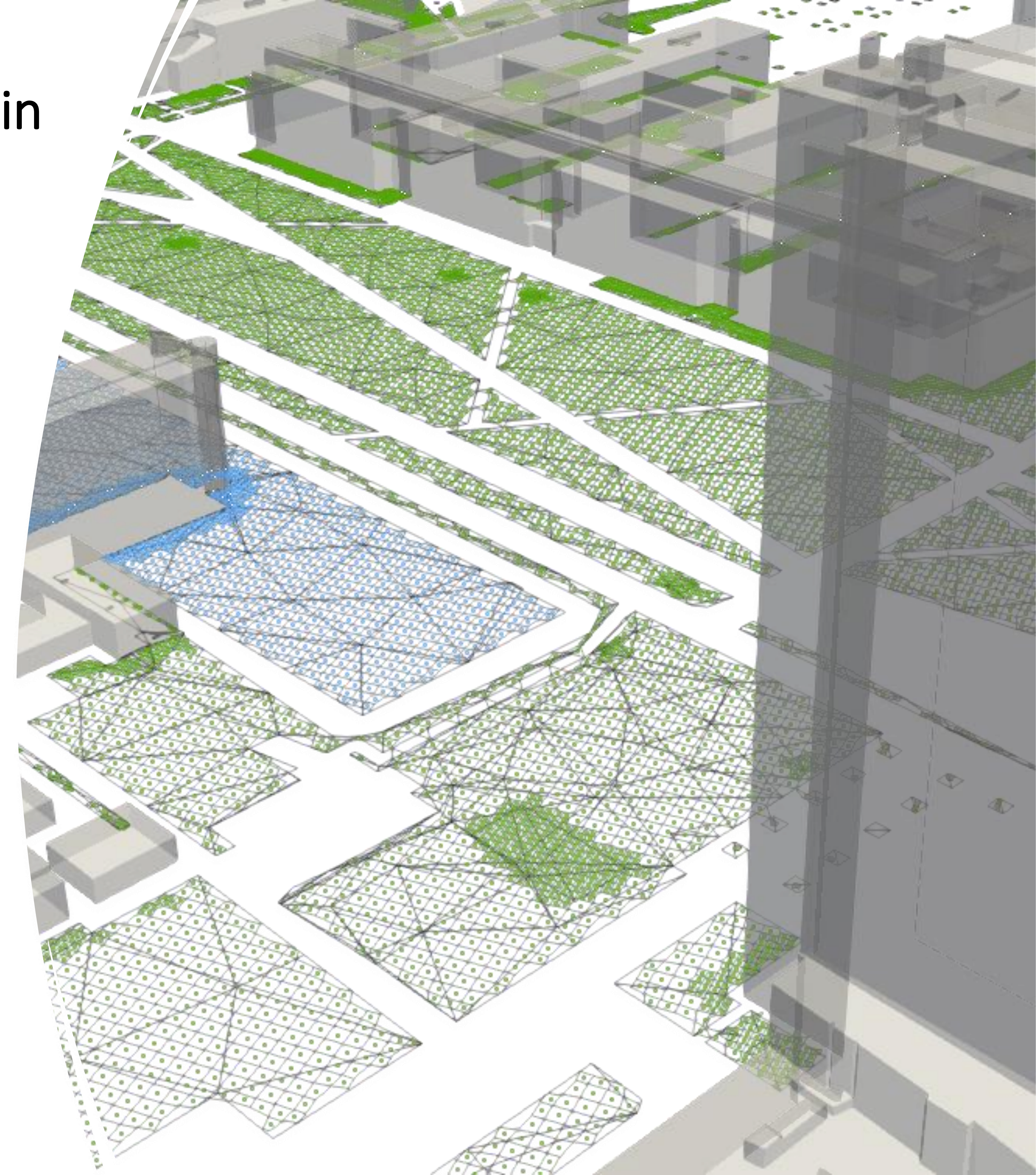

Plan overview

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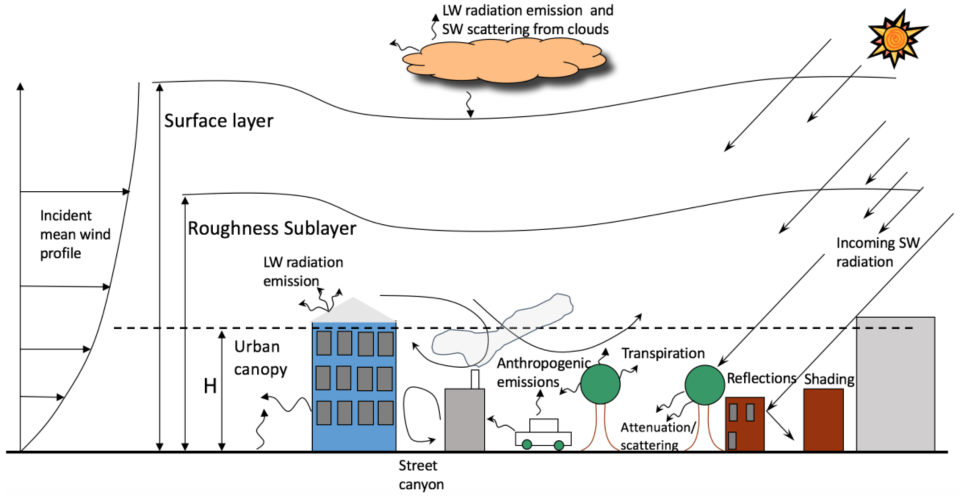
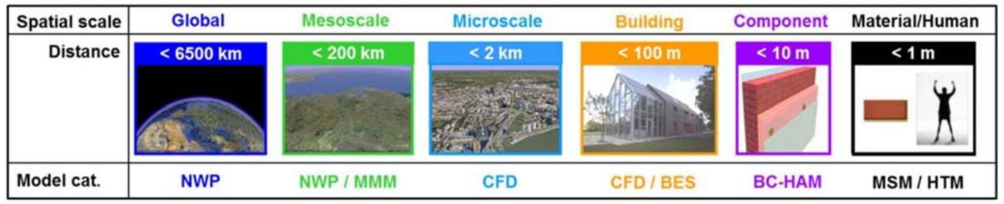
Introduction
CFD

- CFD is mainly implemented for processes in the microscale
- Predictive scenarios
- Time and cost efficient



Transport processes in the UBL[Pardyjak and Stoll, 2017]

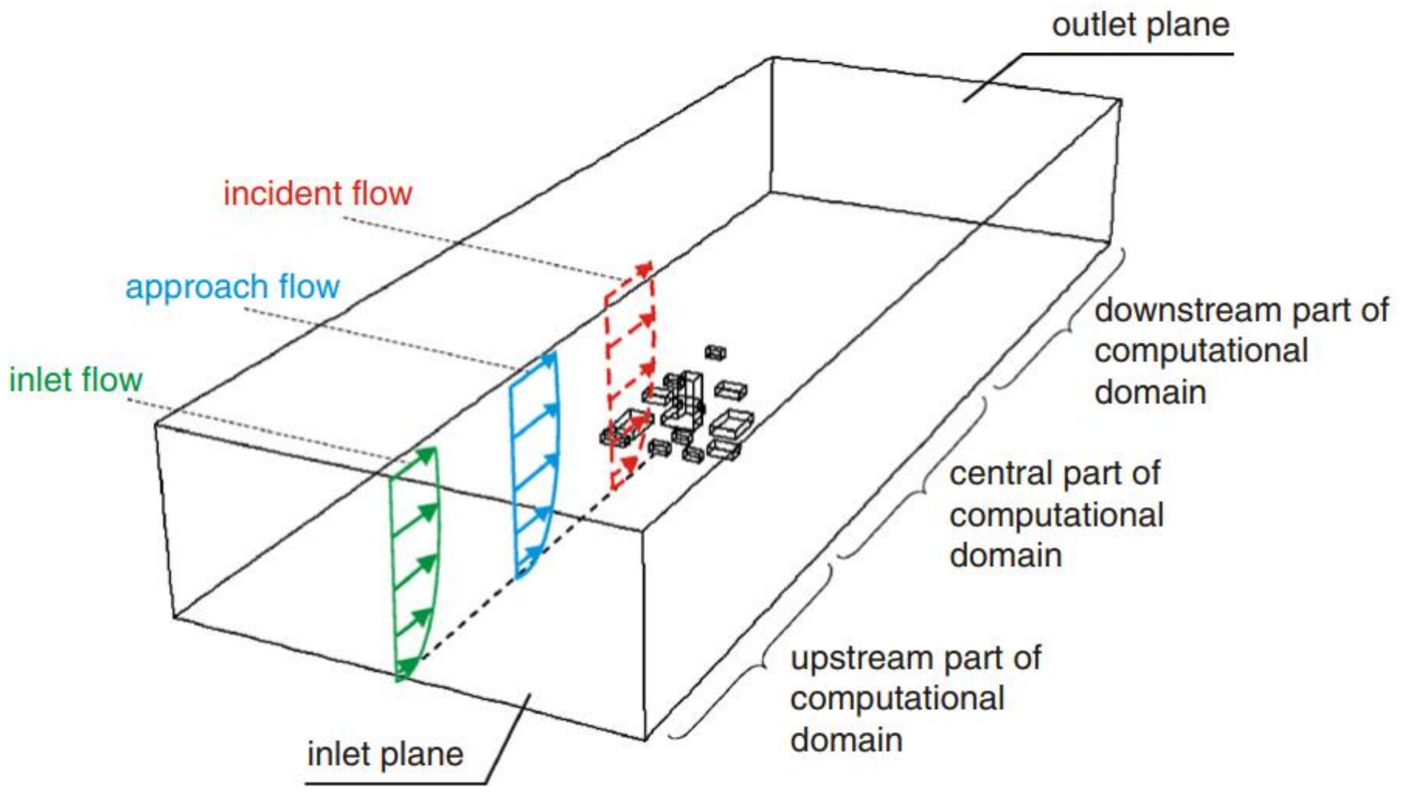


Horizontal spatial scales of the UBL [Blocken, 2015]

Introduction
CFD

- Values of the flow parameters are computed inside the defined boundaries of a computational domain, at discrete point locations.

- Use of explicit representation of urban morphology

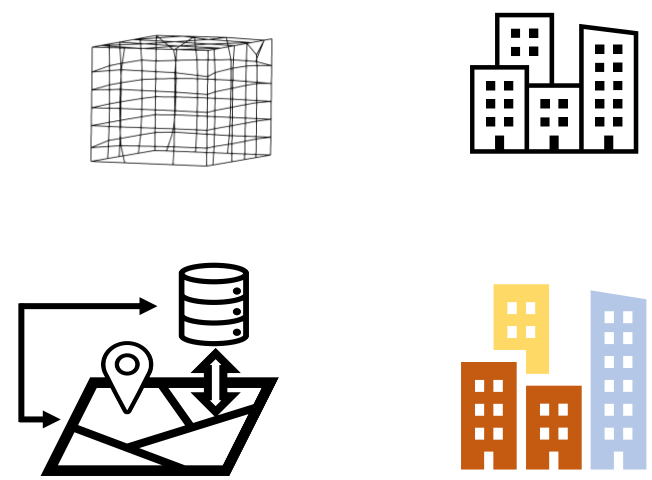


Computational domain areas from [Blocken et al., 2007]

Introduction

CFD - GIS

- Mesh generation
- Spatial databases for CFD
- 3D models
- Semantic 3D models

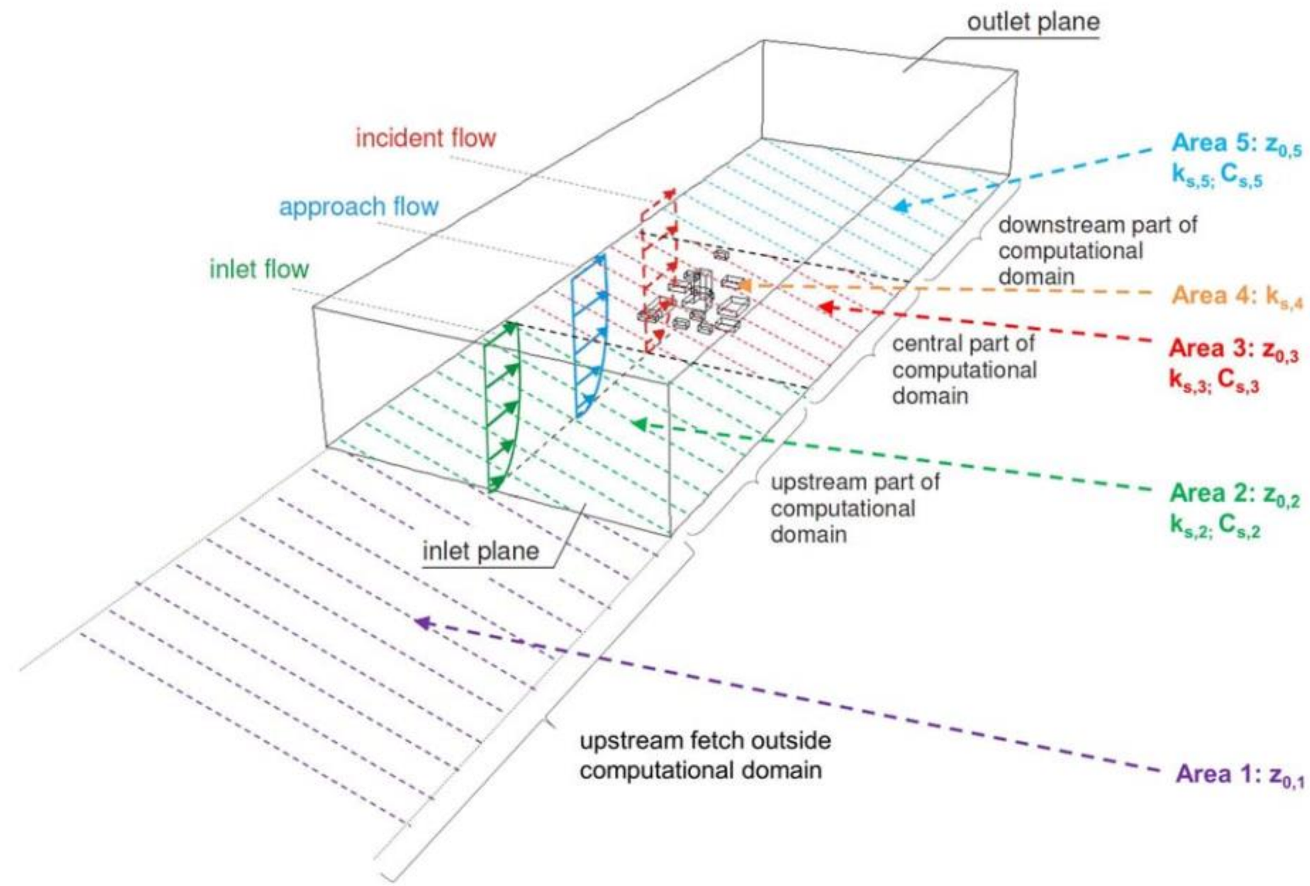


Introduction

Roughness length

The height above the surface of the Earth at which the mean logarithmic wind profile becomes zero [Oke, 1978]

- Implicit representation



Computational domain areas from [Blocken et al., 2007]

Research Questions

Main research question:

How can non-uniform roughness length be integrated in a CFD software like OpenFOAM through the use of 3D model semantics?

Sub-questions:

- To what extent can the integration be automated?
- How does the modified assignment process of roughness length at the bottom of the domain influences the process and results of the simulation?
- How does the modified assignment process for non-uniform roughness length at the inlet of the domain influences the process and results of the simulation?
- Which other relevant to CFD parameters could be used as 3D model semantics with the built application?

Suggested parameters

Geometric:

- LAD/LAI: Leaf area per unit volume of space/ Integration of LAD over height

Radiative:

- Albedo: Determines the absorptivity of a surface
- Emissivity: Ratio of radiation emitted by a material to that emitted by a blackbody at the same temperature [Oke, 1978].

Thermal:

- Thermal conductivity: Measure the ability of a material to conduct heat [Oke, 1978].
- Thermal admittance: quantifies the ability of a surface to absorb and release heat from/to space over time [Oke, 1978].

Other:

- Colour: Darker coloured surface materials can contribute to the absorption of radiation.

Related work

Implementations of non-uniform z0 in OpenFOAM

01

OpenFOAM implementation:

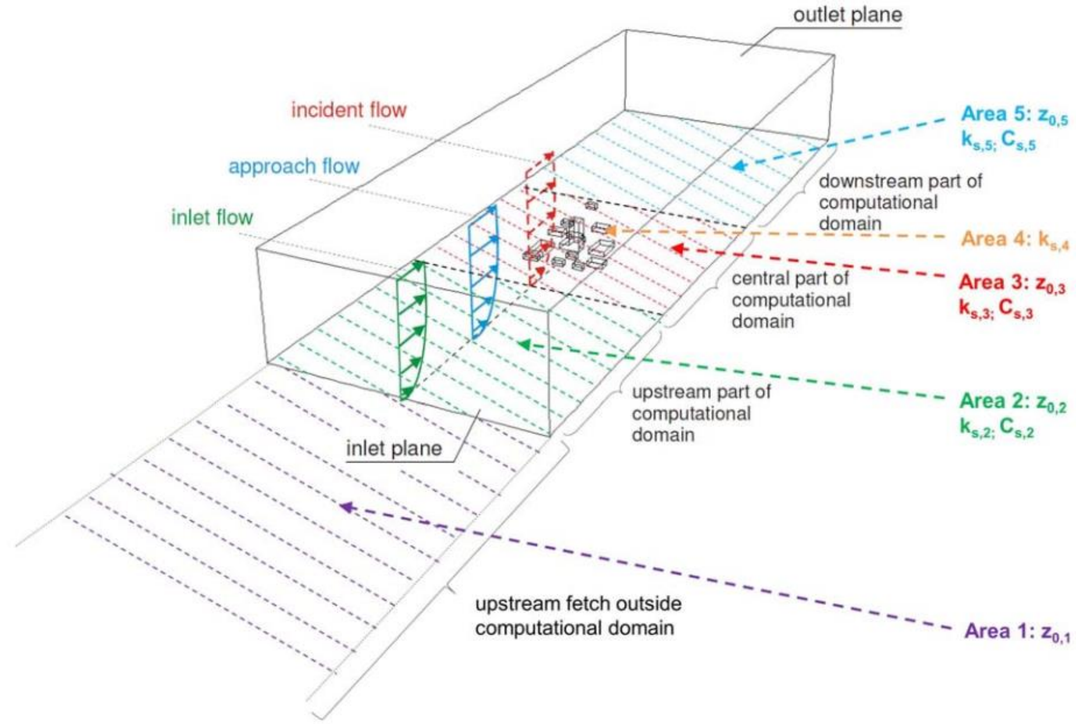
- Separate geometries
- Need for specification of multiple entries

Segersson (2017):

- Specification through fvOptions utility
- Roughness length is stored in a raster file
- Requires structured grid

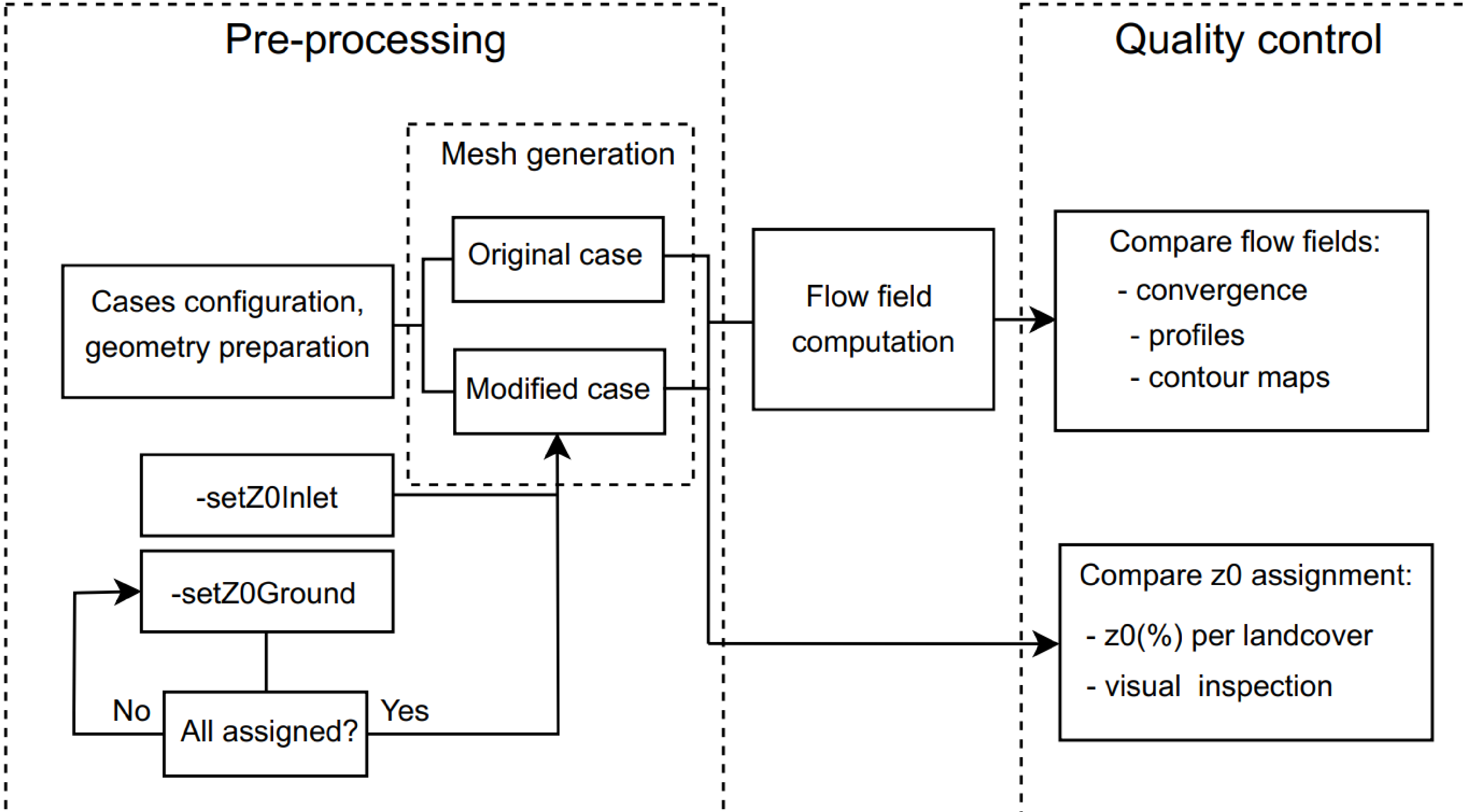
Azevedo (2013):

- Specified z0 entry as a non-uniform scalar field



Computational domain areas from [Blocken et al., 2007]

Methodology
Workflow



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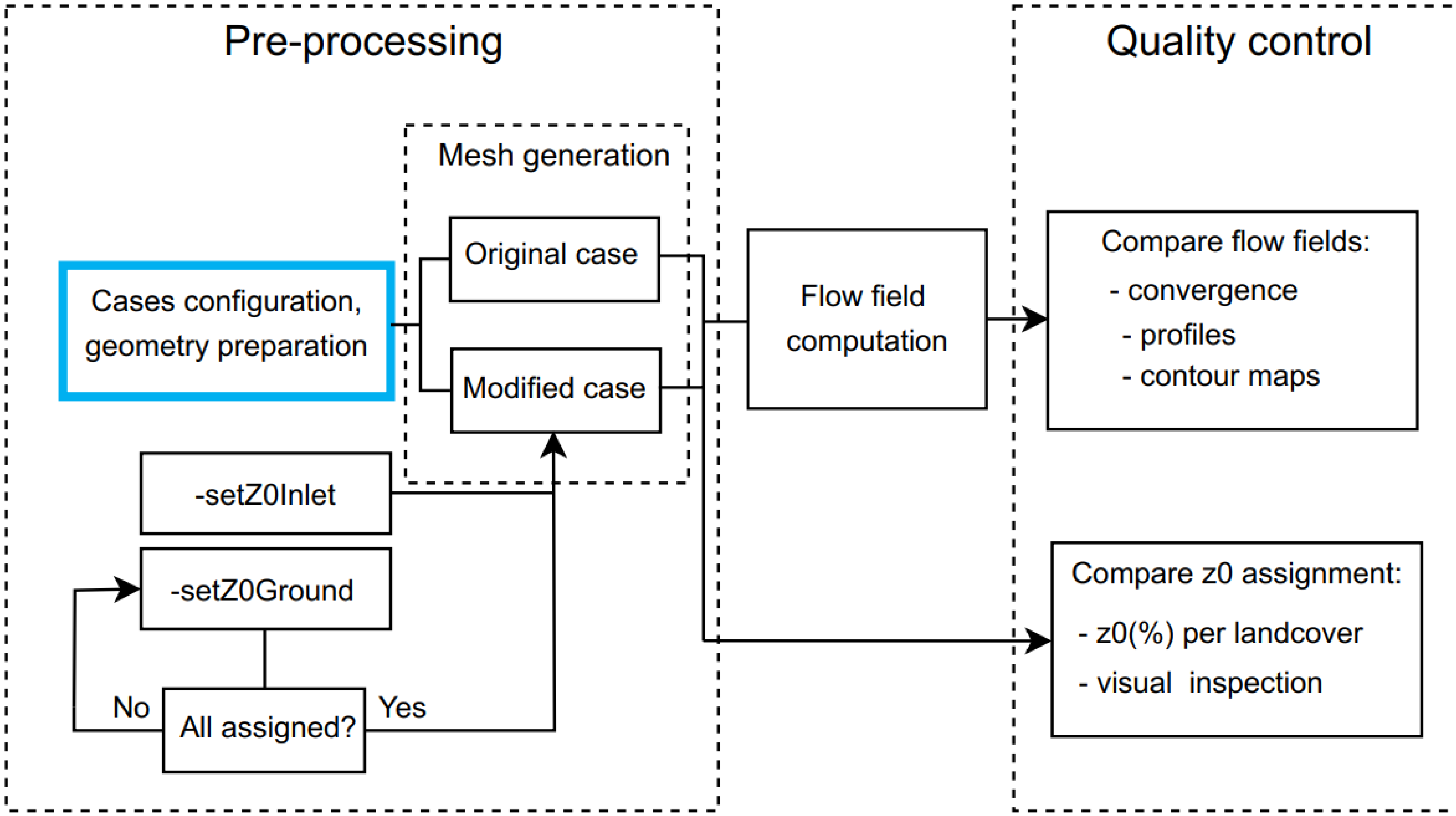
Methodology
Workflow – Pre-processing

