Delft University of Technology

MSc Geomatics

The effect of building footprint uncertainty on CFD simulations

Author: Christos Chontos

1st Supervisor: Dr. Clara García-Sánchez
2nd Supervisor: Dr. Akshay Patil
Co-reader: Dr. Hugo Ledoux

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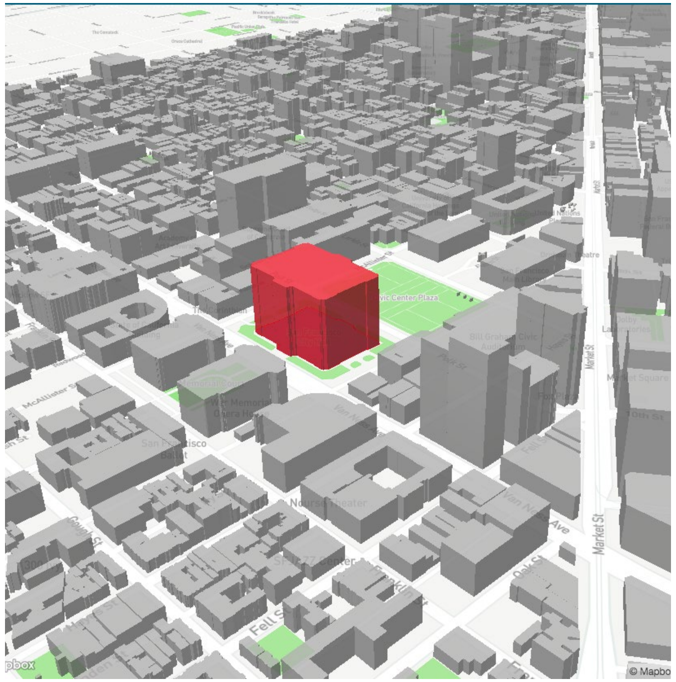
Today's Agenda

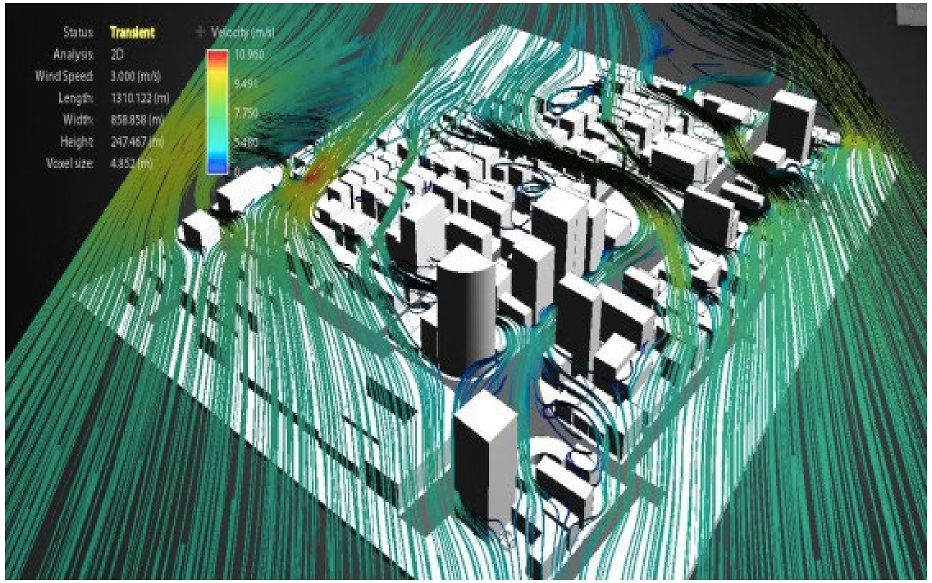
- Introduction-Thesis objectives
- Related work
- Methodology
- Implementation and validation
- Results and analysis
- Conclusions