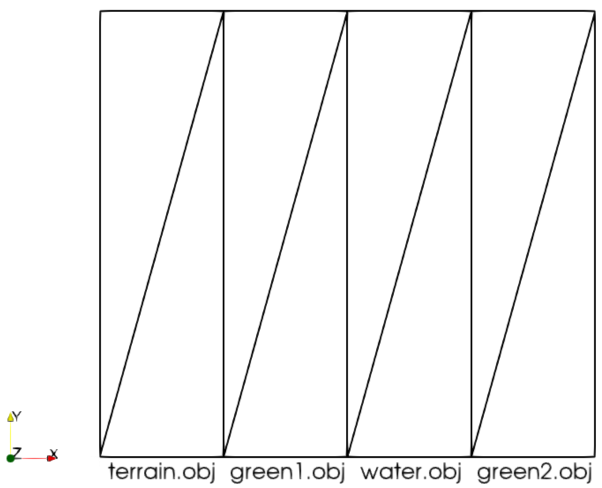


Methodology

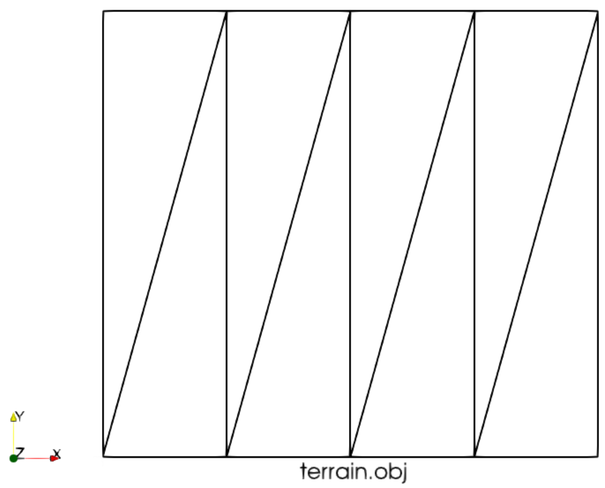
Geometry preparation – Ideal cases input models

Case	Faces	Vertices	Patch name	Landcovers
s_0	2	4	terrain	1
	2	4	green1	1
	2	4	water	1
	2	4	green2	1
s_1	8	10	terrain	3
s_2	11	12	terrain	3

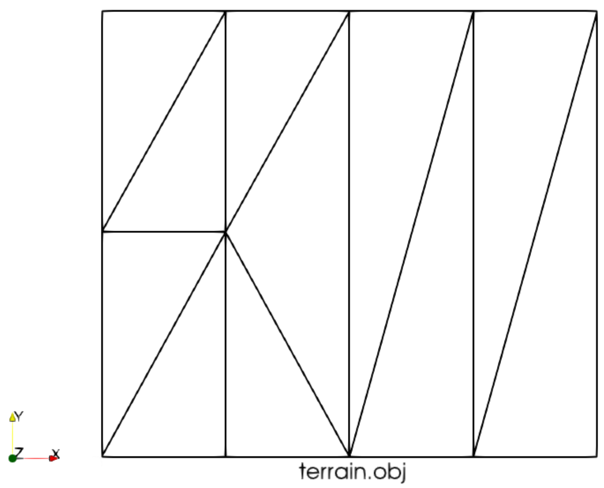
Geometry and patch details



s_0 model



s_1 model

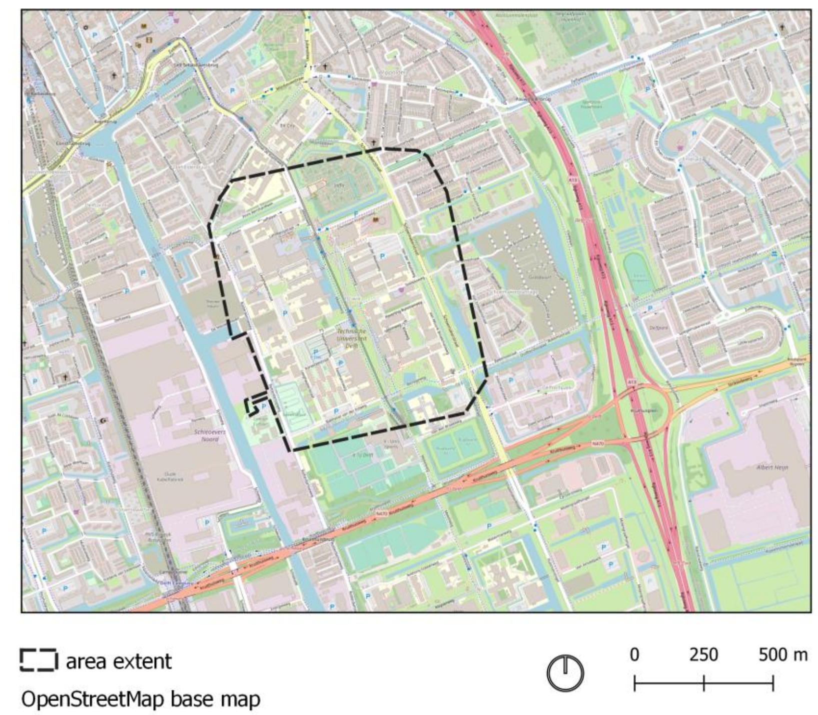


s_2 model

Methodology

Geometry preparation – TU Delft cases input models

c_0 model



Area of interest at TU Delft campus

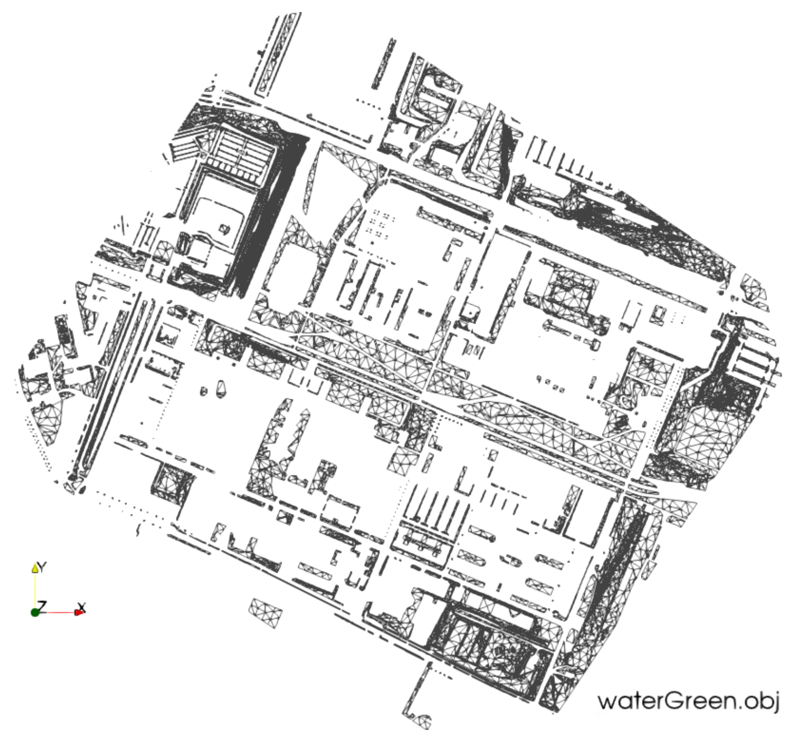
Methodology

Geometry preparation – TU Delft cases input models

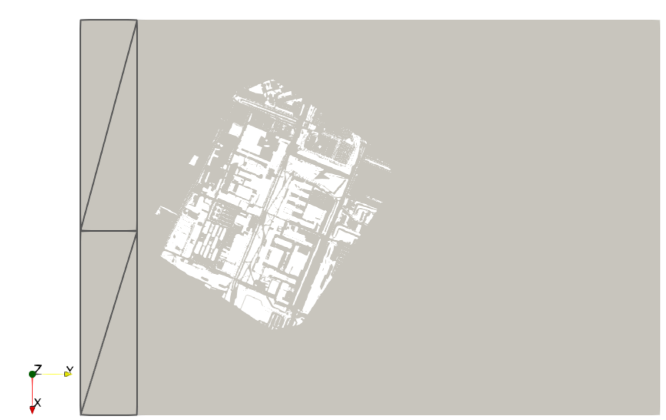
Case	Faces	Vertices	Patch name	Landcovers
c_0	24,468	20,050	Green	1
	9,495	6,127	Water	1
c_1	33,963	26,049	WaterGreen	3
c_1_1	33,963	26,049	WaterGreen	2
c_2	14	6	Terrain	2
	33,963	26,049	WaterGreen	2

Geometry and patch details

c_0 model



c_1 and c_1_1 model

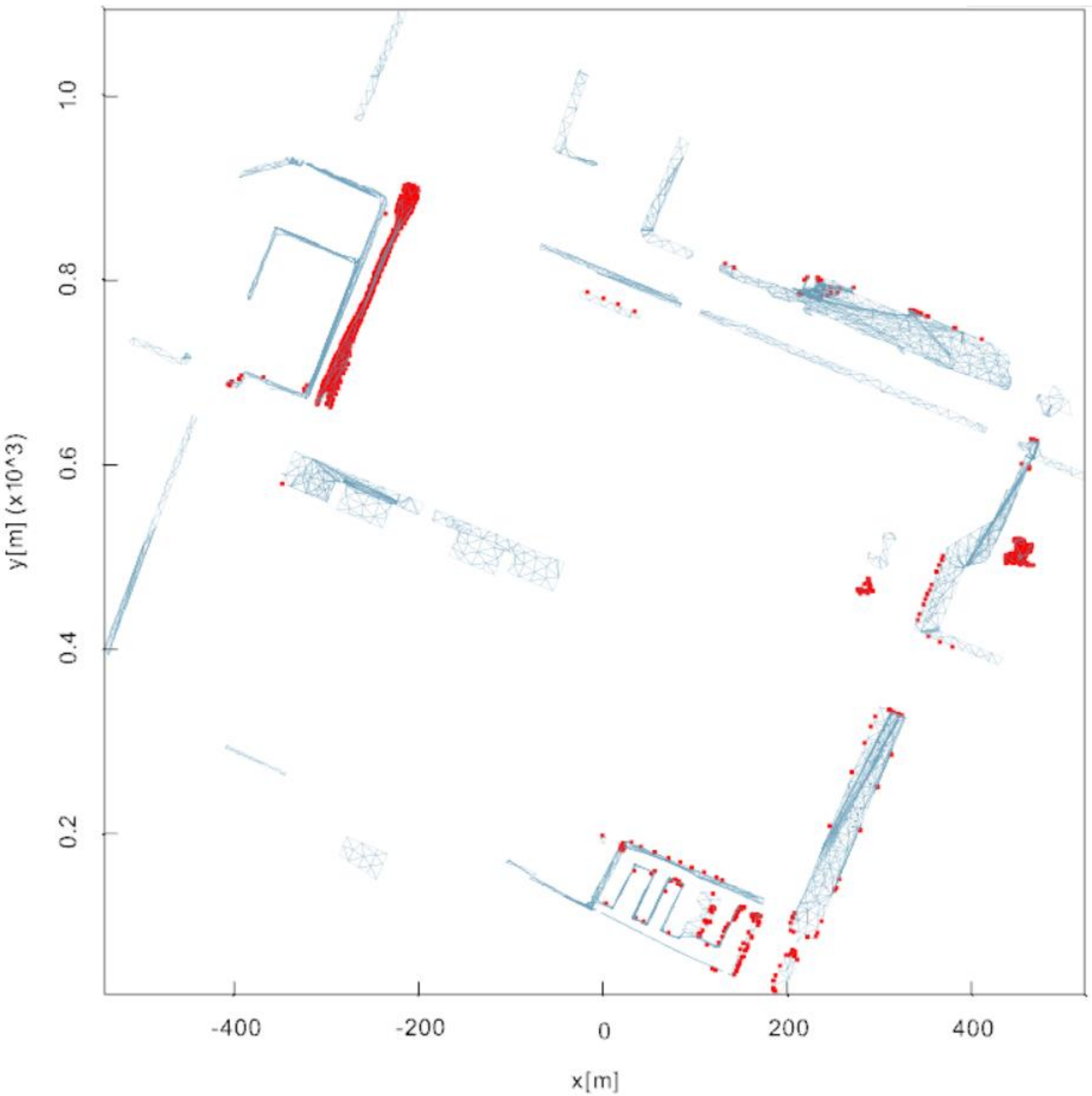


c_2 model

Methodology

Geometry preparation – TU Delft cases input model detected overlaps

- Blue : water surfaces
- Red : water surfaces that are overlap with vegetations



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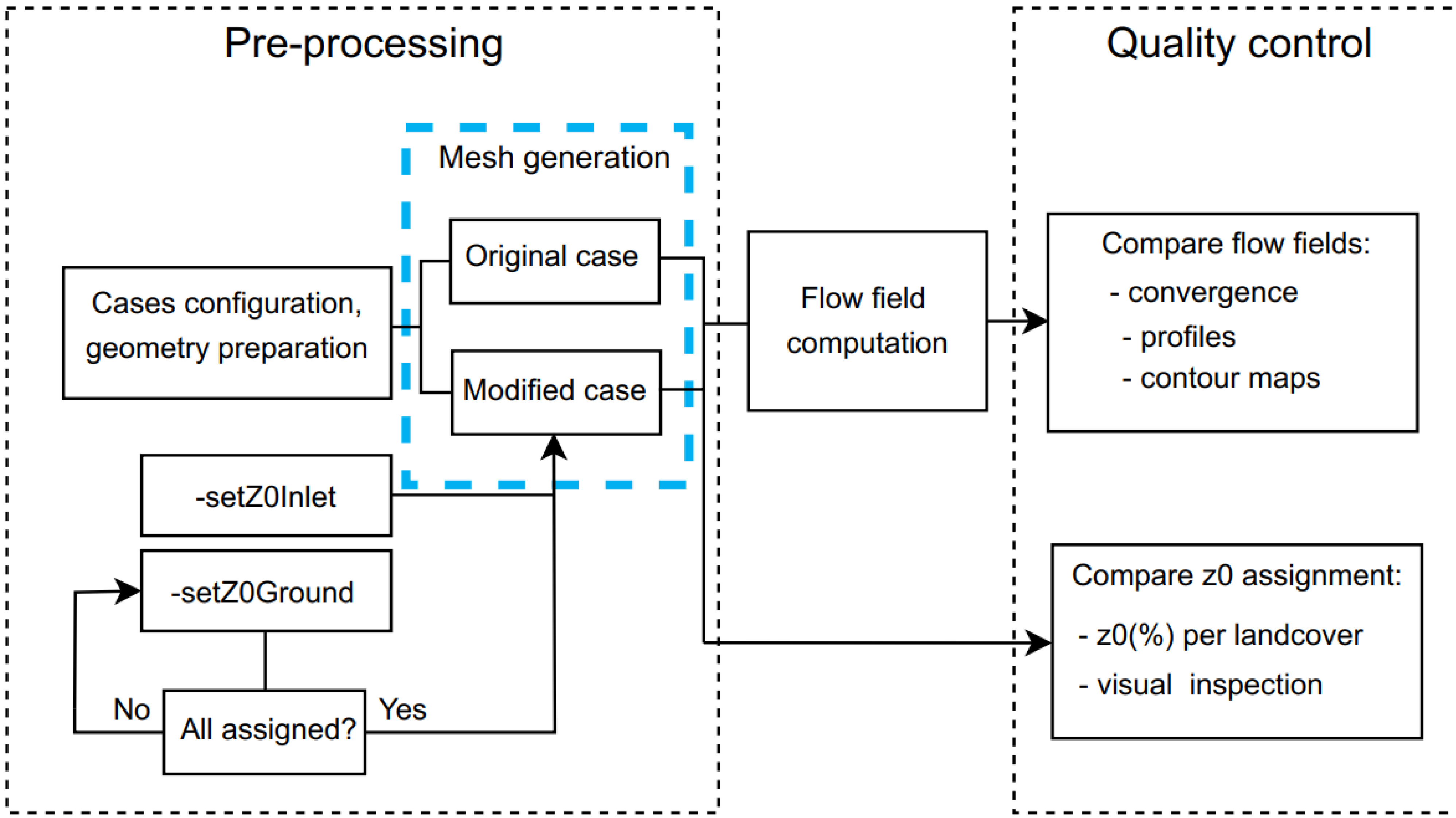
Methodology

Case configuration

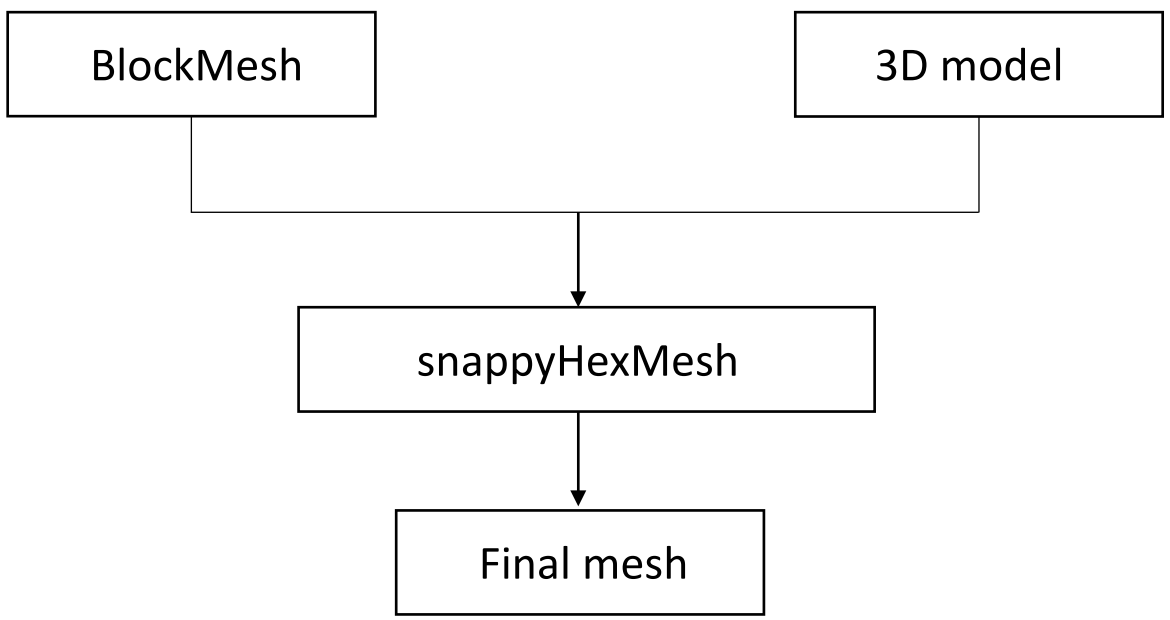
Case	Patch name	Landcovers	z_0
s_0	terrain	1	0.05
	green1	1	0.03
	water	1	0.0002
	green2	1	0.03
	inlet	-	0.05
s_1	terrain	3	[0.05, 0.03, 0.0002]
	inlet	-	0.05
s_2	terrain	3	[0.05, 0.03, 0.0002]
	inlet	-	[0.05, 0.03]
s_2_1	terrain	3	[0.05, 0.03, 0.0002]
	inlet	-	0.05
c_0	Green	1	0.03
	Water	1	0.0002
	Terrain	1	0.5
	y0	-	0.5
c_1	WaterGreen	2	[0.03, 0.0002]
	Terrain	1	0.5
	y0	-	0.5
c_1_1	WaterGreen	2	[0.03, 0.0002]
	Terrain	1	0.5
	y0	-	0.5
c_2	WaterGreen	2	[0.03, 0.0002]
	Terrain	3	[0.5, 0.03, 0.0002]
	y0	-	[0.03, 0.0002]
c_2_1	WaterGreen	2	[0.03, 0.0002]
	Terrain	3	[0.5, 0.03, 0.0002]
	y0	-	0.03

- Steady Reynolds –averaged Navier-Stokes (RANS)
- Standard k - ϵ
- Modified epsilon wall function to accommodate the non-uniform roughness based on Parente et al. (2011)

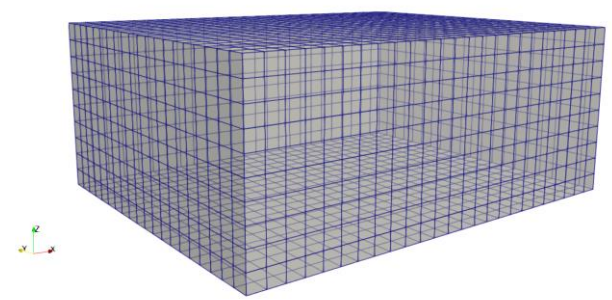
Methodology
Workflow – Mesh generation



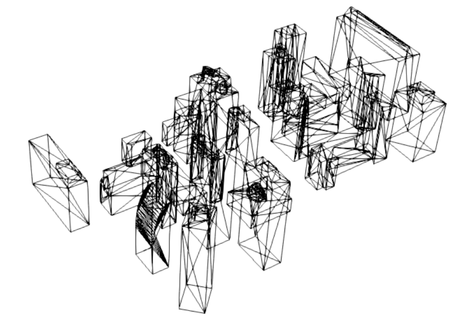
Methodology
Mesh generation – utilities



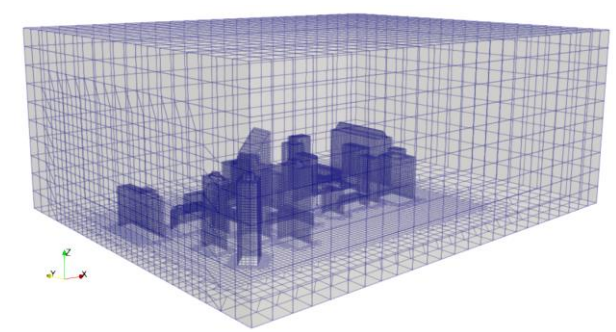
Background mesh



Triangulated model

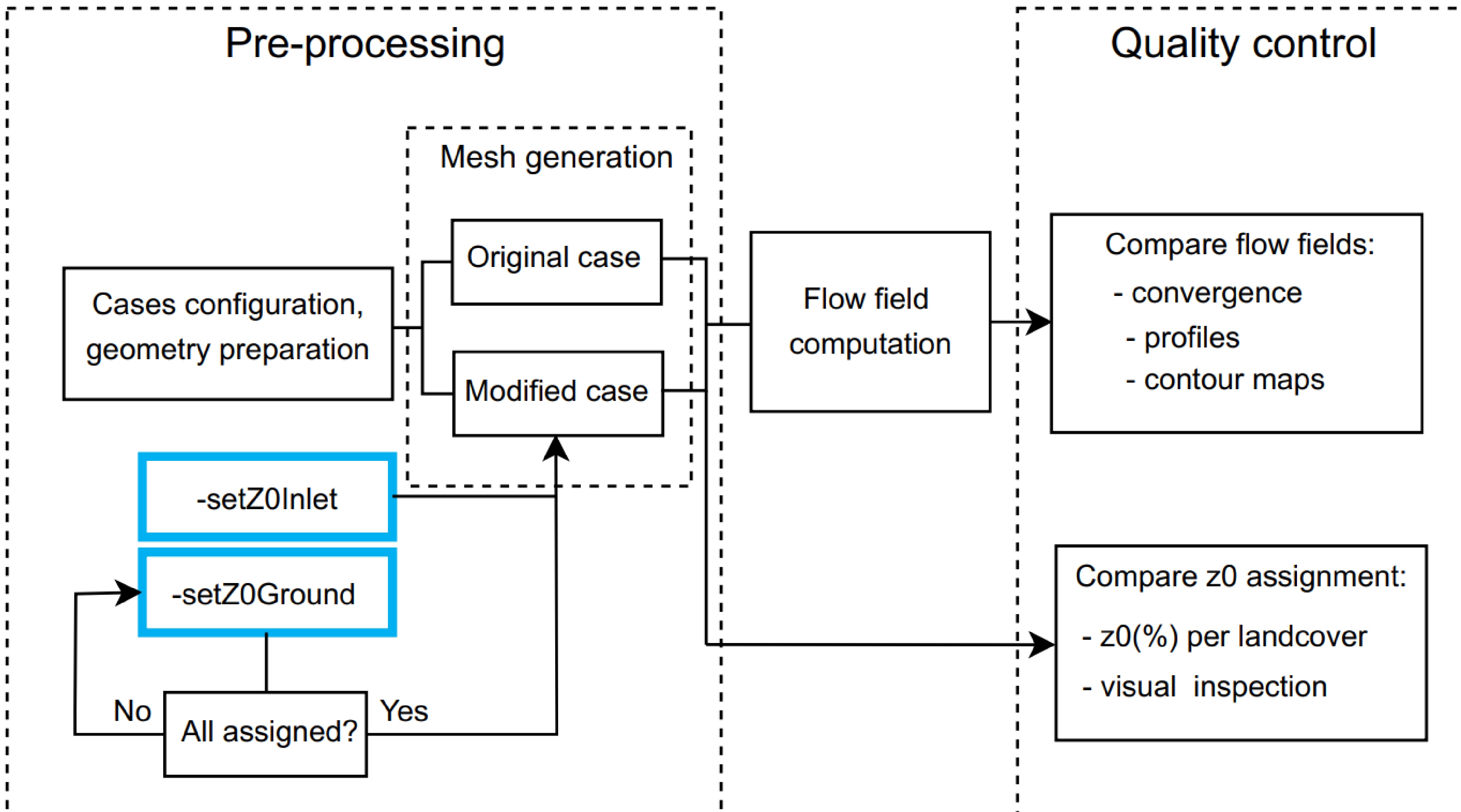


Refined mesh



Screenshots based on tutorial case ‘windAroundBuildings’

Methodology
Workflow – Options



Methodology

Application - options

- entry
- setZ0Ground <patch name>
- setZ0Inlet <patch name>
- writeZ0
- writeCoords
- exportToVtk
- setZ0NoGeom <z0 value>
- setParams

```
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "constant";
    object      setZ0;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

    inputFile     "constant/triSurface/terrain4nonUniformInlet_translated.obj" ;
    inputMtl      "constant/triSurface/terrain.mtl";
    flowDir     (1 0 0);
    nearDist    0.8;

    z0_values
    {
        Terrain     0.05;
        Water       0.0002;
        Green       0.03;
    }

    Params_Inlet
    {
        Uref        10;
        Zref        20;
        Cmu        0.09;
        kappa       0.41;
    }


// ************************************************************************* //
```

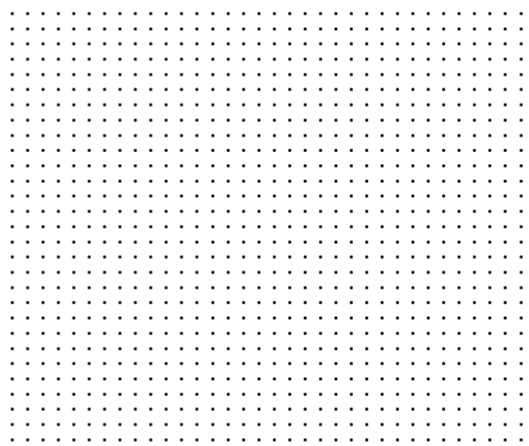
User-specified dictionary

```
medium_v0$ setZ0 0/include/ABLConditions  -entry z0 -setZ0Ground terrain
```

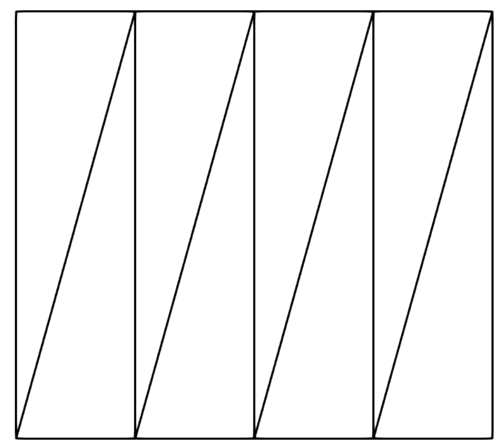
App name | Destination dictionary | Entry in dict name | Option name

Methodology
Application – options - Input

-setZ0Ground

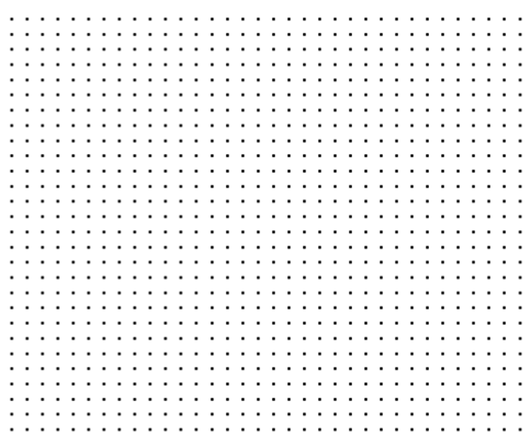


+



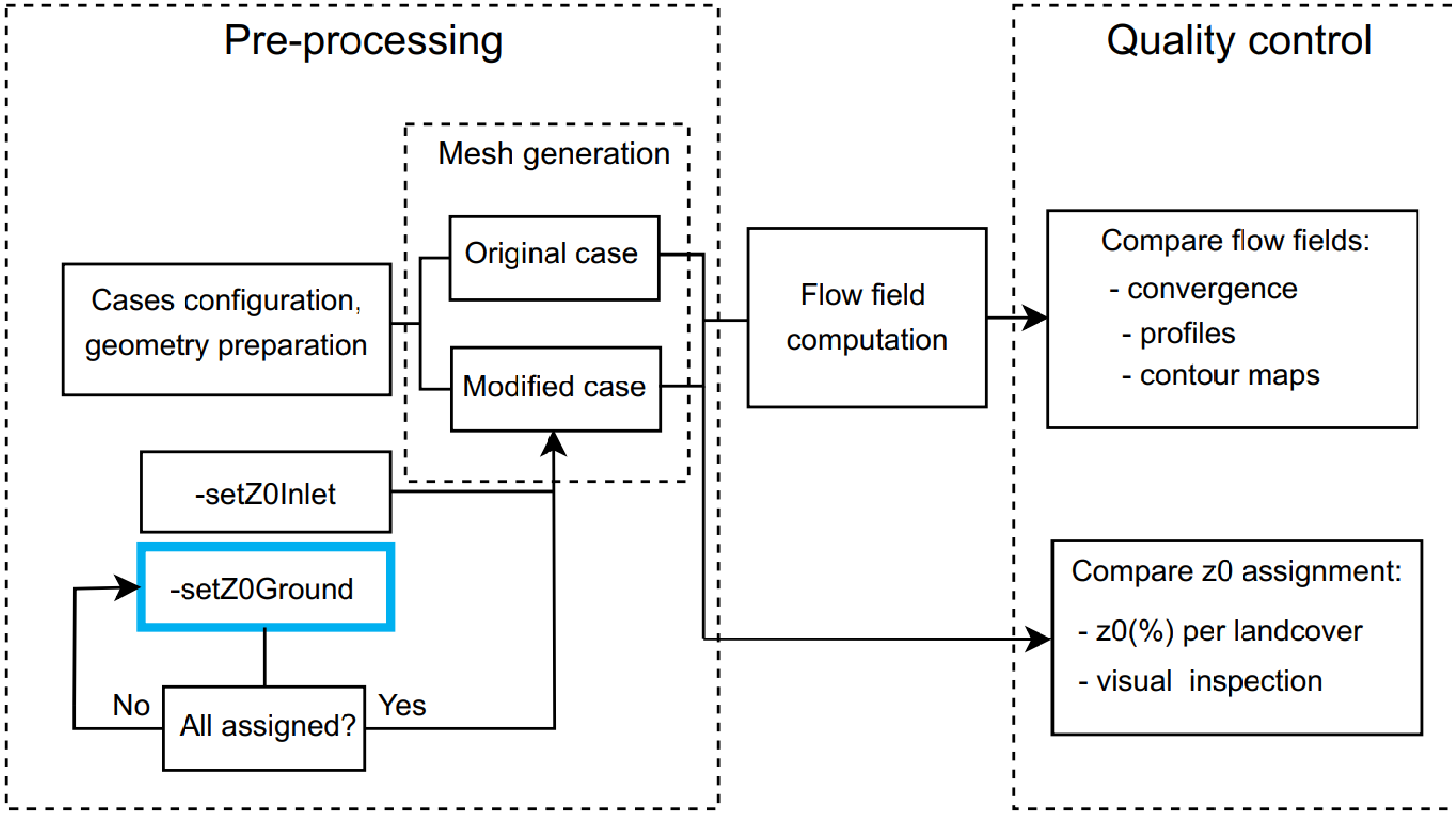
+ User – specified parameters

-setZ0Inlet



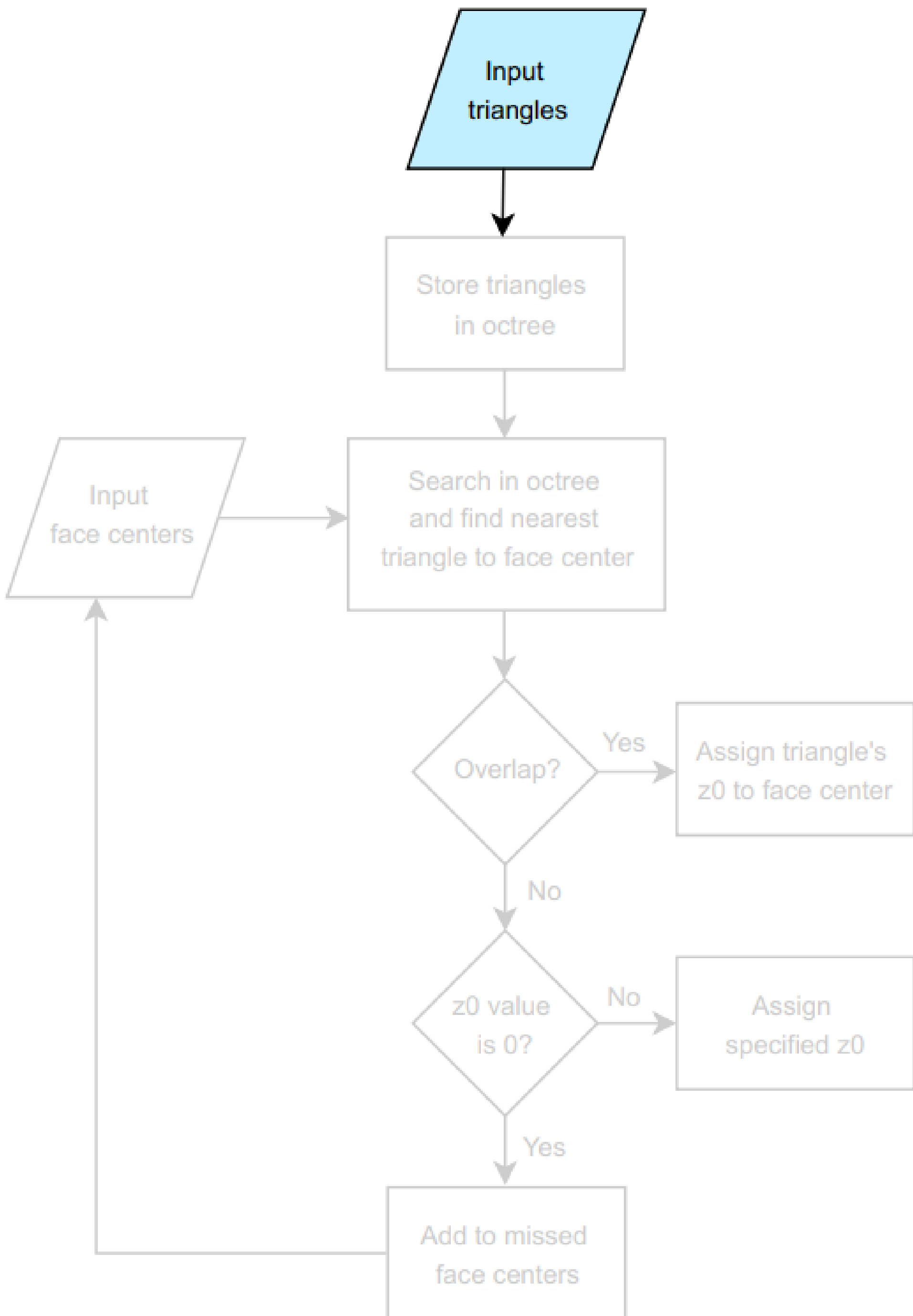
+ User – specified parameters

Methodology
Workflow – option -setZ0Ground



Methodology

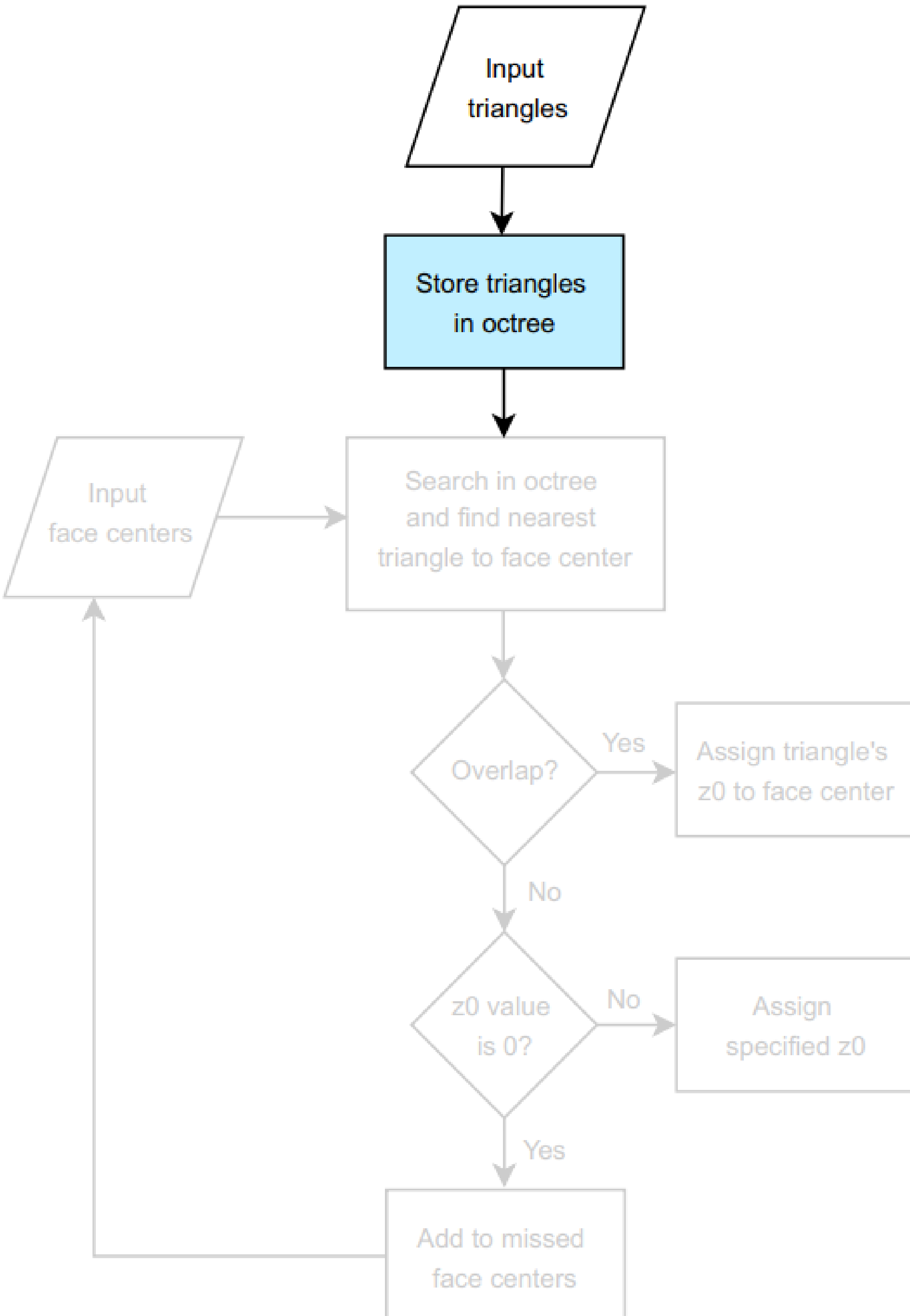
Option –setZ0Ground – Input geometry requirements

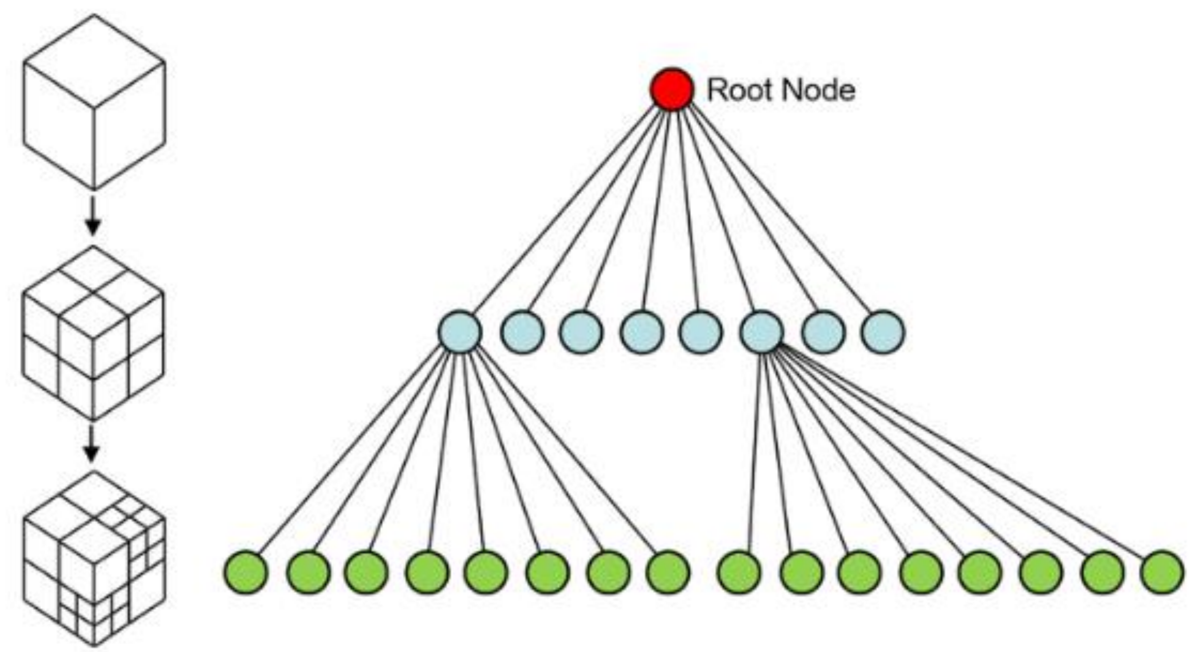


Geometry requirement:

- No duplicate vertices
- Compact content
- No self-intersections
- Watertight

Option –setZ0Ground – Octree specifications





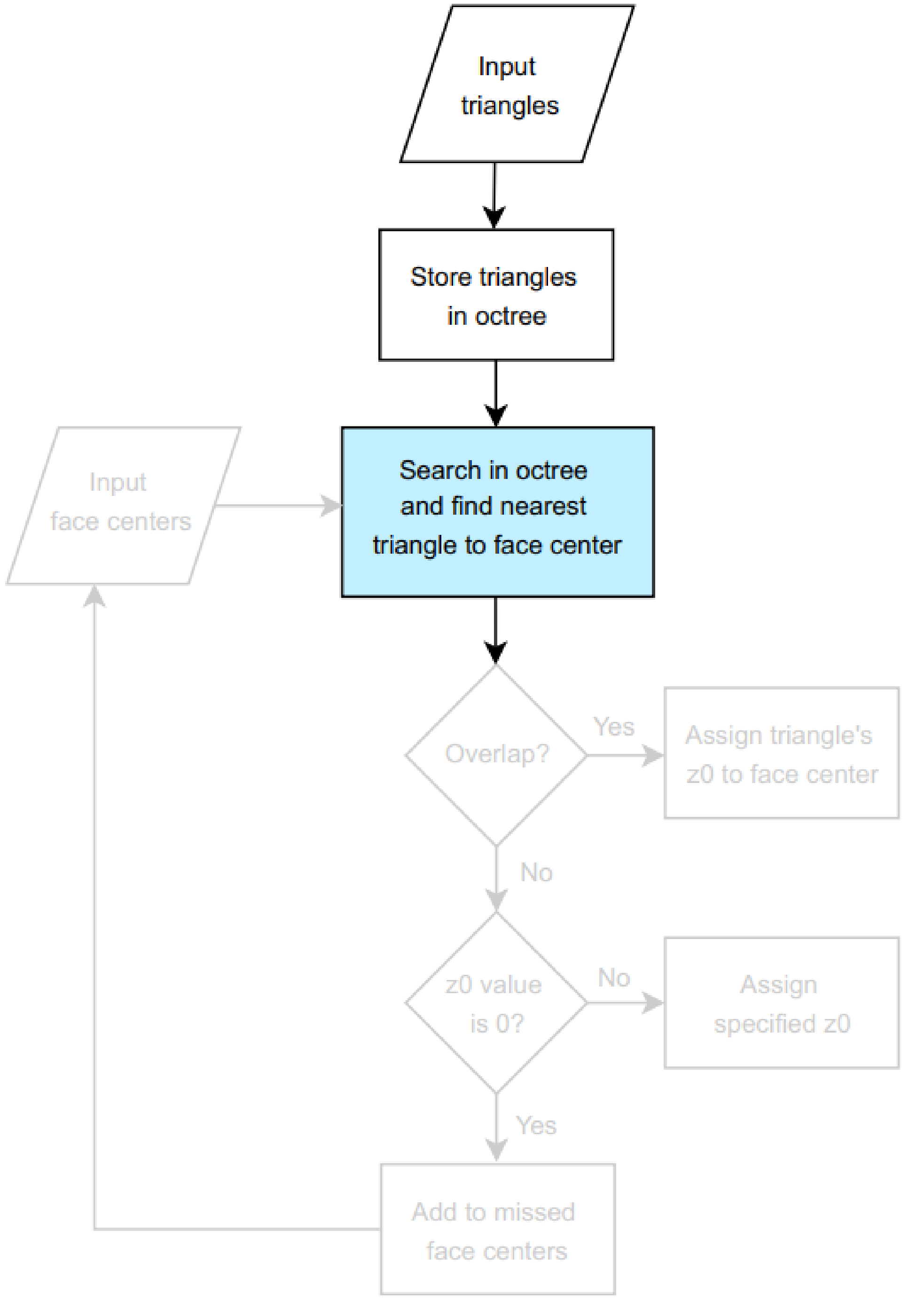
Ocree of depth 2 visualisation and graph illustration [Su et al., 2016]

Requirements:

- Maximum 10 triangles per leaf
- Every triangle maximum 3 references

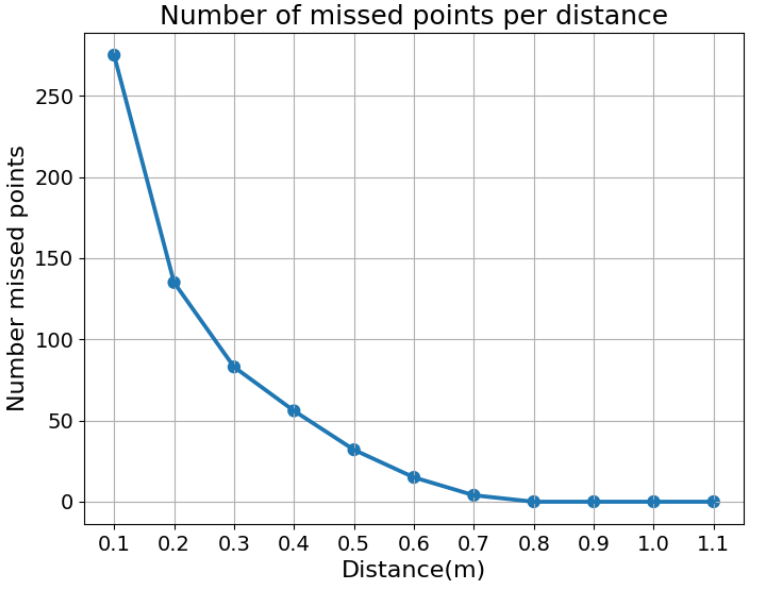
Methodology

Option –setZ0Ground – Octree search



Transform user-defined nearDist to the distance that will be used in the find nearest search as follows:

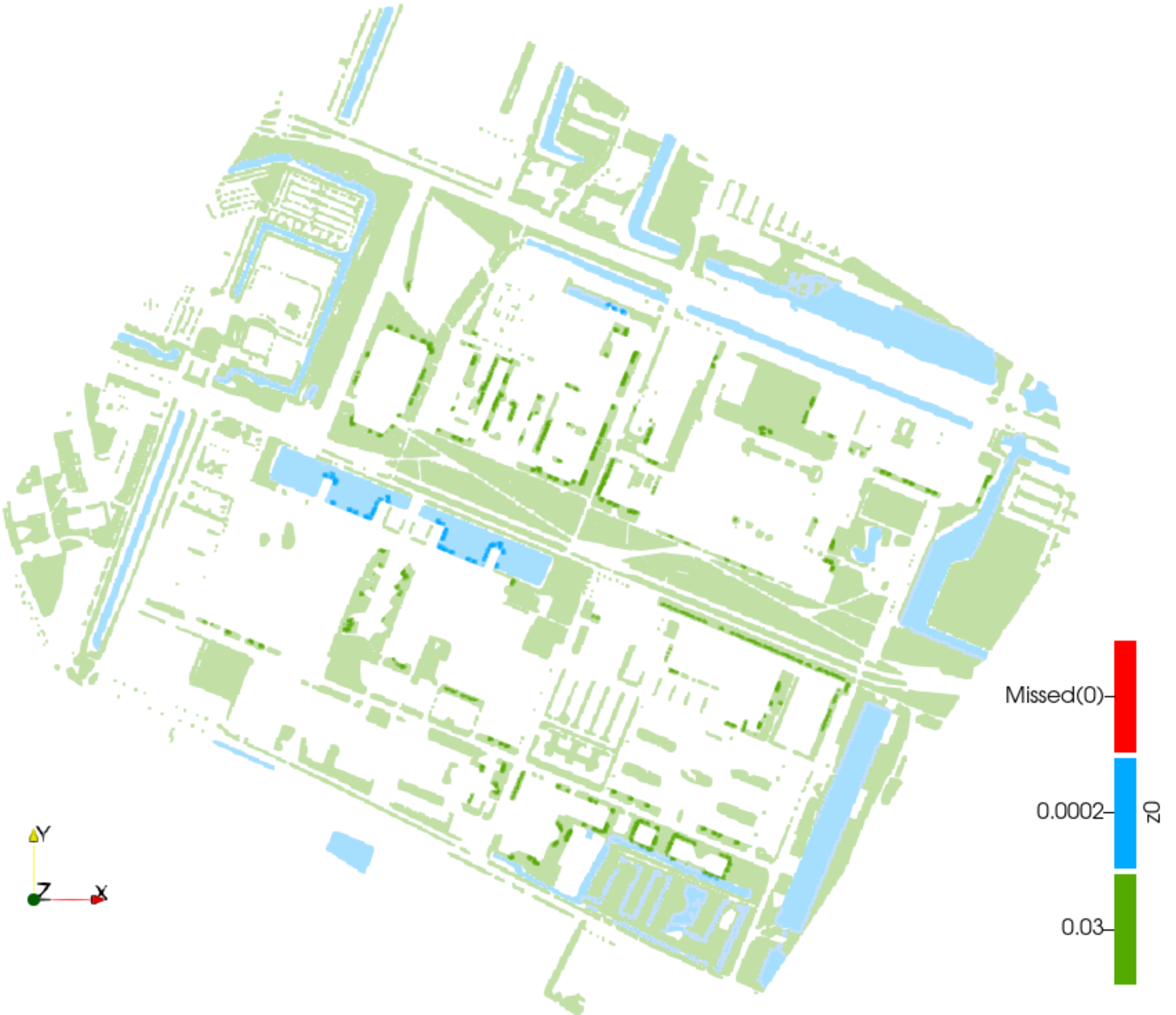
$$nearDistSqr = 0.25 * (nearDist^2 + nearDist^2 + nearDist^2)$$