Motivation

Source: https://wiki.openstreetmap.org/wiki/Microsoft_Building_Footprint_Data



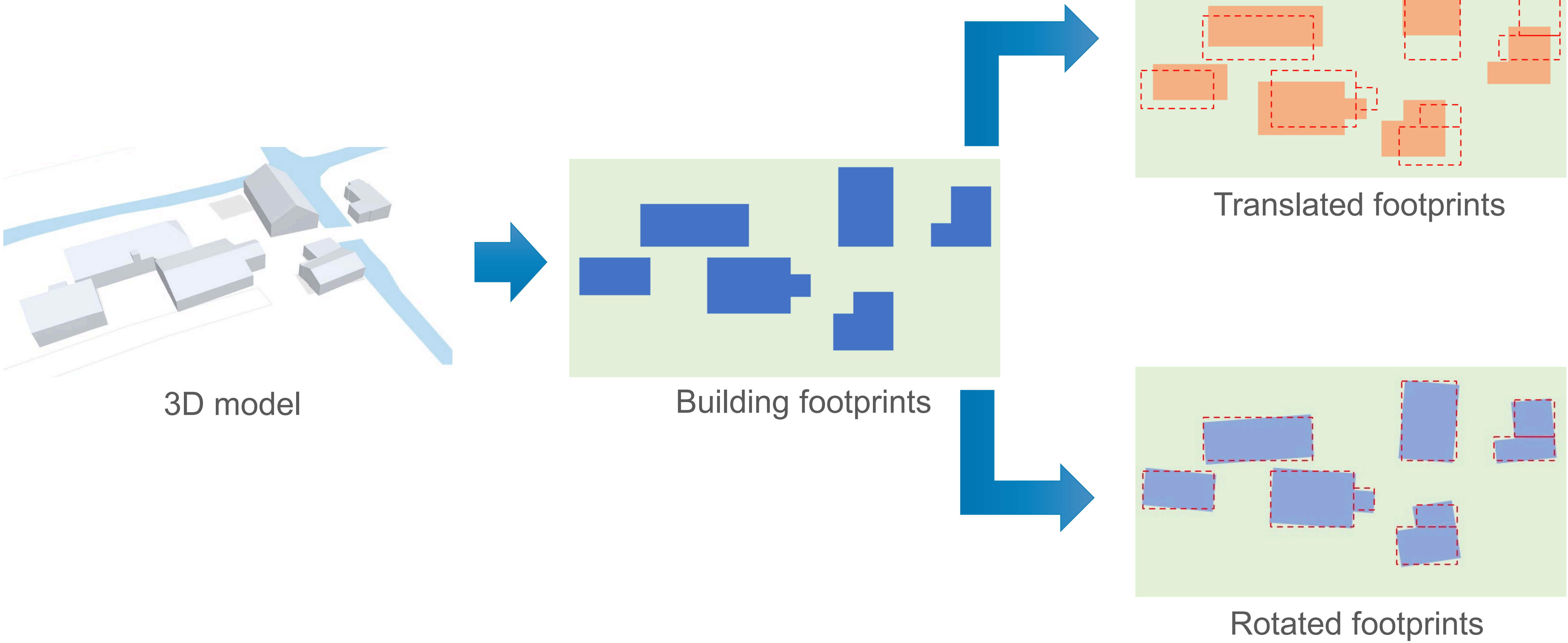
Source: https://datasf.org/blog/new-sf-building-footprints-released-with-3d-characteristics/



Wind flow pattern at 12m from ground level from the south-east direction. Source: Datta (2017)

From building footprints to 3D models, using them to perform CFD simulations

Such uncertainties can be **rotations** and **translations**



Thesis Objectives

Research Questions

Question 1

Validation of our CFD cases compared to the wind tunnel data

Question 2

How much do different geometry uncertainties affect the reliability of our CFD simulations compared to the reference cases?

Sub-Question 1

What is the impact of geometrical uncertainties derived from perturbing the buildings' geometry through translation?

Sub-question 2

What is the impact of geometrical uncertainties derived from perturbing the buildings' geometry through rotation?