Methodology

Option –setZ0Ground – Seed distance used in octree search

nearDist 0.1 m



nearDist 1,000,000 m

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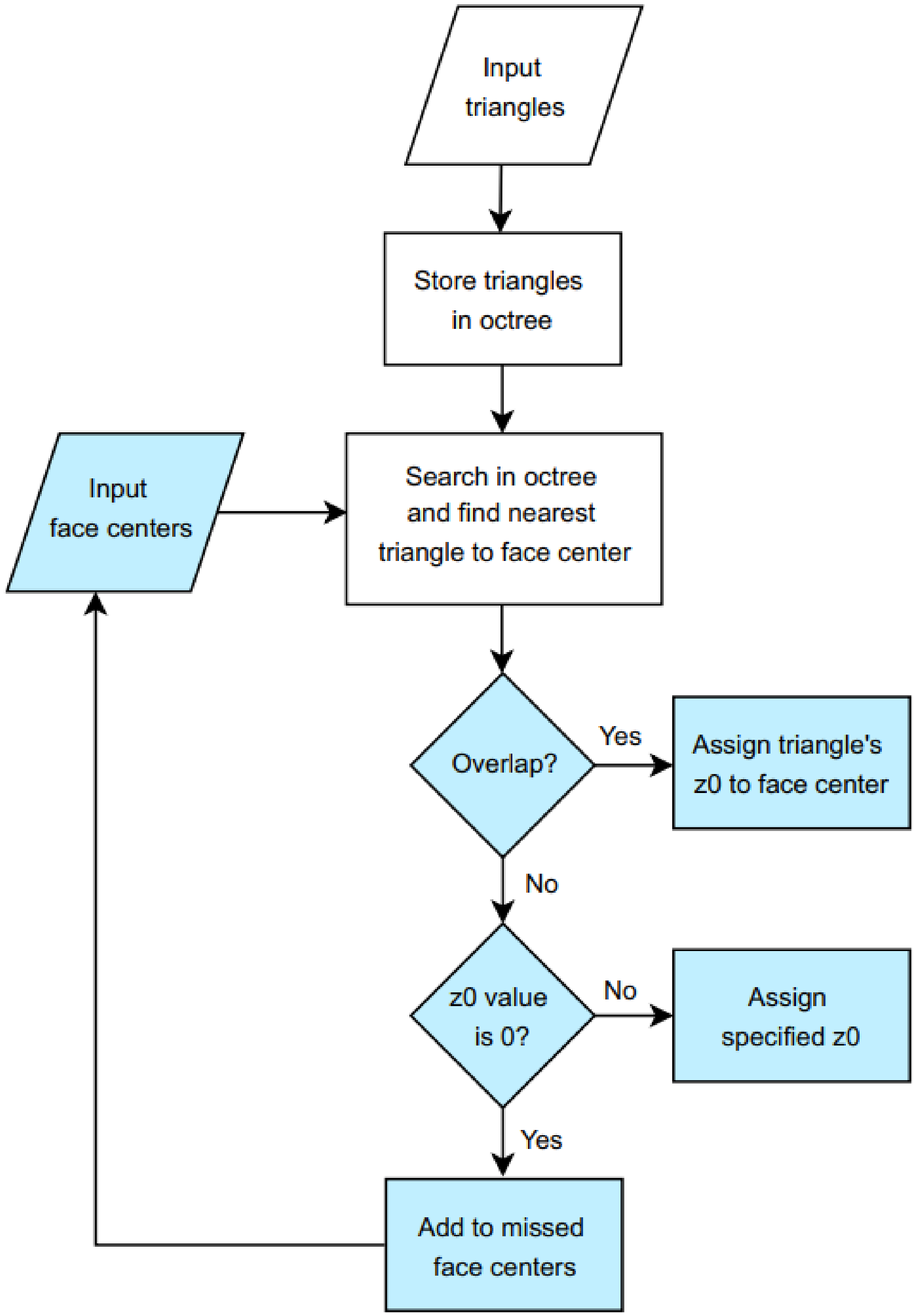
Methodology

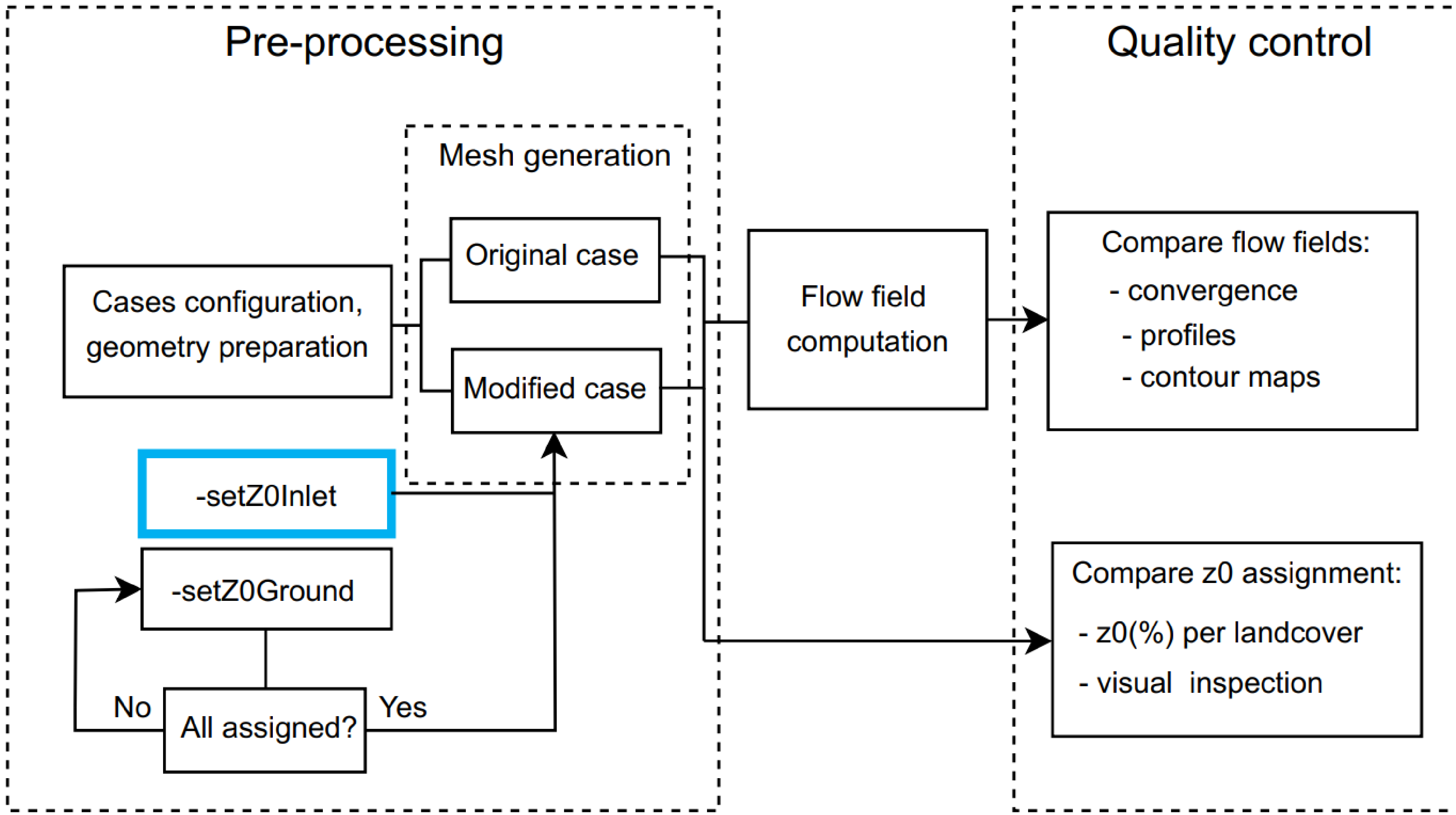
Option –setZ0Ground – z0 assignment and option setZ0NoGeom



Option –setZ0NoGeom:

- A z0 value needs to be specified for the face centers that are not within the boundaries of the input geometry

Methodology
Workflow – option -setZ0Inlet



Methodology

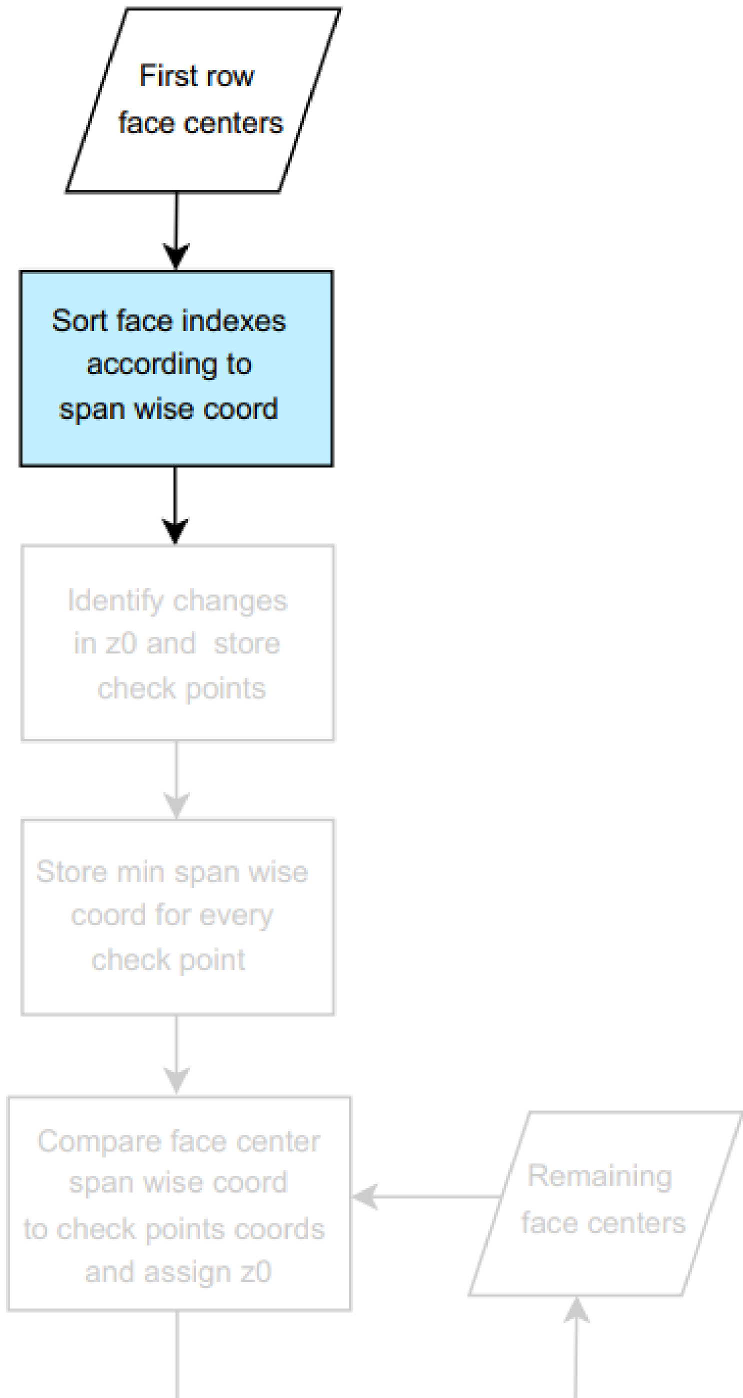
Option –setZ0Inlet – Input

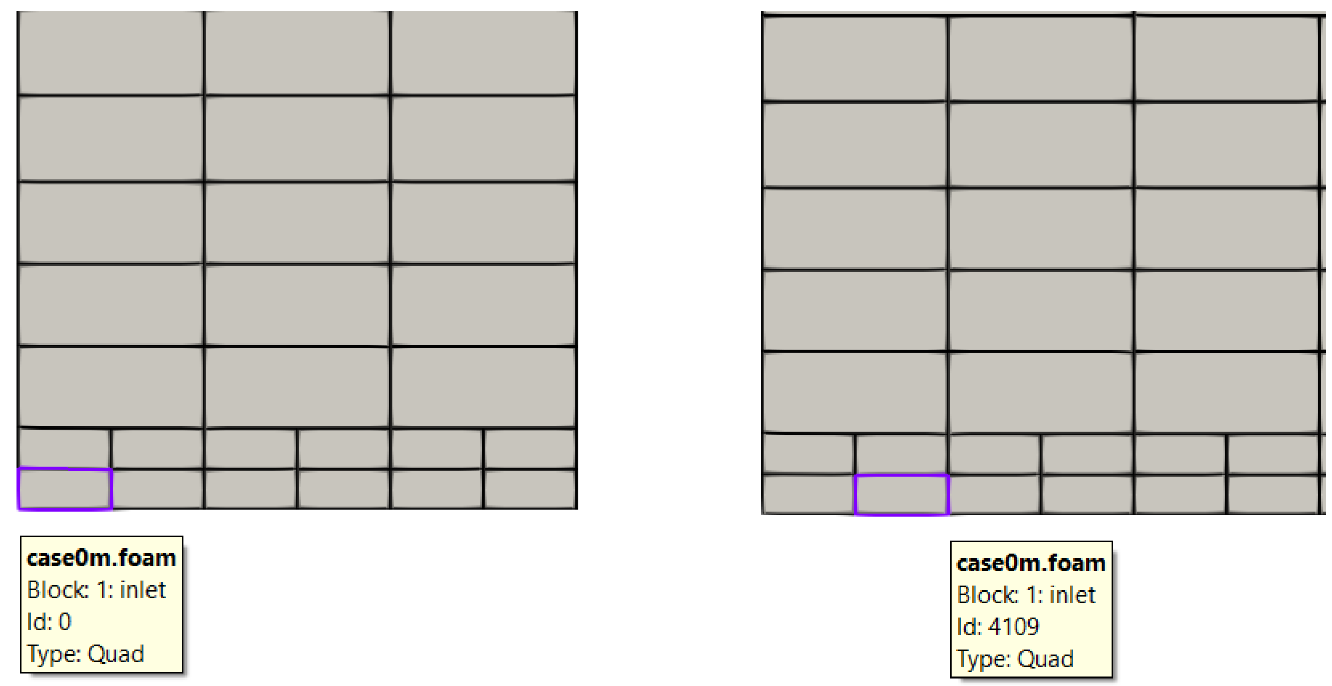
First row faces

- Roughness length should already be assigned to the ground

Methodology

Option –setZ0Inlet – Index sorting





- Indexing of faces does not follow spatial proximity

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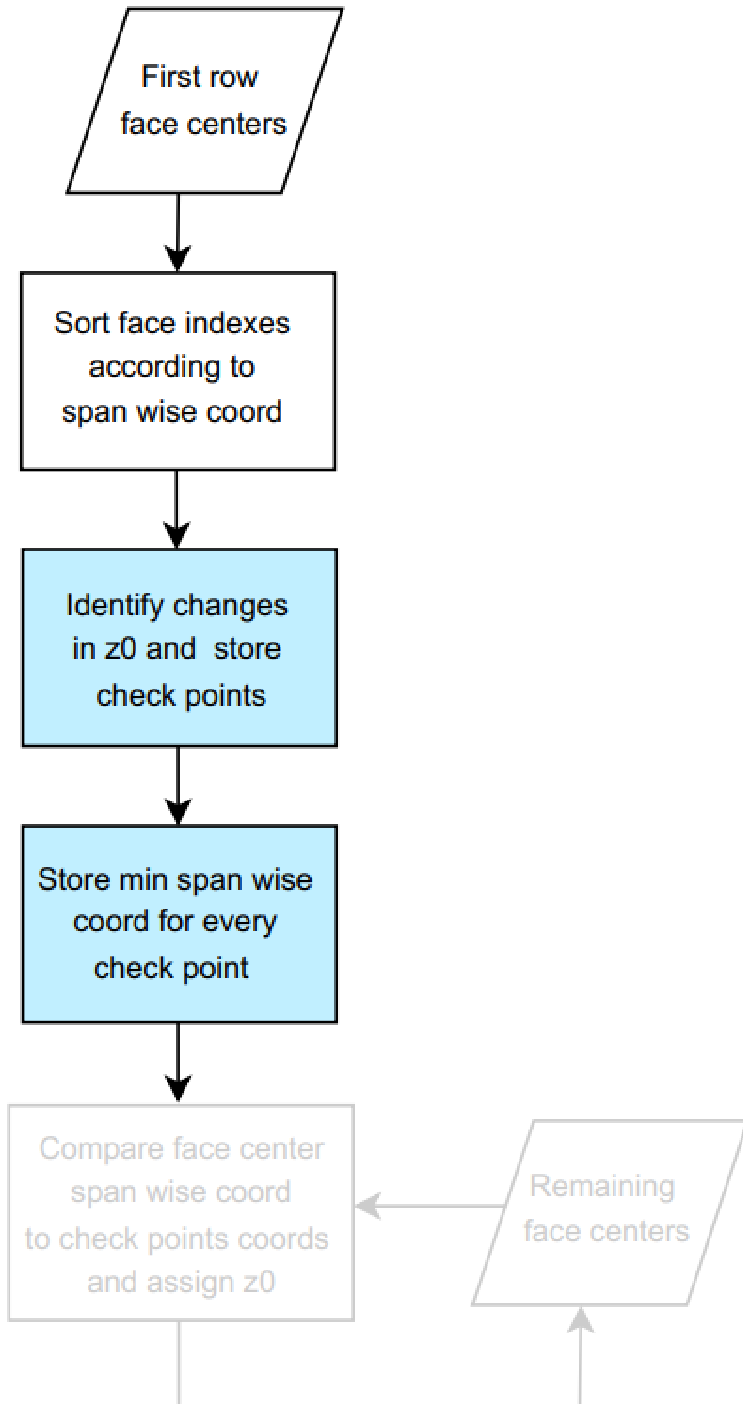
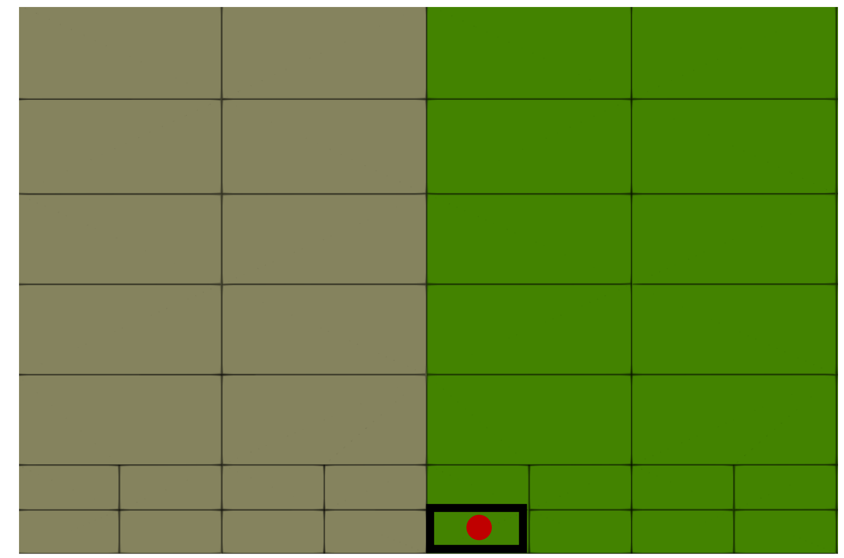
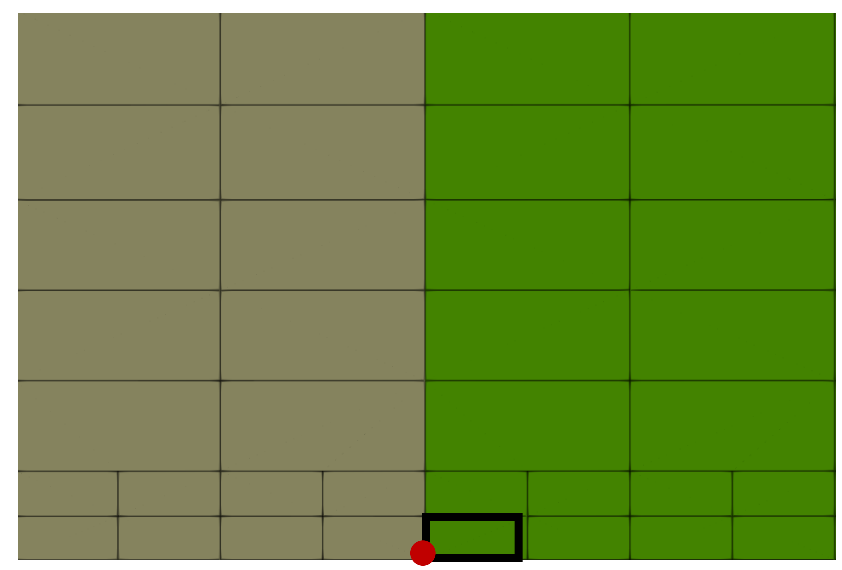
Methodology

Option –setZ0Inlet – Check points and check points coordinates





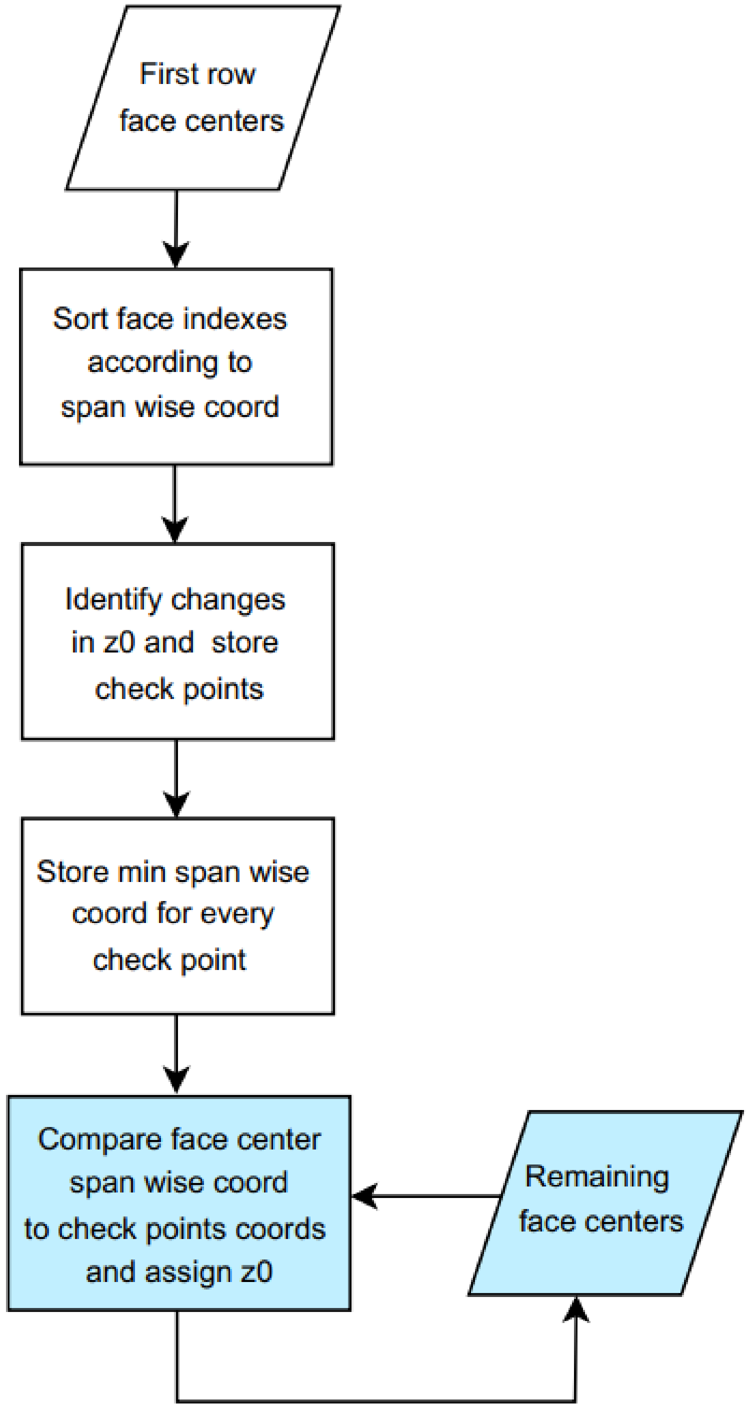
Check point

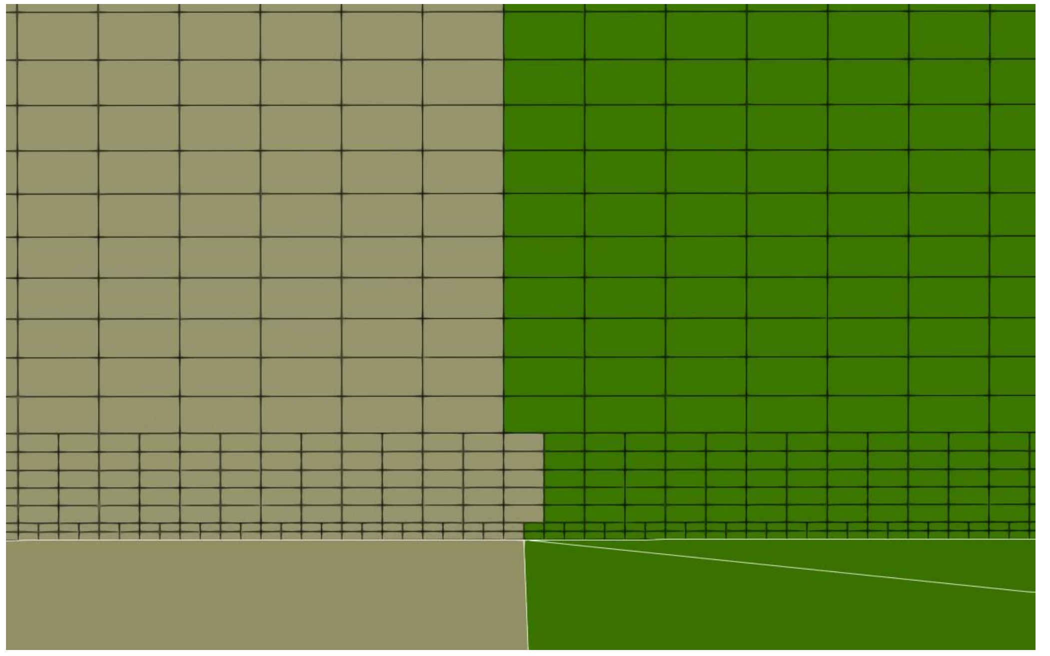


Check coord

Methodology

Option –setZ0Inlet – z0 assignment and ground geometry requirement

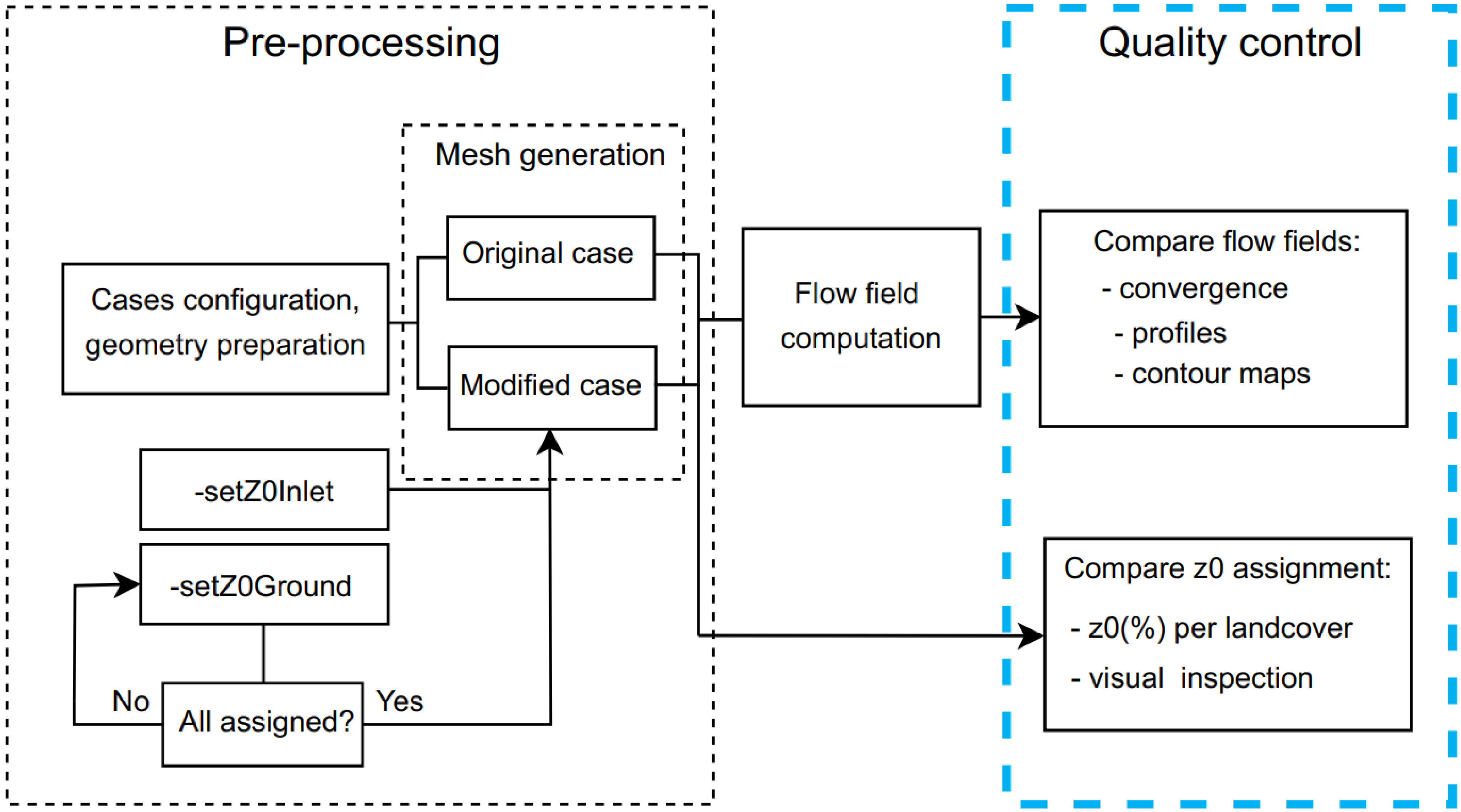




Screenshot from inlet with misassigned cells

- Geometries shared edges located at the separation between different z0 values should be specified explicitly

Methodology
Workflow – Quality control



Quality control

Cases	-setZ0Ground	-setZ0Inlet	-setZ0NoGeom
s_1	x		
s_2	x	x	
s_2_1	x		
c_1	x		
c_1_1	x		
c_2	x	x	x
c_2_1	x		x

Testing set up

-setZ0Ground:

Comparison s_0 – s_1 and c_0 – c_1 cases:

- Mesh similarity
- z0% assigned per landcover
- Visual inspection of assigned values
- Convergence at selected point locations
- Difference maps and Contour maps

-setZ0Inlet:

- Visual inspection of z0 assigned values

Comparison s_2 – s_2_1 and c_2 – c_2_1 cases:

- Convergence at selected point locations

Results

Option – setZ0Ground – Mesh similarity

Characteristic	Simple cases		Complex cases		
	s_0	s_1	c_0	c_1	$Diff_{c\_0-c\_1}$
Max skewness	≈ 0.33	≈ 0.33	≈ 13.66	≈ 13.66	0
Skew nfaces	0	0	301	306	-5
nCells(type:hexahedra)	3,507,378	3,507,378	15,031,780	15,031,775	5
nCells(type:prisms)	0	0	87,745	87,767	-22
nCells(type:tet wedges)	0	0	251	254	-3
nCells(type:polyhedra)	284,382	284,382	681,315	681,263	52

Mesh characteristics

Ref level \ nCells	Simple cases		Complex cases		
	s_0	s_1	c_0	c_1	$Diff_{c\_0-c\_1}$
0	270,840	270,840	23,628	23,628	0
1	704,184	704,184	186,624	186,624	0
2	1,083,360	1,083,360	1,539,577	1,539,577	0
3	1,733,376	1,733,376	8,280,903	8,280,904	-1
4	-	-	4,543,981	4,543,976	5
5	-	-	1,226,378	1,226,350	28
Total	3,791,760	3,791,760	15,801,091	15,801,059	32

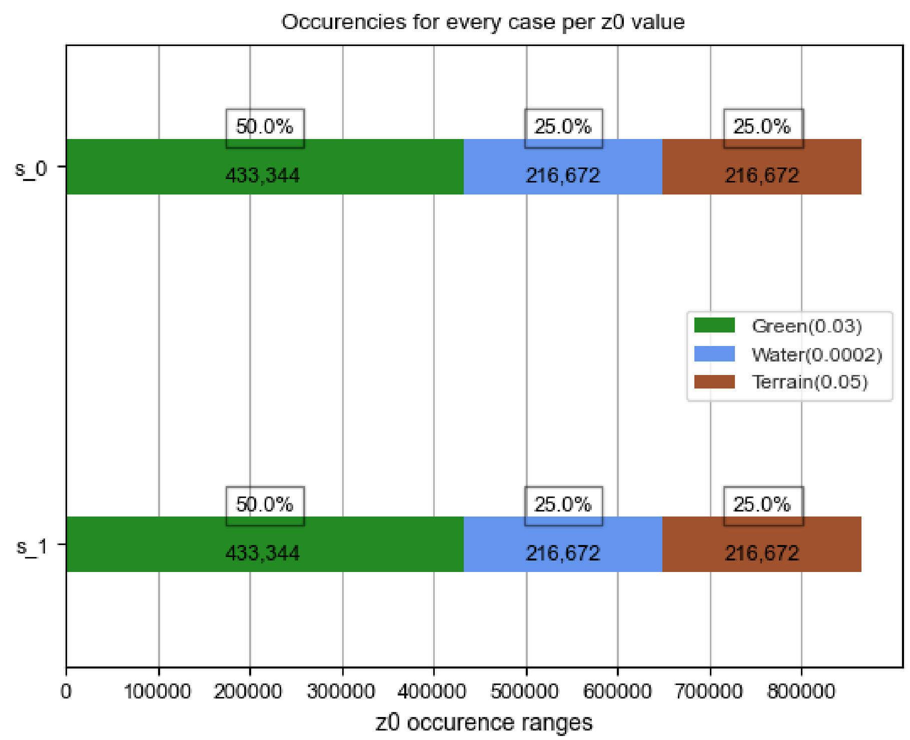
Cells per refinement level

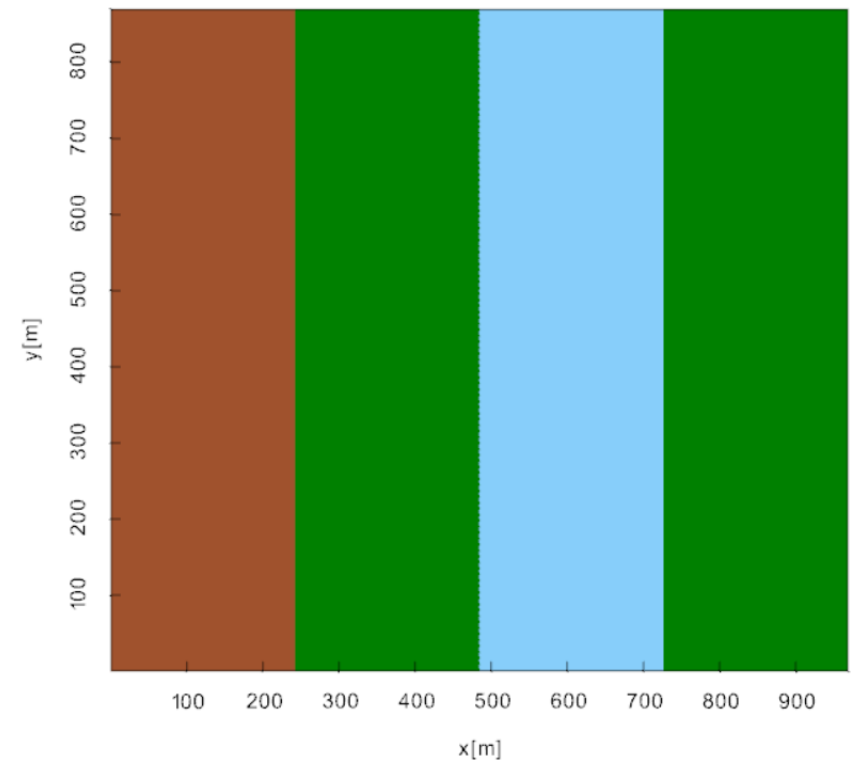
Patch \ nFaces	Simple cases		Complex cases		
	s_0	s_1	c_0	c_1	$Diff_{c\_0-c\_1}$
Green1	216,672	866,688	-	-	-
Green2	216,672		-	-	-
Terrain	216,672		995,944	995,942	2
Water	216,672		20,926	90,380	19
Green	-	-	69,473		
Buildings	-	-	481,005	480,986	19
Top	13,542	13,542	4,212	4,212	0
Inlet	9,102	9,102	6,480	6,480	0
Outlet	9,102	9,102	6,480	6,480	0
Sides(symmetric)	20,008	20,008	18,720	18,720	0
Total	918,442	918,442	1,603,240	1,603,200	40

Cells per patch

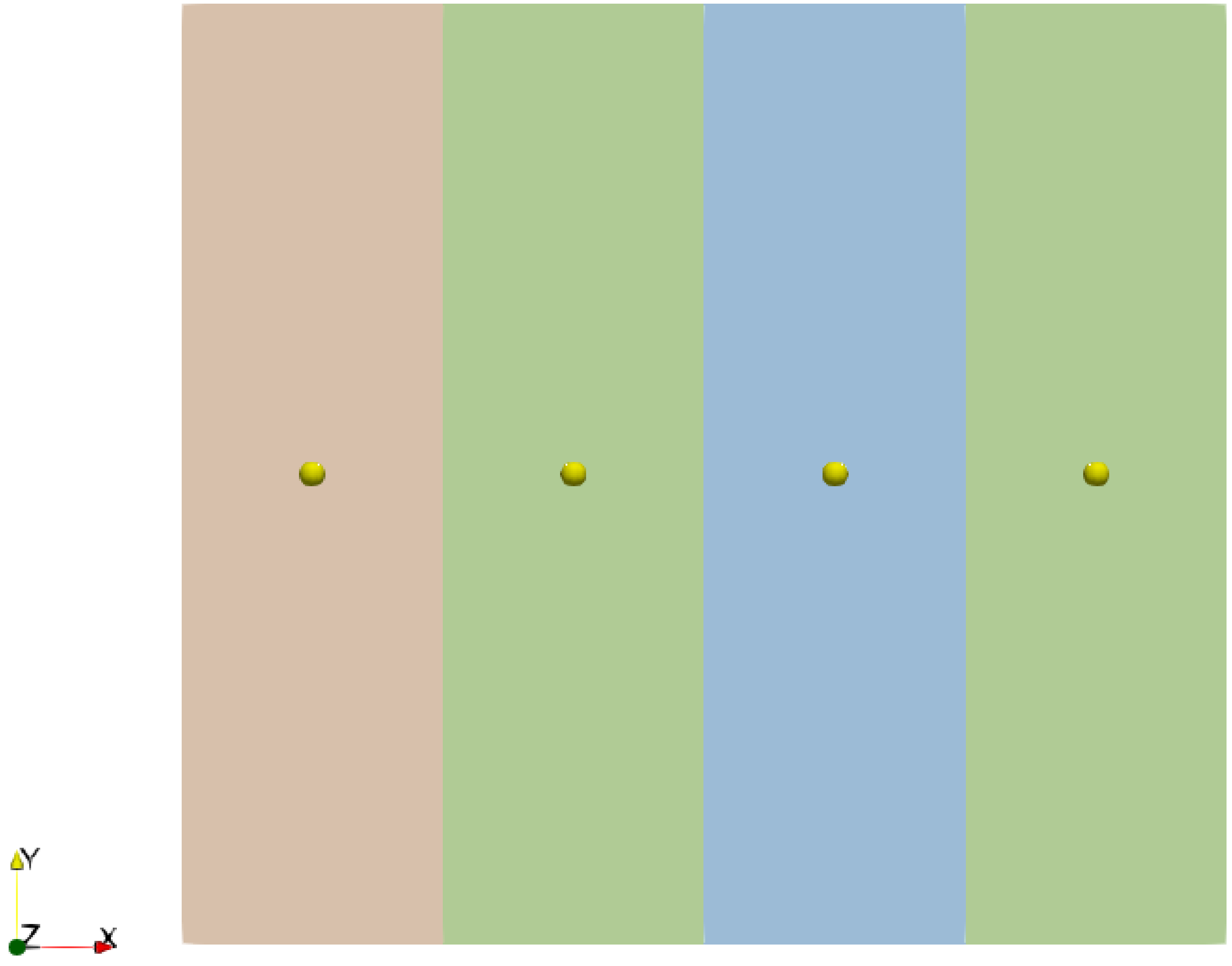
Results

Option – setZ0Ground – Ideal case assigned z0



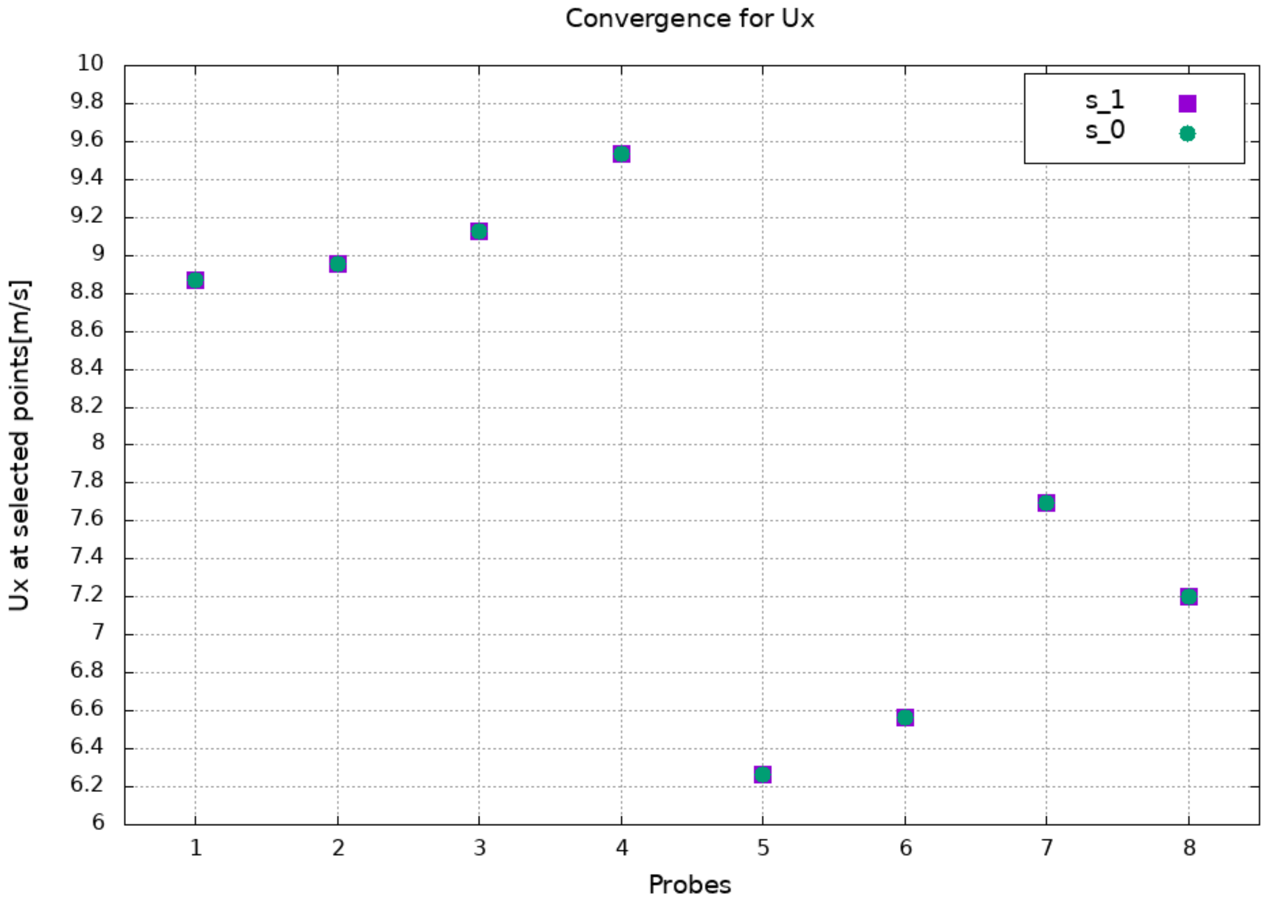


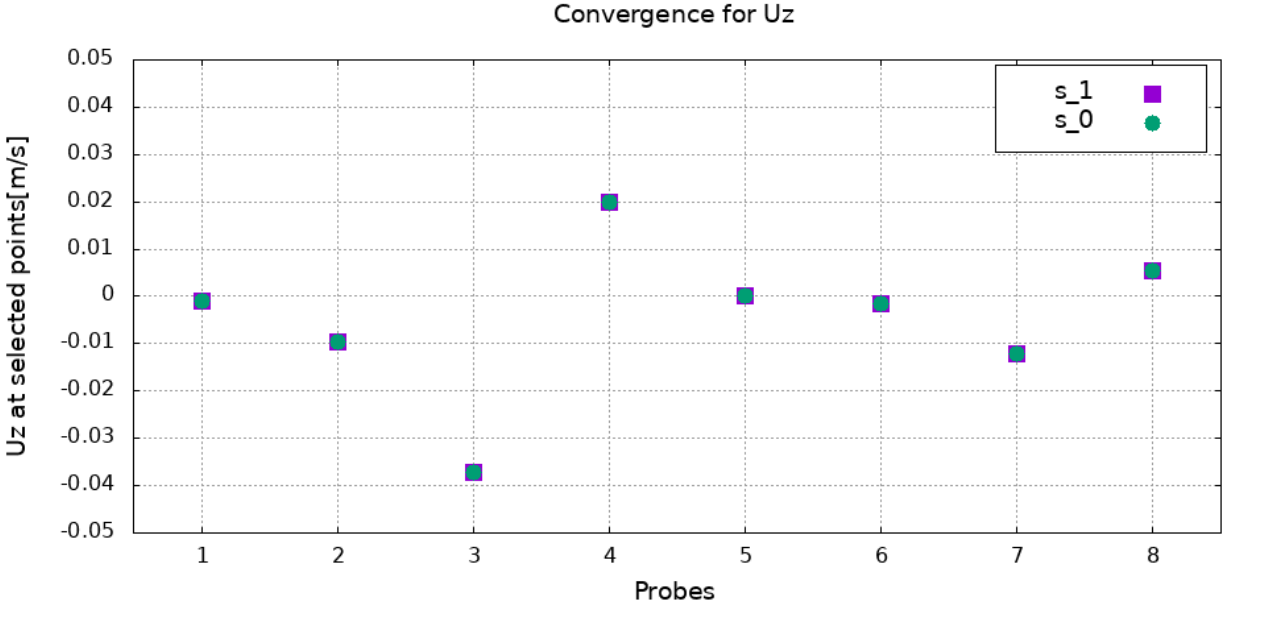
Option – setZ0Ground – Ideal case probe locations



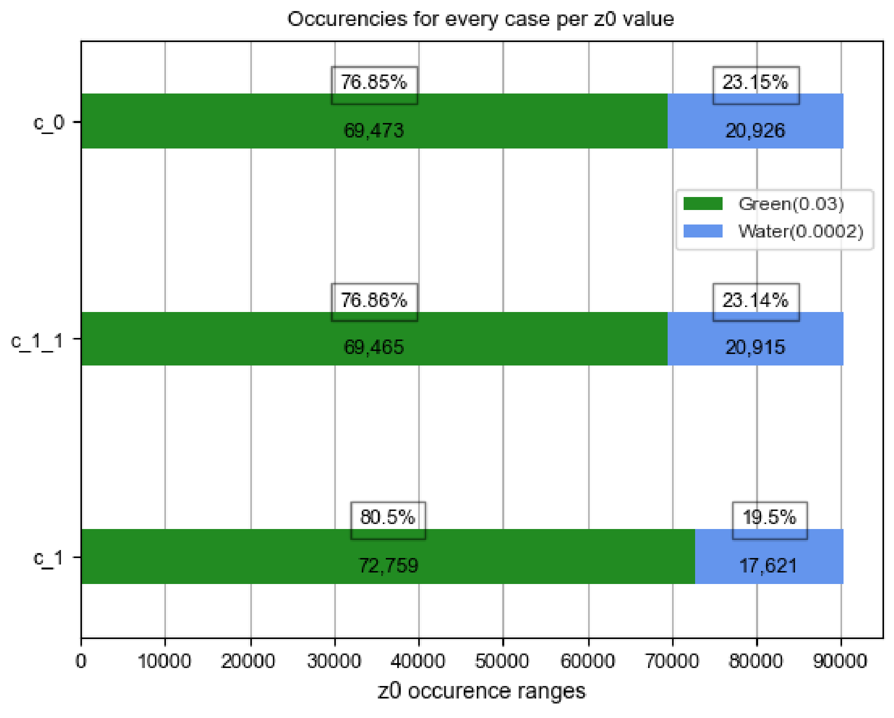
Results

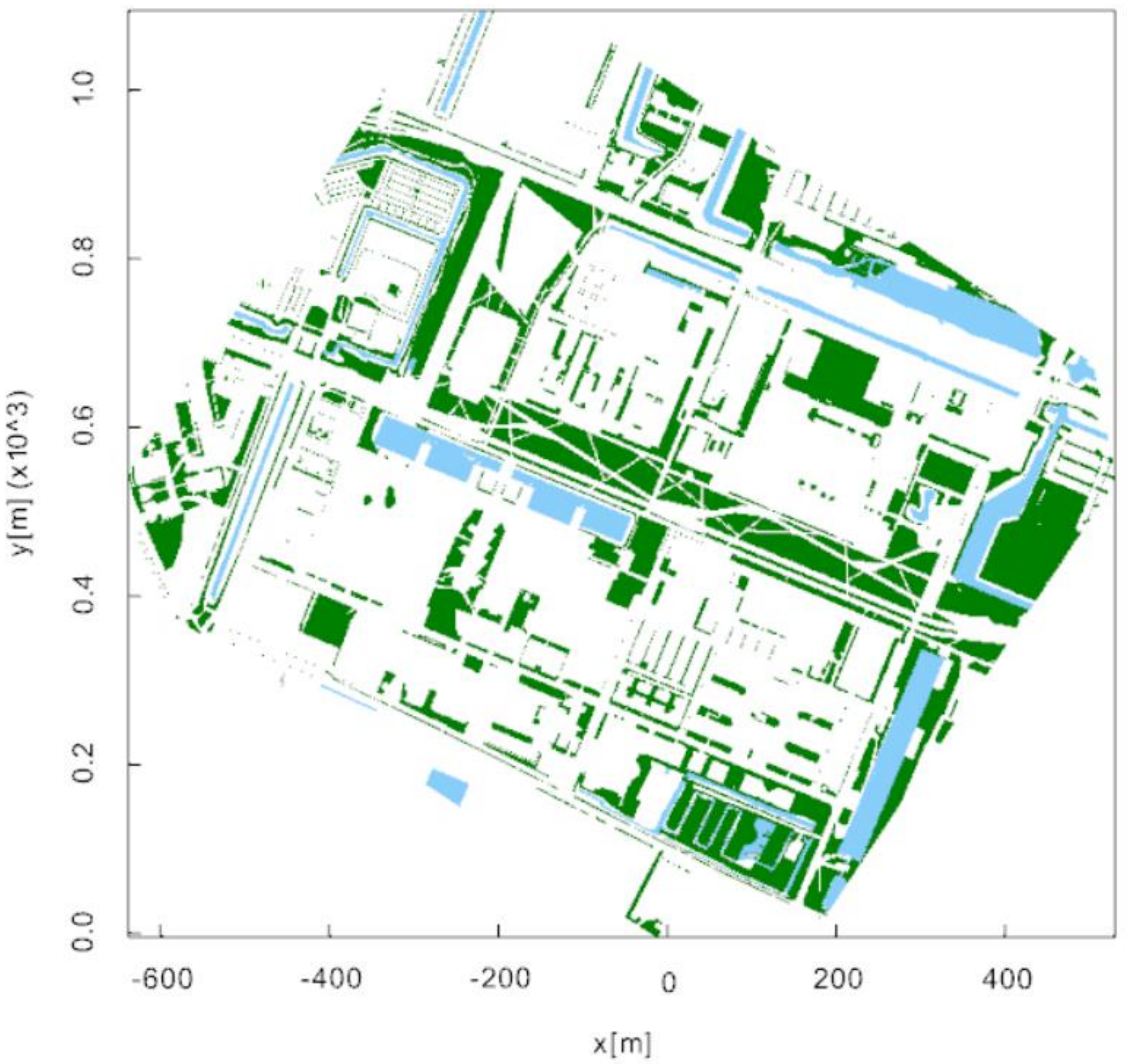
Option – setZ0Ground – Ideal case convergence values for Ux and Uz





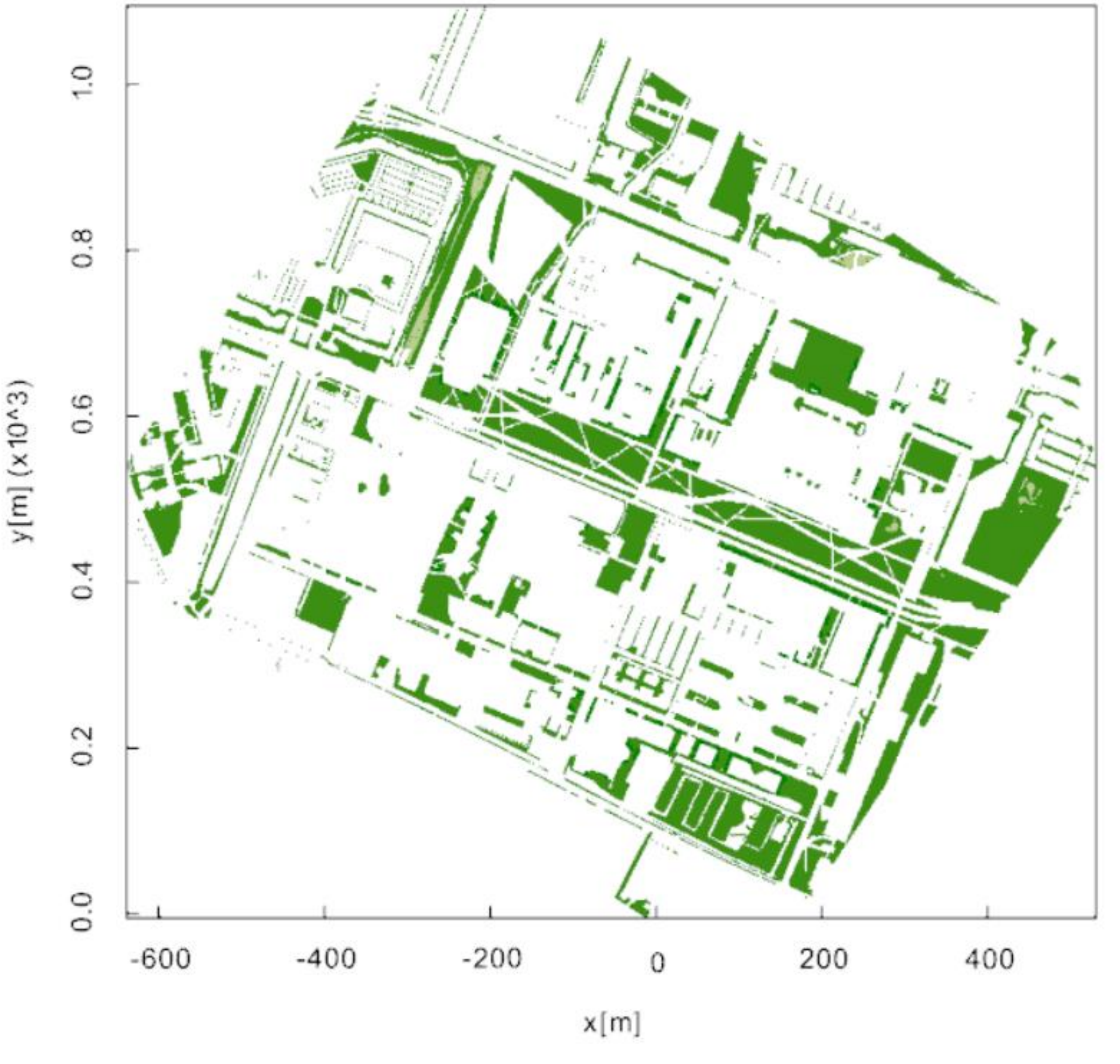
Option – setZ0Ground – TU Delft case assigned z0

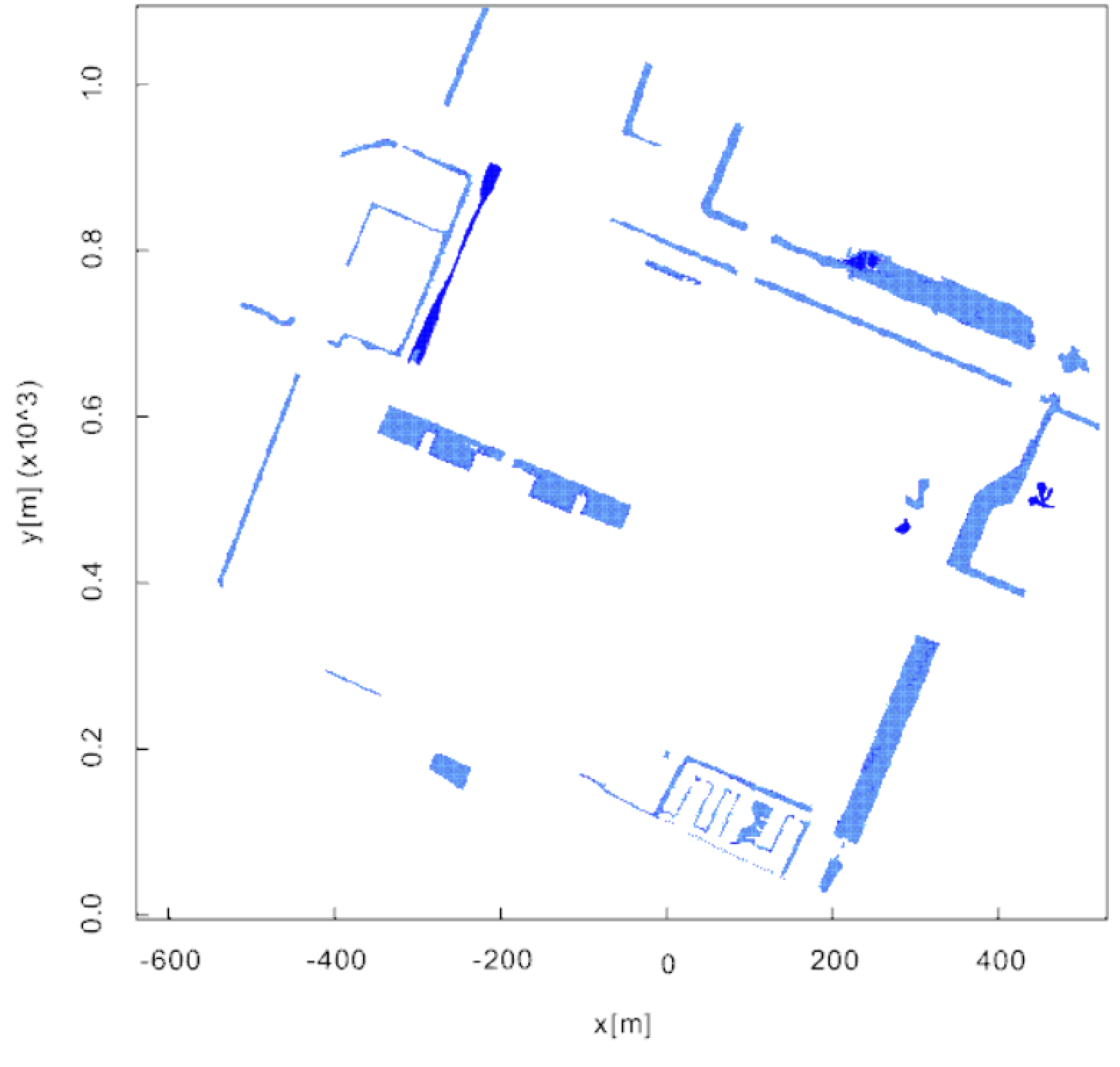




Results

Option – setZ0Ground – TU Delft case (c_0 – c_1) z0 difference maps



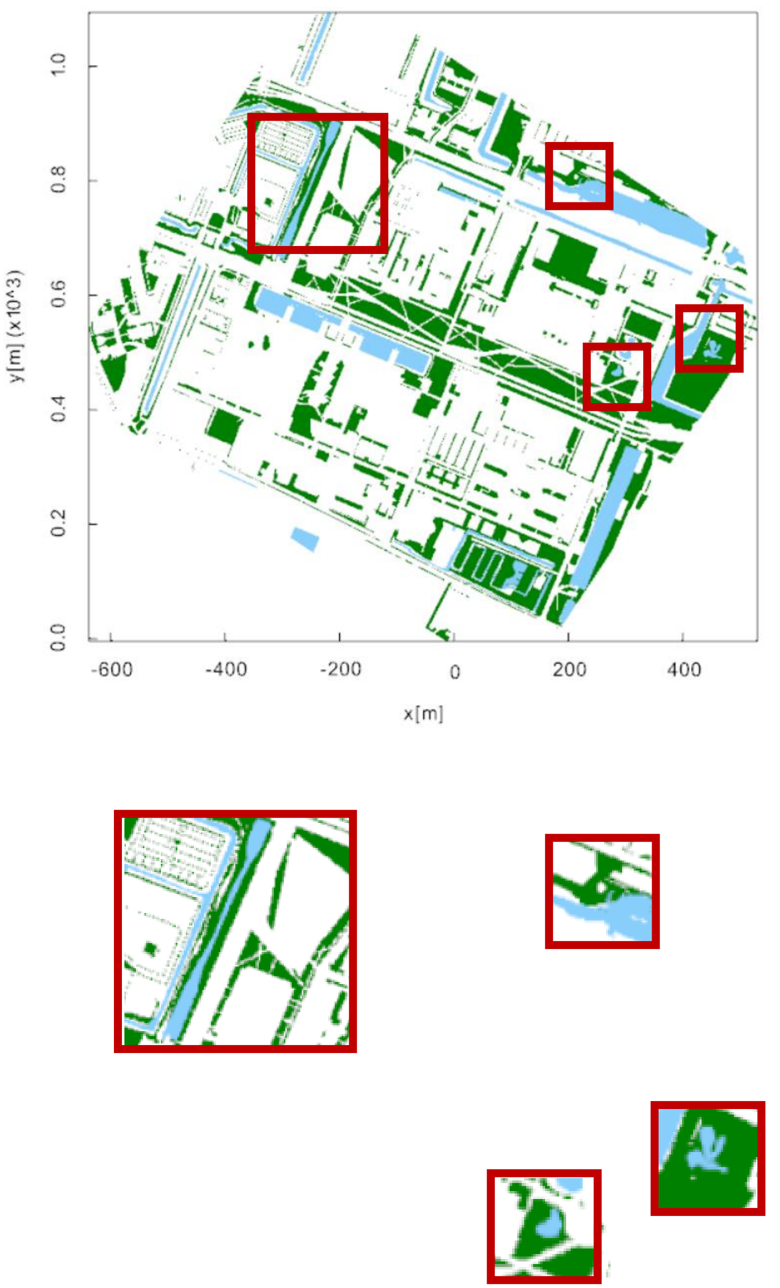


TU Delft

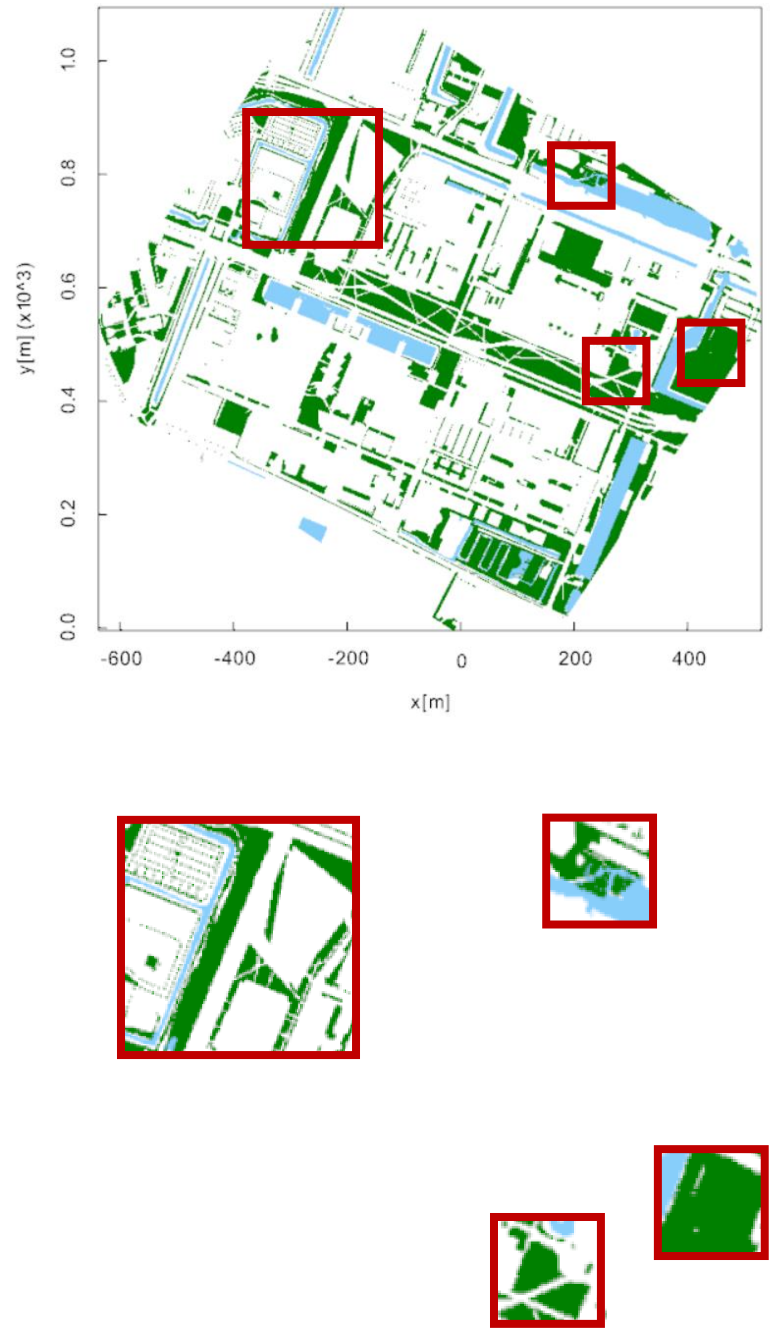
Results

Option – setZ0Ground – TU Delft case assigned z0

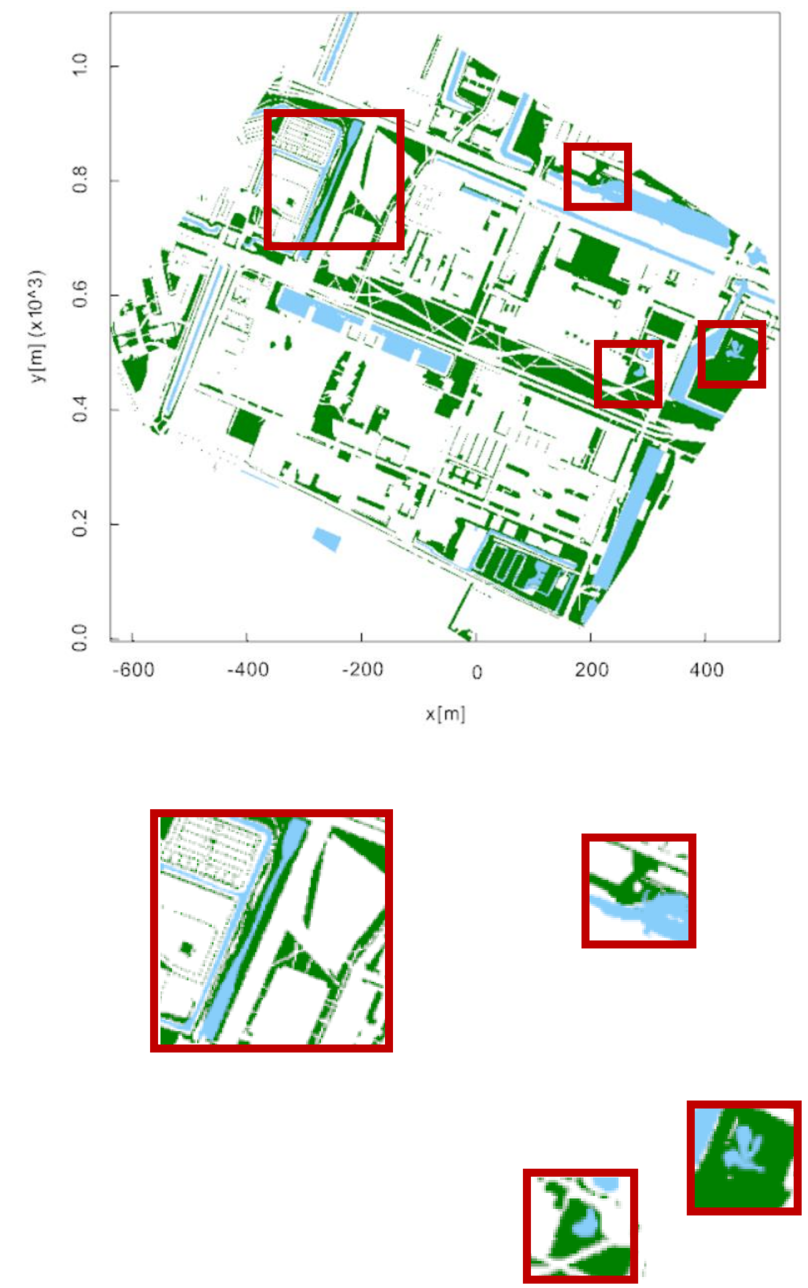
c_0



c_1



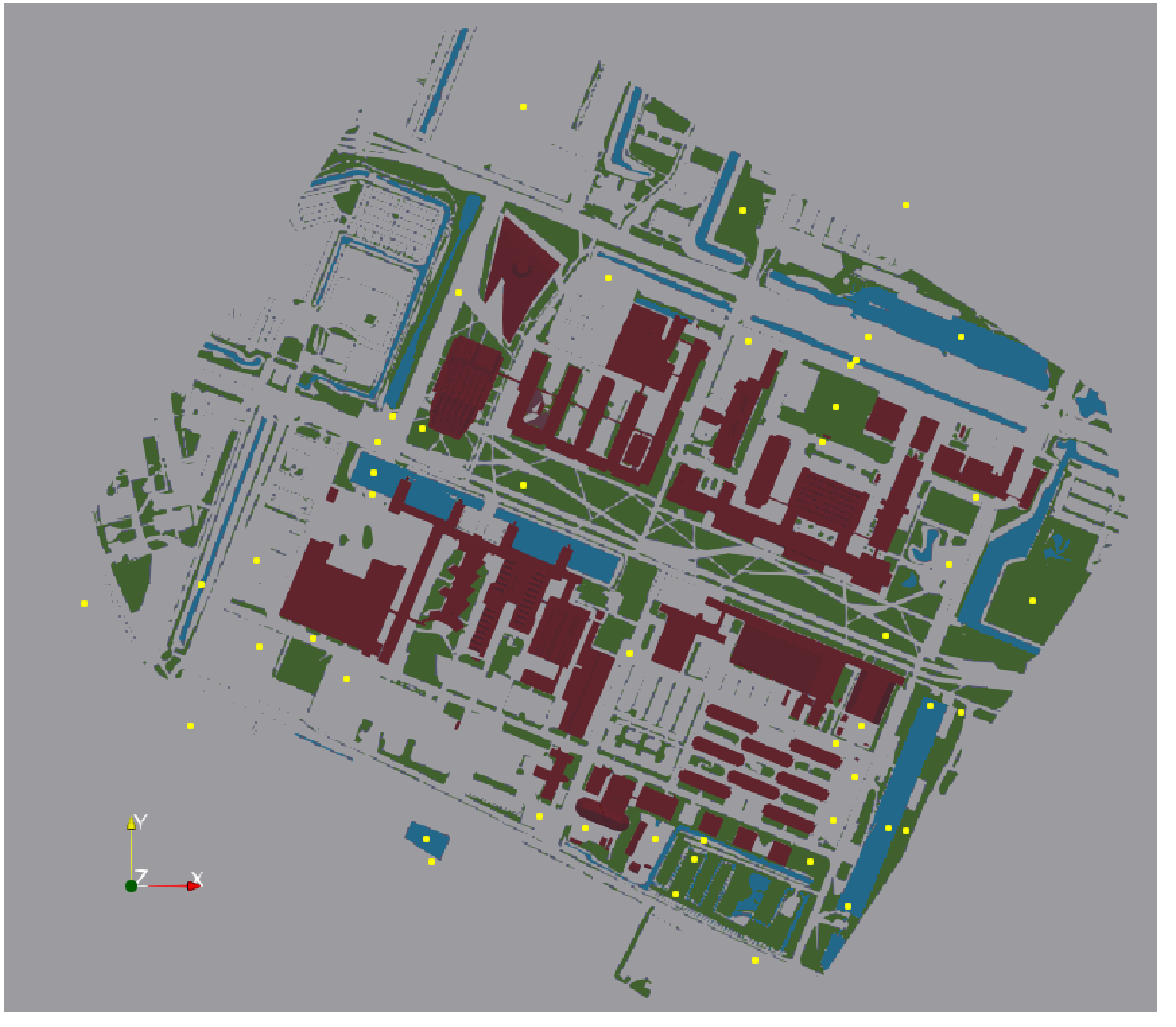
c_1_1



TU Delft

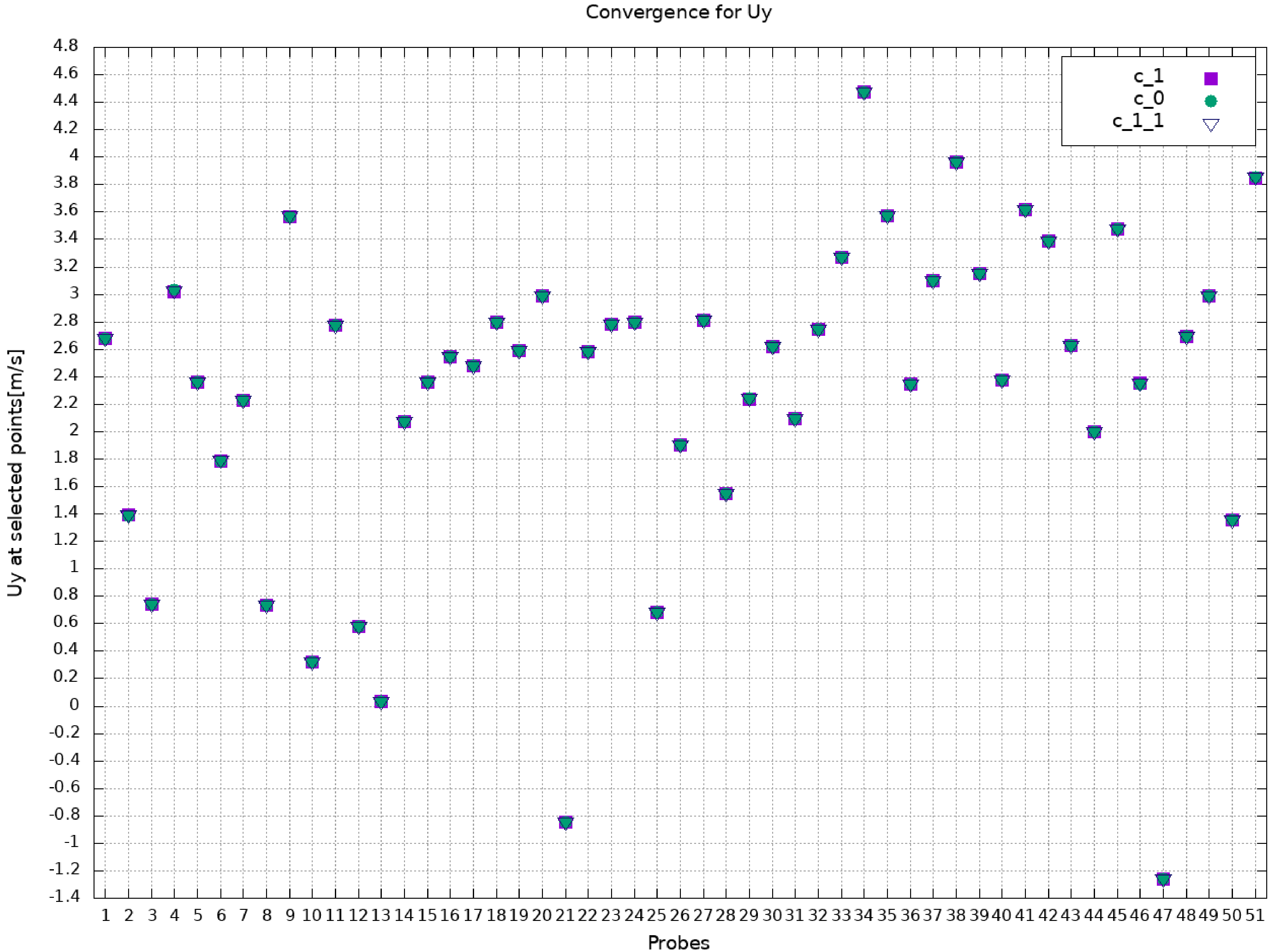
Results

Option – setZ0Ground – TU Delft case probe locations



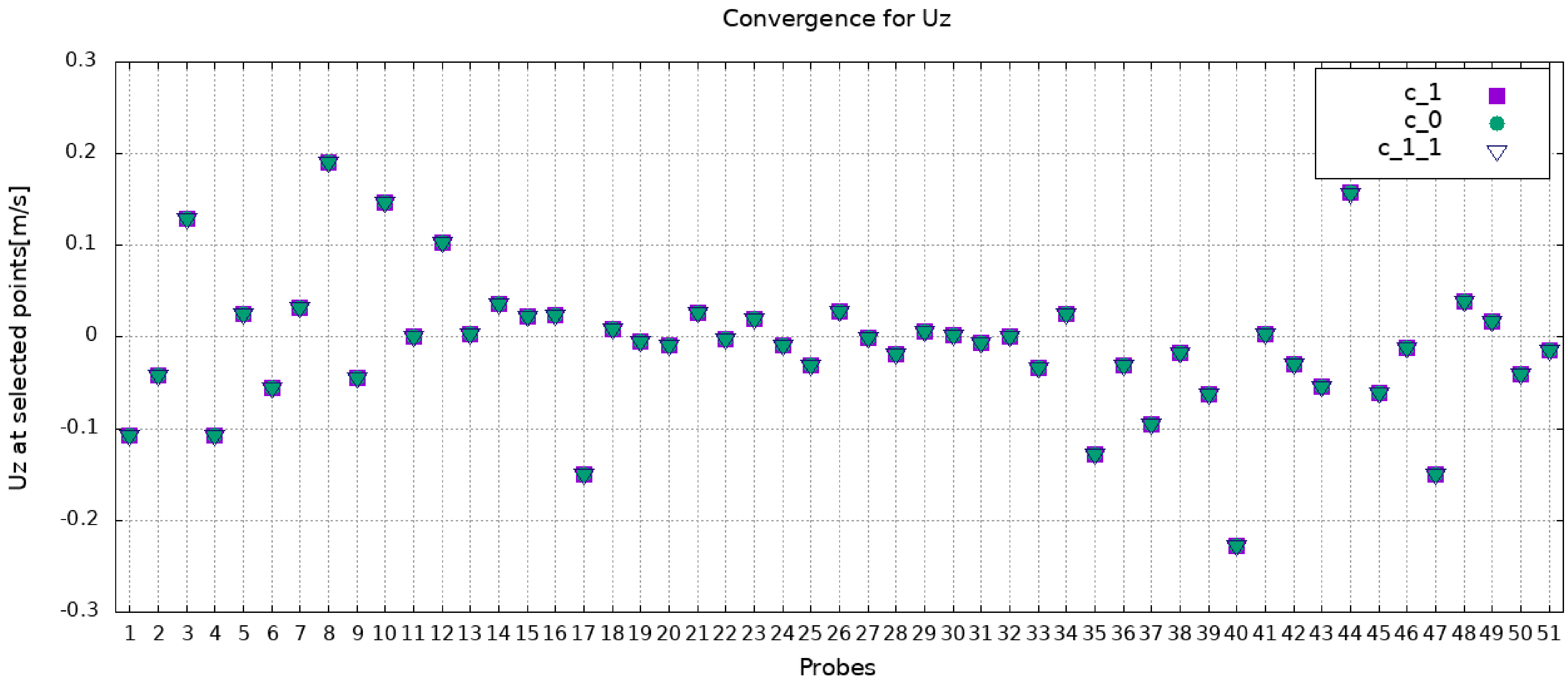
Results

Option – setZ0Ground – TU Delft case convergence values for Uy



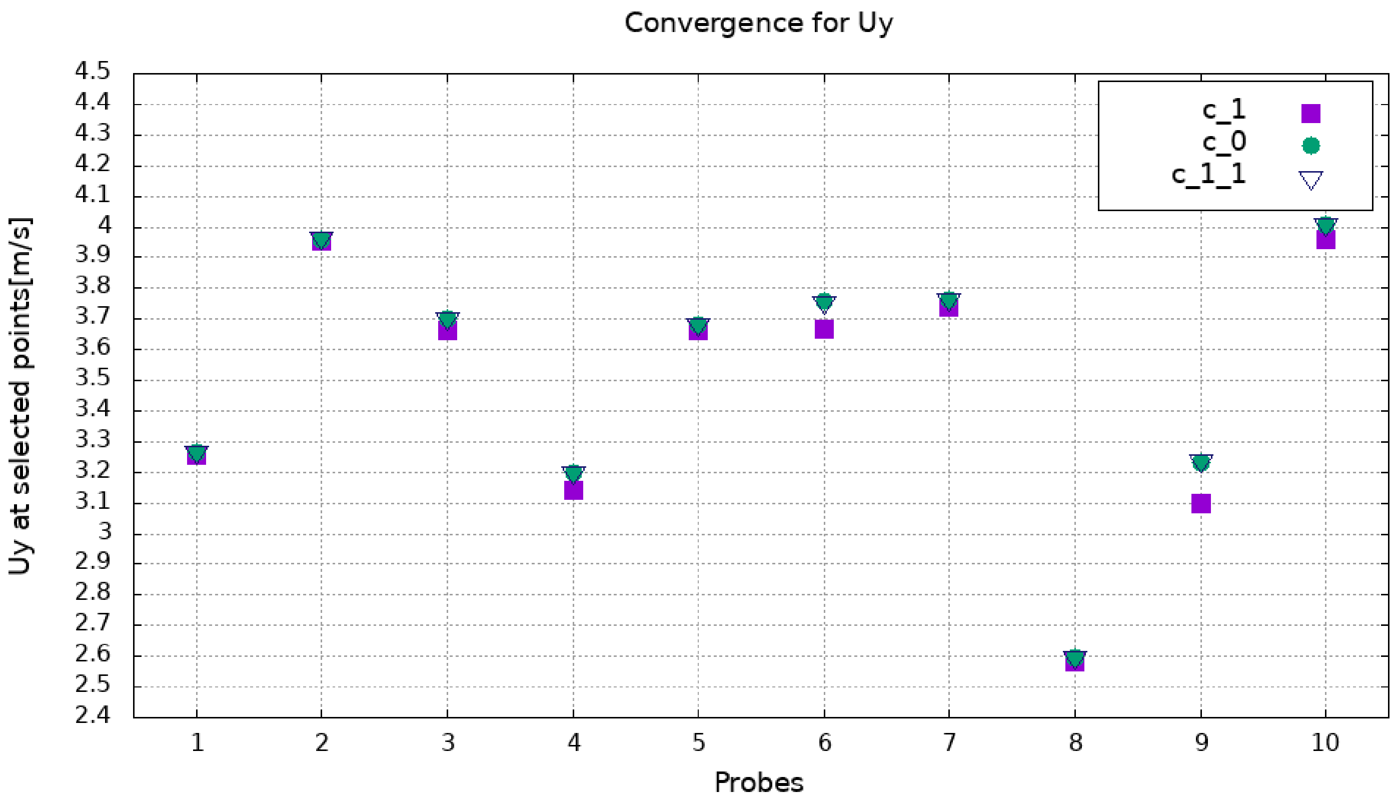
Results

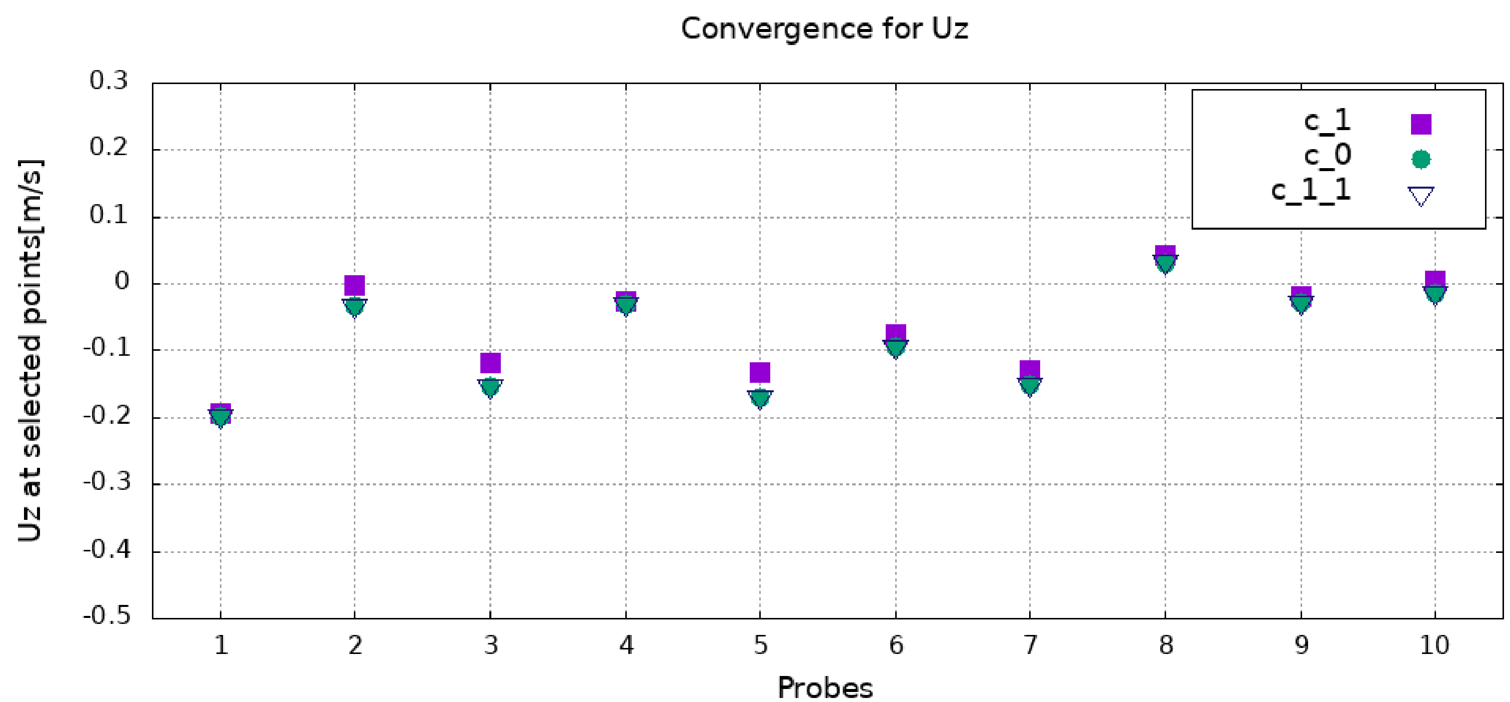
Option – setZ0Ground – TU Delft case convergence values for Uz



Results

Option – setZ0Ground – TU Delft case convergence values for Uy and Uz at locations with overlaps

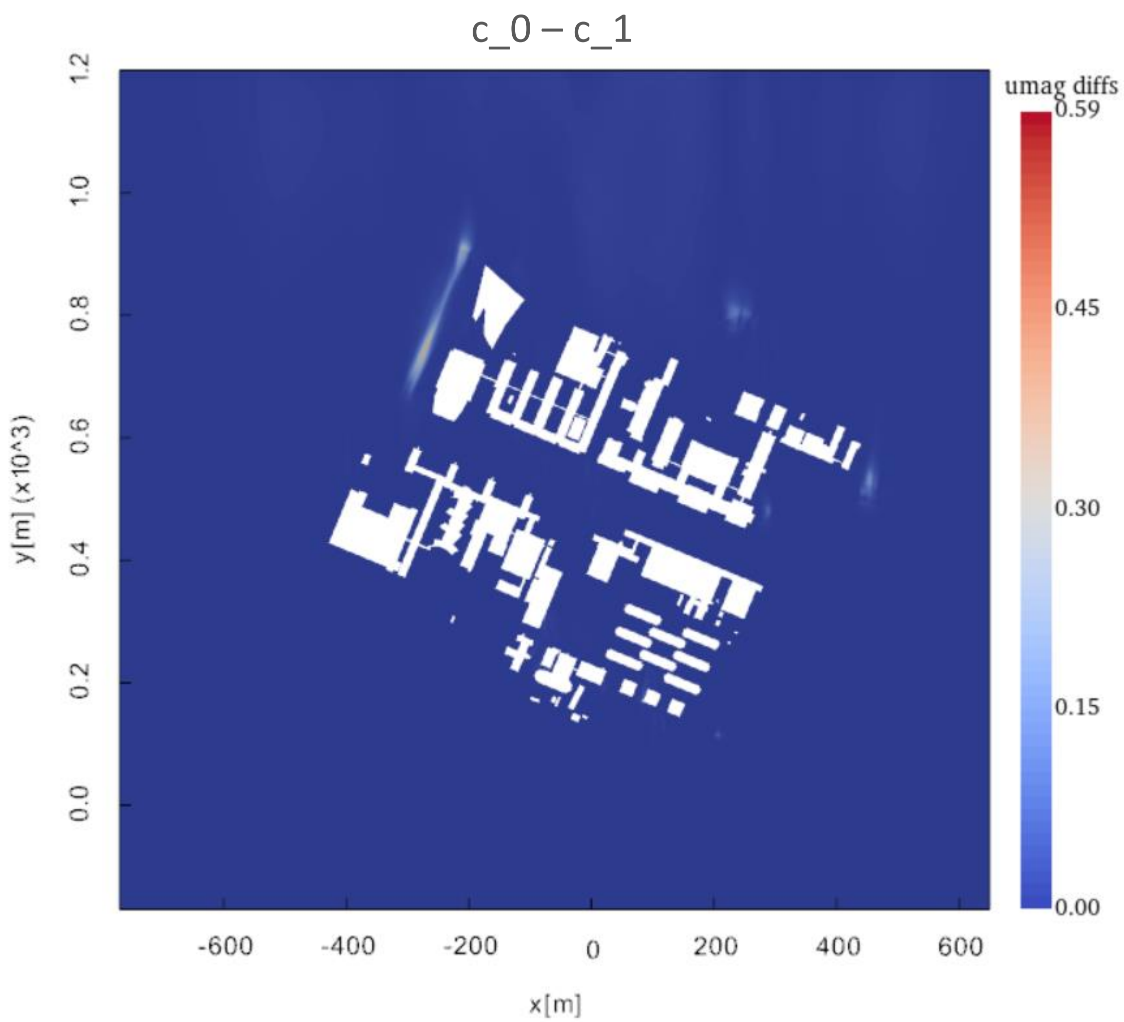


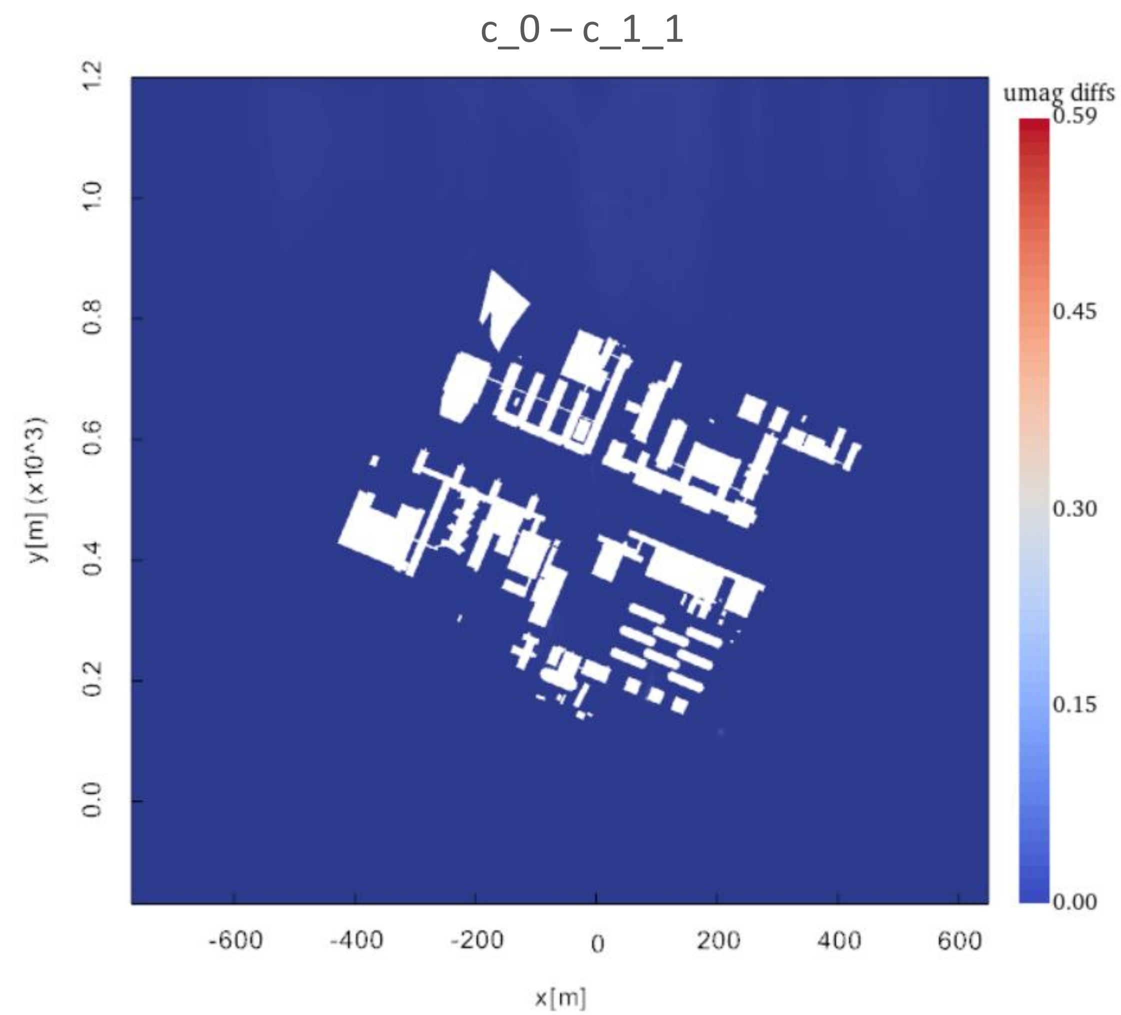


Results

Option – setZ0Ground – TU Delft case Umagnitude differences

Umag diff ranges	c_0-c_1	c_0-c_1_1
[0, 0.05]	1,070,253	1,071,993
(0.05, 0.1]	892	31
(0.1, 0.15]	428	7
(0.15, 0.2]	226	5
(0.2, 0.25]	129	1
(0.25, 0.3]	80	2
(0.3, 0.45]	35	4
(0.45, 0.59]	2	2





Results

Option – setZ0Ground – TU Delft case Umagnitude differences

Umag diff ranges	c_0-c_1	c_0-c_1_1
[0, 0.05]	1,070,253	1,071,993
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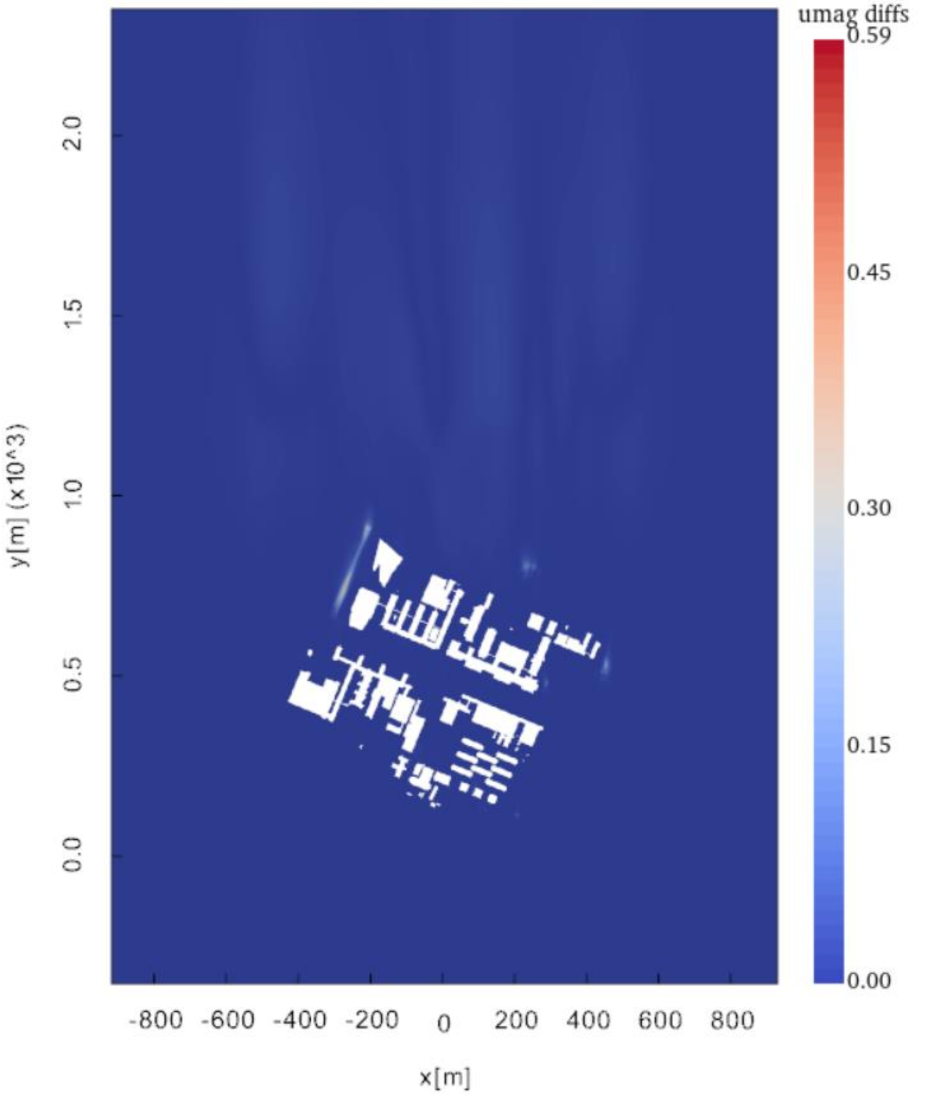
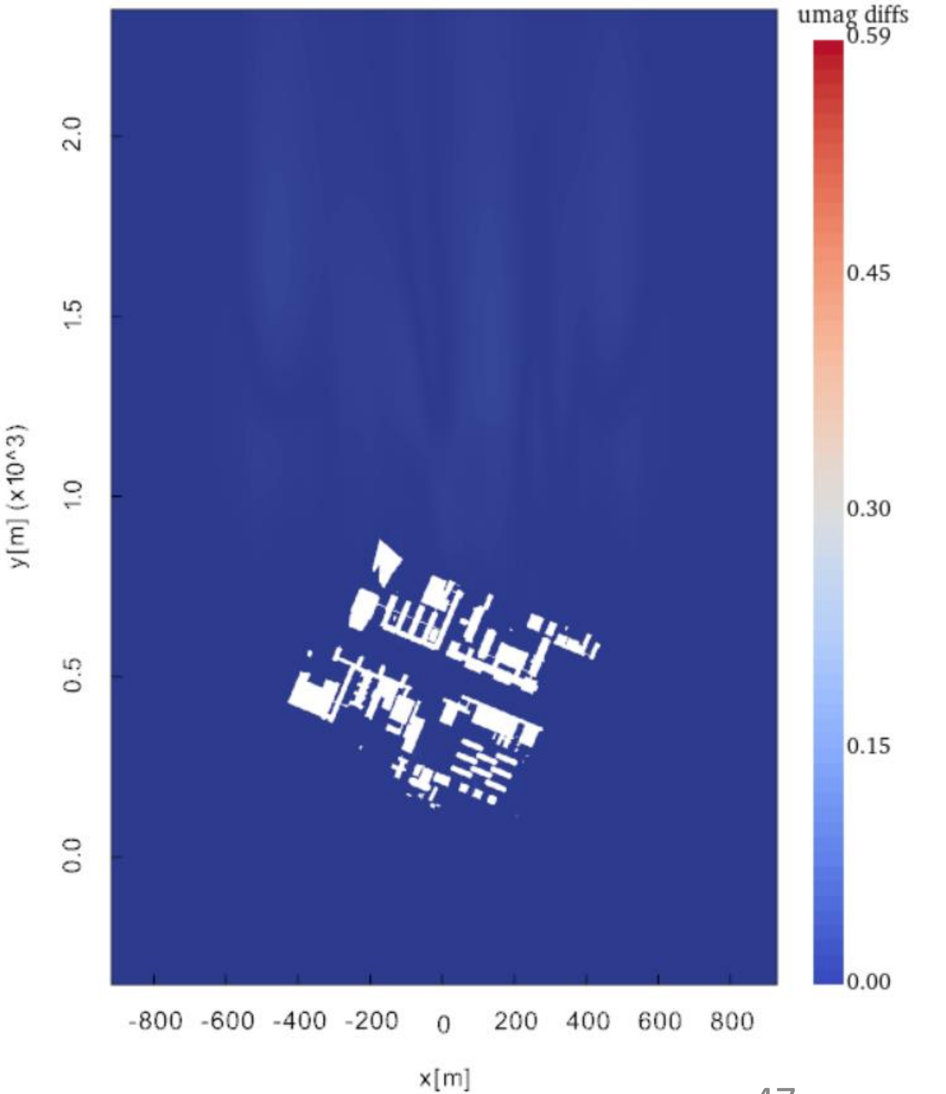
(0.15, 0.2]	226	5
(0.2, 0.25]	129	1
(0.25, 0.3]	80	2
(0.3, 0.45]	35	4
(0.45, 0.59]	2	2

c_0 – c_1



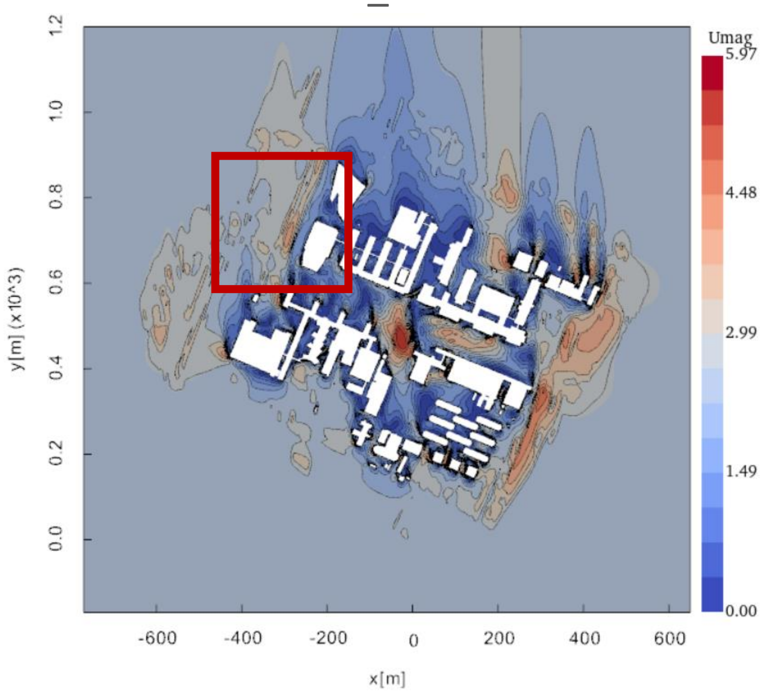
c_0 – c_1_1



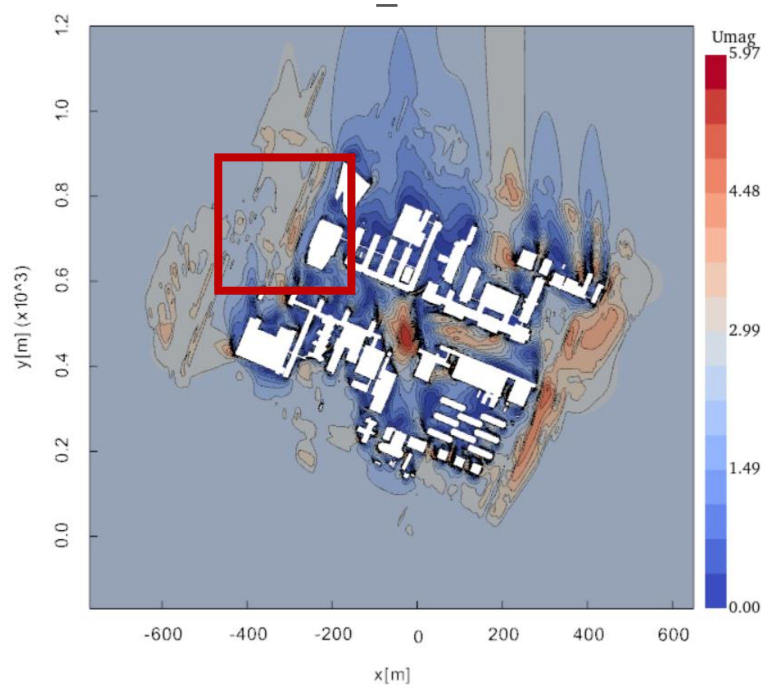
Results

Option – setZ0Ground – TU Delft case contour maps

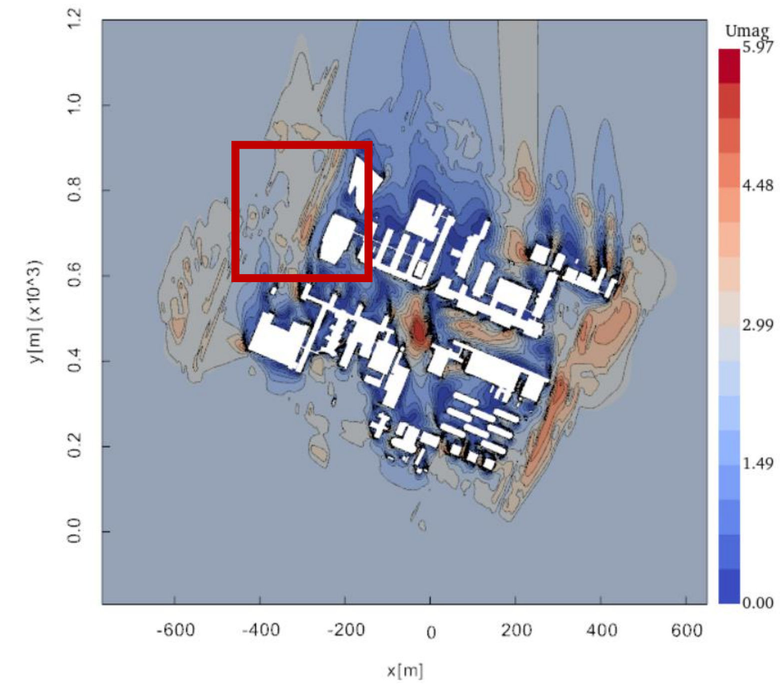
c_0

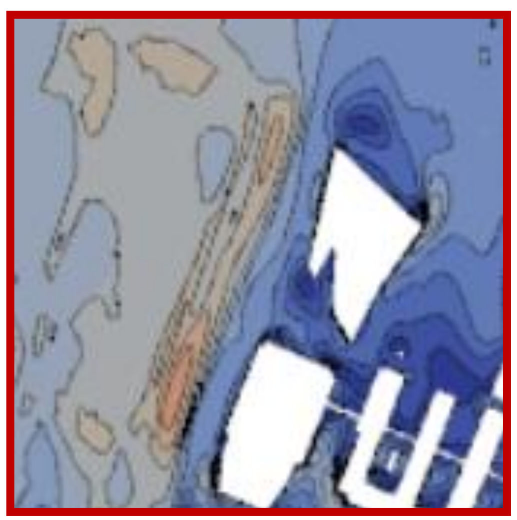


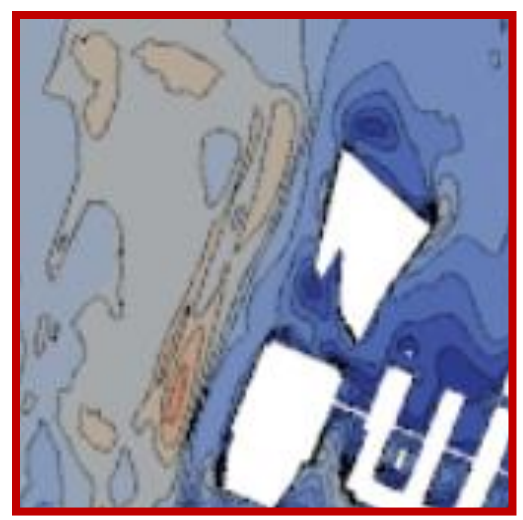
c_1

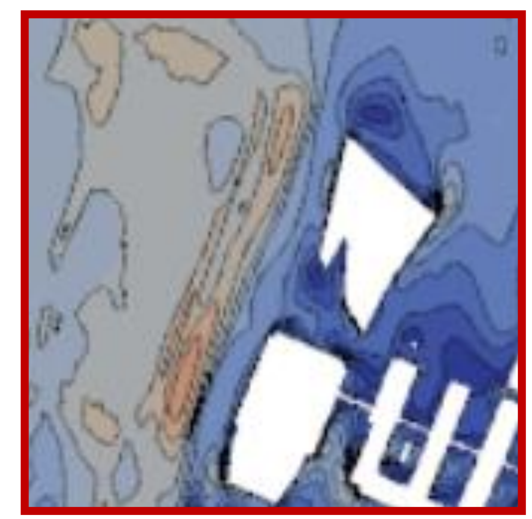


c_1_1





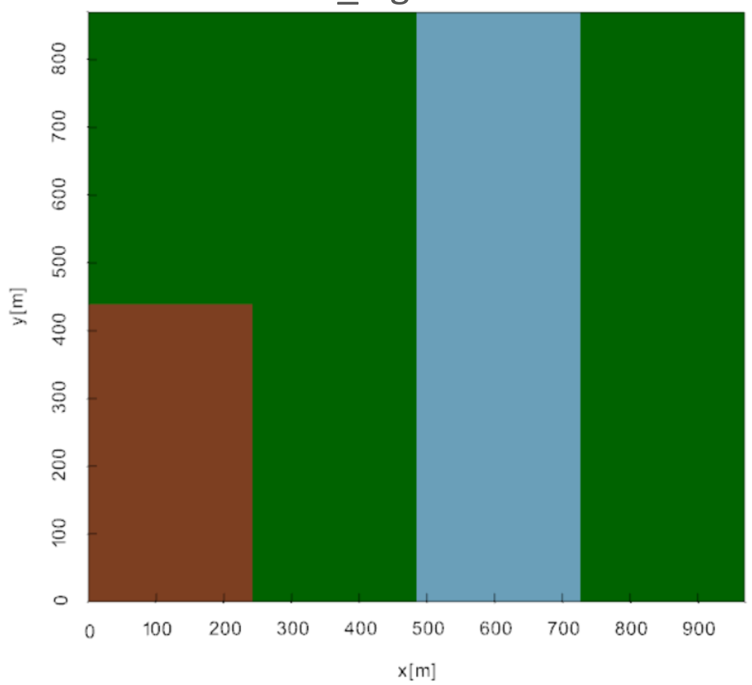




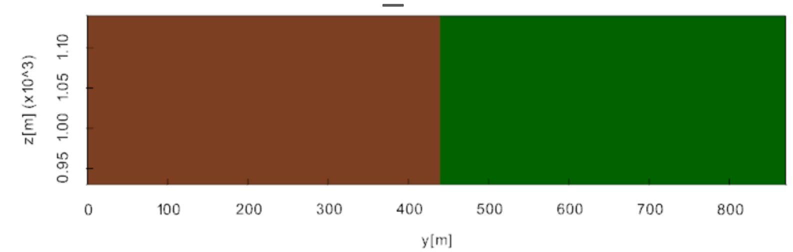
Results

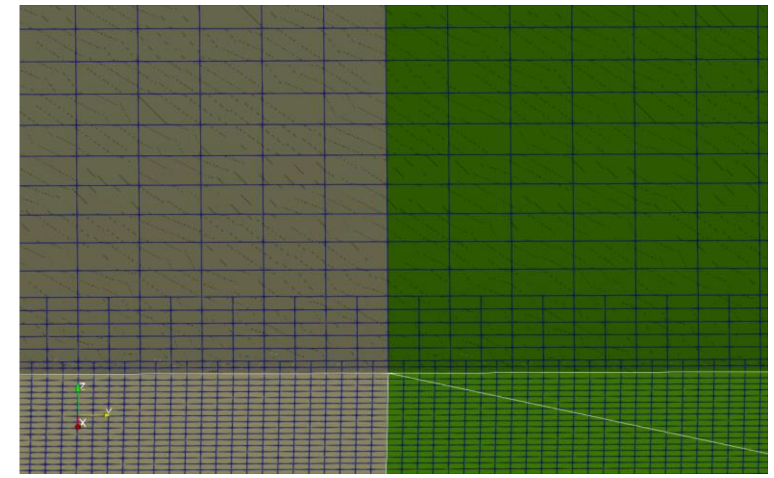
Option – setZ0Inlet – Assigned z0 values

s_2 ground

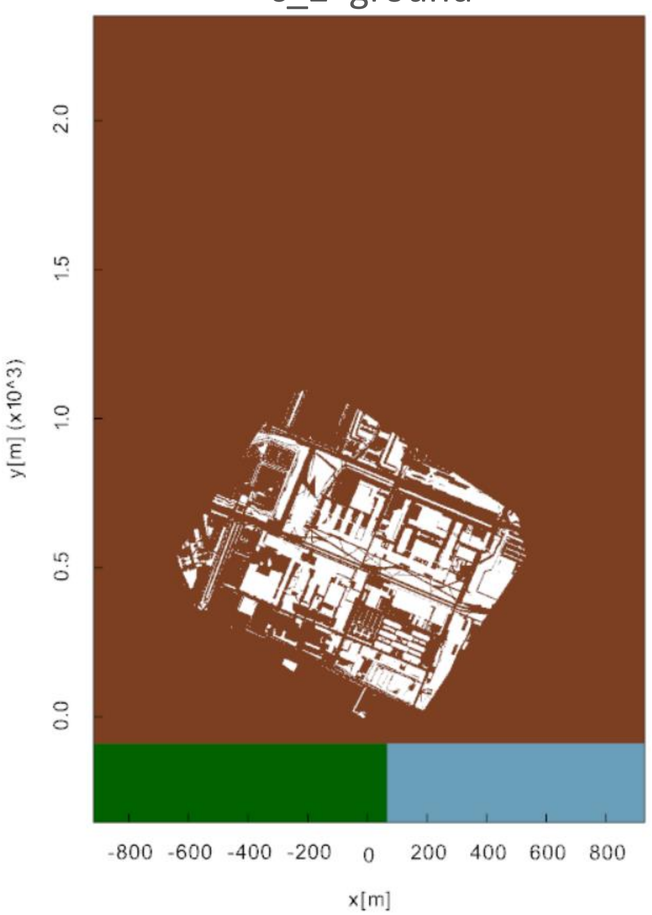


s_2 inlet

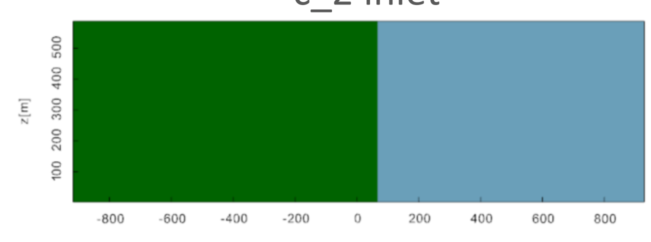


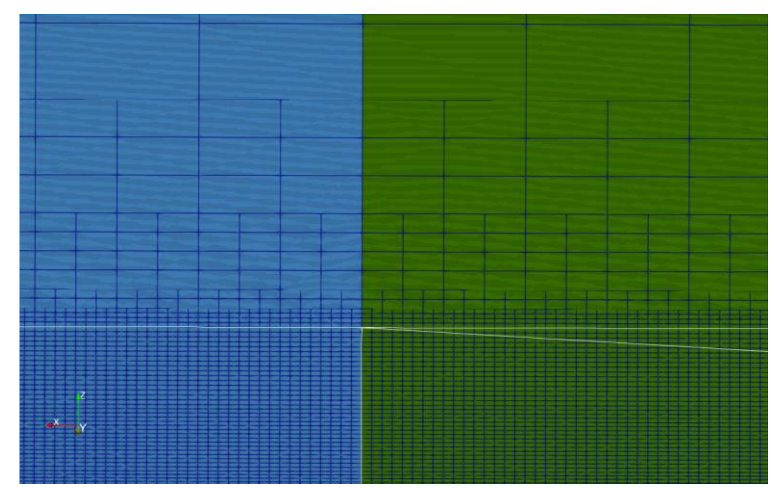


c_2 ground

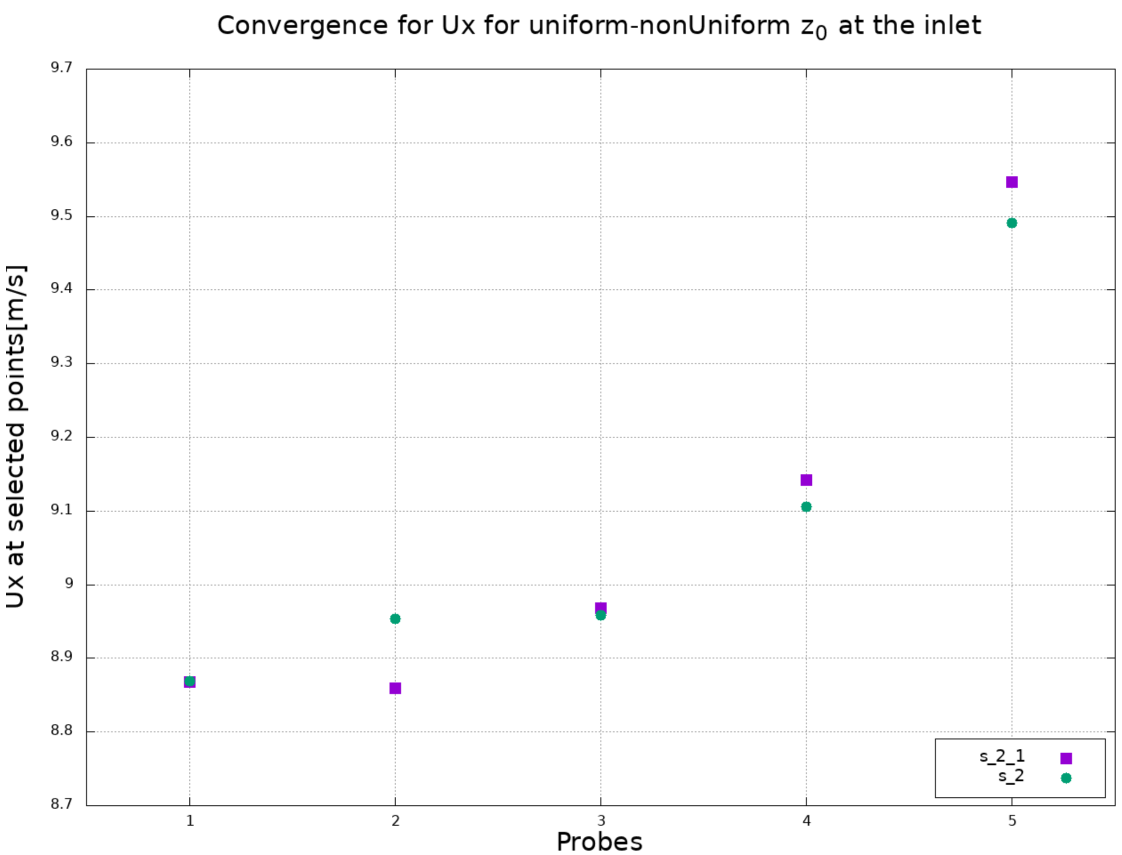


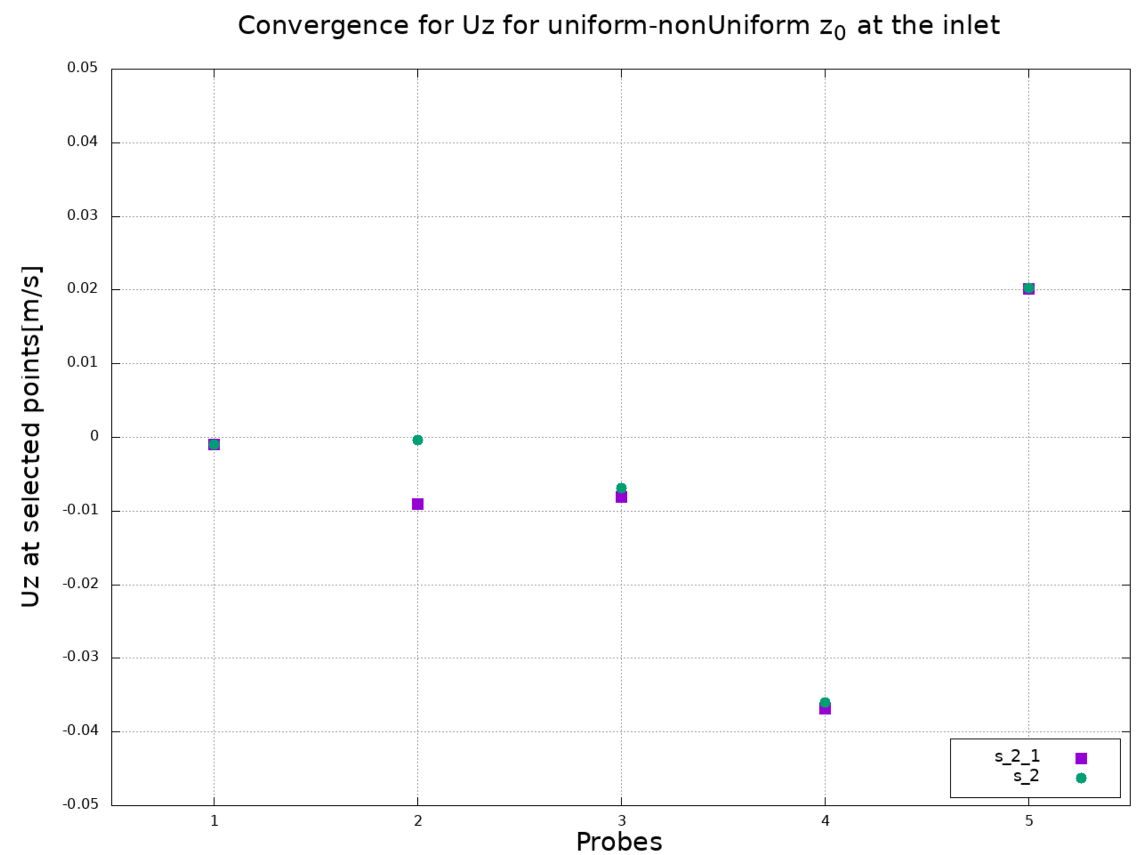
c_2 inlet





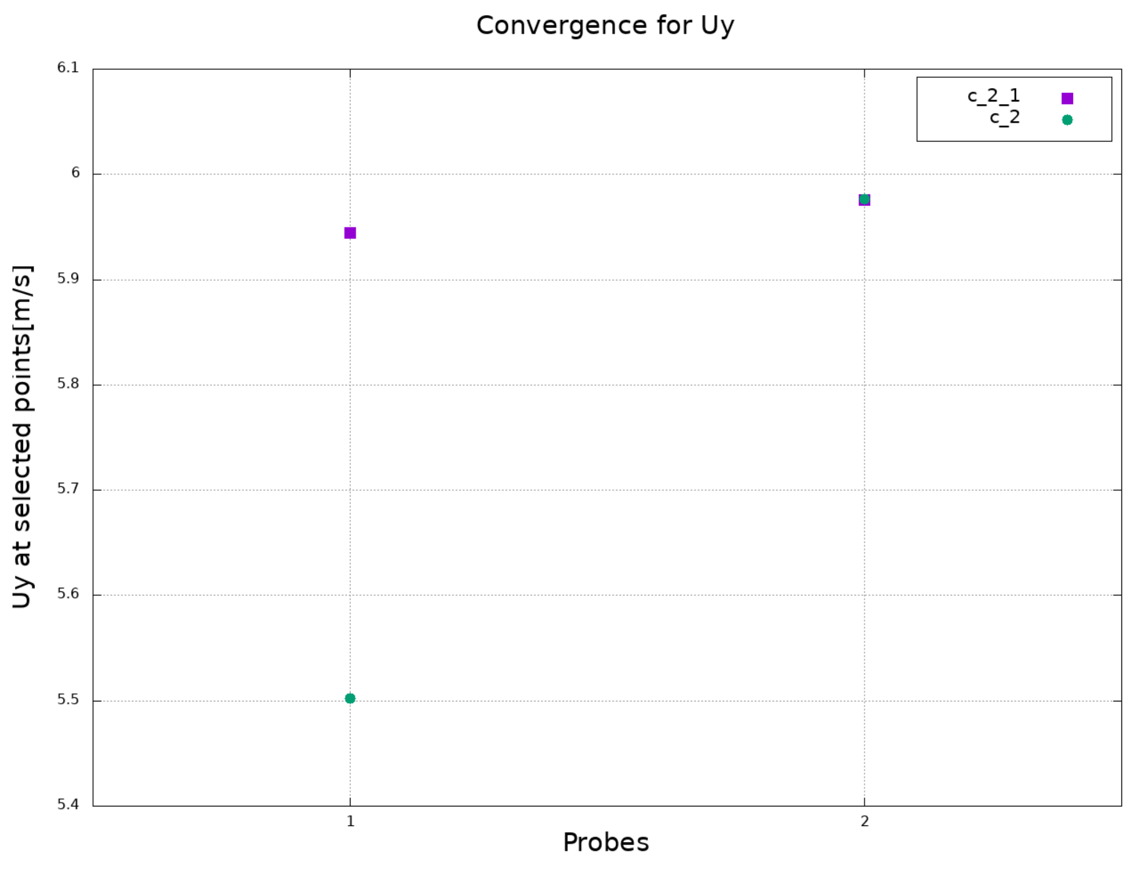
Option – setZ0Inlet – Ideal case s_2 – s_2_1 convergence for Ux and Uz

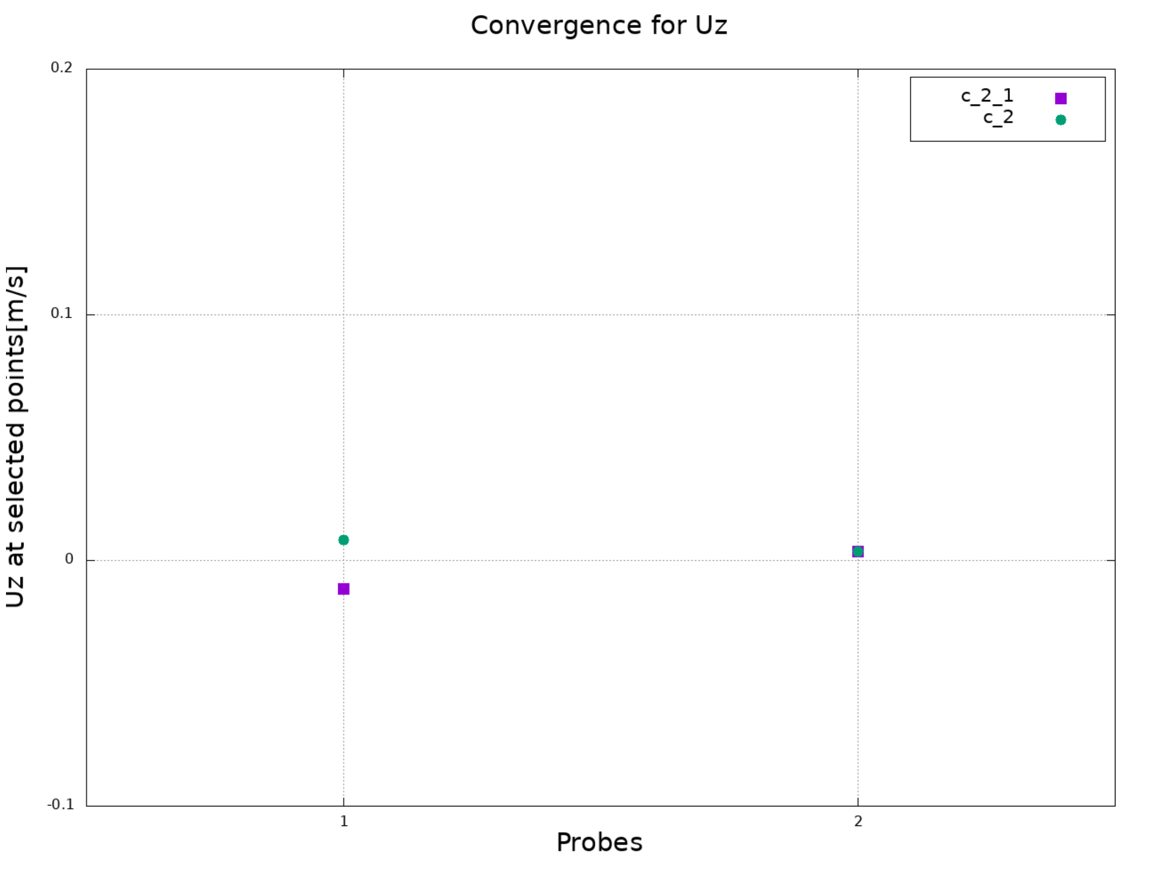




Results

Option – setZ0Inlet – TU Delft case c_2 – c_2_1 convergence for Ux and Uz





TU Delft

Conclusions

Q1: To what extent can the integration be automated?

It is semi-automated

- *Need for user-specified parameters*
- *Option –setZ0Ground, might need testing for 'nearDist' until all values are assigned*
- *Option –setZ0Inlet, ground geometry requires explicit specification to fit the needs of the application*

Q2: How does the modified assignment process of roughness length at the bottom of the domain influences the process and results of the simulation?

- *Facilitates the specification of the z0 in the dictionary files*
- *Specifying the required search distance can pose a hurdle*
- *No significant deviations were observed in the simulation results*

Q3: How does the modified assignment process for non-uniform roughness length at the inlet of the domain influences the process and results of the simulation?

- *Need for tailored ground geometries*
- *Differences for uniform – non uniform z0 at the inlet, however further testing Is required*

Q4: Which other relevant to CFD parameters could be used as 3D model semantics with the built application?

LAD/LAI, albedo, emissivity, thermal conductivity, thermal admittance and colour

Discussion

- Testing is limited to flat surface models, however, the proposed methodology can accommodate 3D surface models.
- Specifying the search distance can pose a hurdle in the use of the application.
- Self-intersections between landcovers did not produce different results with OpenFoam implementation.
- Although assigning non-uniform roughness at the inlet is possible, further testing of the influence on the simulation results is required.

Future Work

- Further testing of option –setZ0Ground with 3D models.
- The search method included in the proposed methodology could be improved with the use of a different data structure.
- Further testing with non-uniform inlet using different geometry configurations, to assess the impact of misassigned values around the separation points.
- Option –setZ0Inlet could be improved by including a method that accounts for cases where the upstream area outside the computational domain has a different roughness than the neighbouring area inside the domain.
- Explore possibilities of different data formats to retrieve the semantics (e.g. raster).
- Investigate further the requirements for including the suggested parameters in the proposed methodology.

THANK YOU!

References

- Azevedo, J. (2013). Development of procedures for the simulation of atmospheric flows over complex terrain, using OpenFOAM.Back, Y., Bach, P. M., Jasper-Tonnies, A., Rauch, W., and Kleidorfer, M. (2021). A rapid fine-scale approach to modelling urban bioclimatic conditions. *Science of The Total Environment*, 756:143732.
- Blocken, B. (2015). Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Building and Environment*,91:219–245.
- Blocken, B., Stathopoulos, T., and Carmeliet, J. (2007). Cfd simulation of the atmospheric boundary layer: wall function problems. *Atmospheric Environment*, 41(2):238–252.
- Oke, T. R. (1978). *Boundary layer climates*. OCLC: 51200739.
- Parente, A., Gorle, C., Beeck, J., and Benocci, C. (2011). Improved k– ´ ϵ model and wall function formulation for the RANS simulation of ABL flows. *Journal of Wind Engineering and Industrial Aerodynamics*, 99:267–278.
- Pardyjak, E. and Stoll, R. (2017). Improving measurement technology for the design of sustainable cities. *Measurement Science and Technology*, 28.
- Segersson, D. (2017). A tutorial to urban wind flow using OpenFOAM. In Proceedings of CFD with OpenSource Software.
- Su, Y.-T., Bethel, J., and Hu, S. (2016). Octree-based segmentation for terrestrial lidar point cloud data in industrial applications. *ISPRS Journal of Photogrammetry and Remote Sensing*, 113:59–74.