Sub-question3

How do all these uncertainties affect the model as we modify the incoming wind direction?

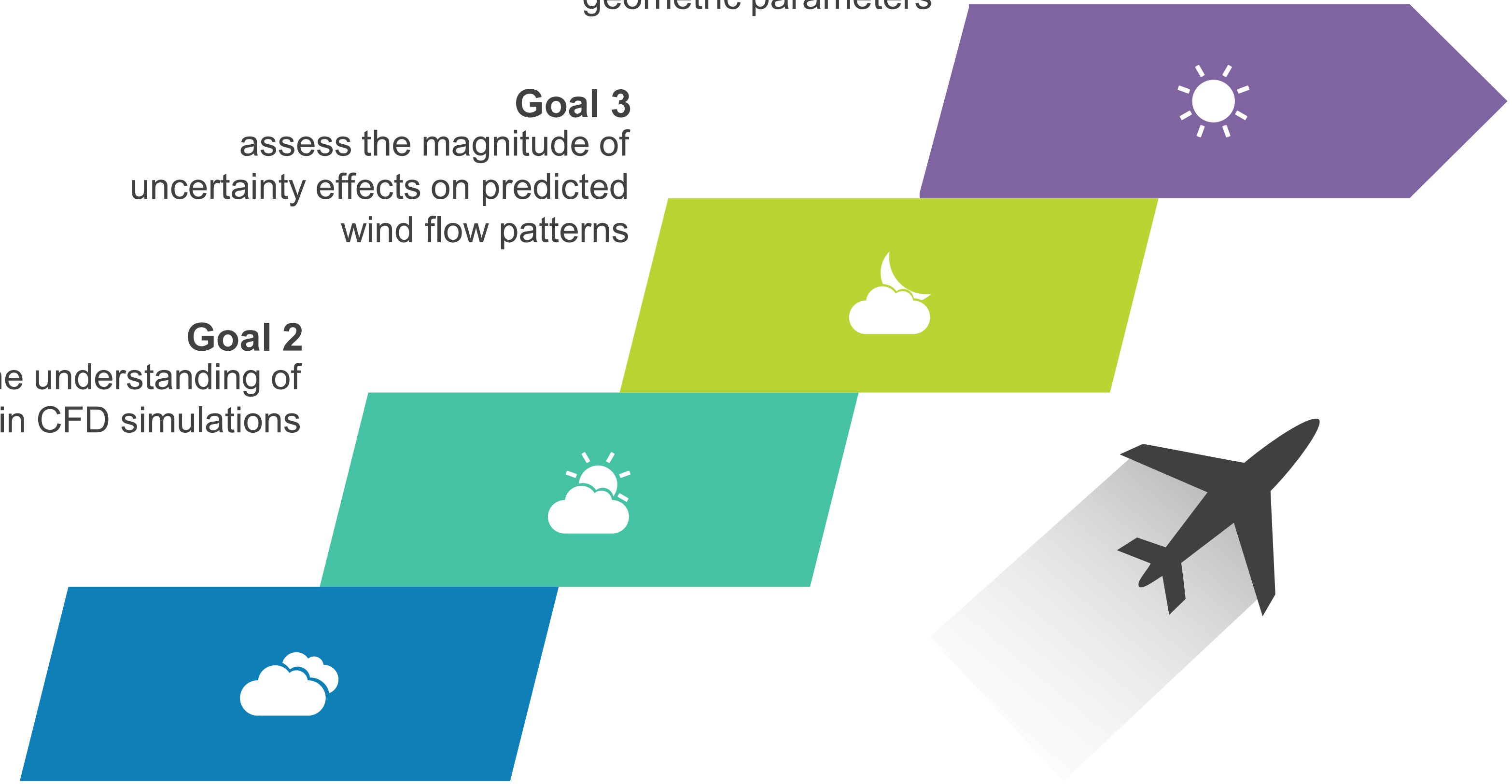
The Goals Of This Thesis

Goal 4
identifying the most influential geometric parameters

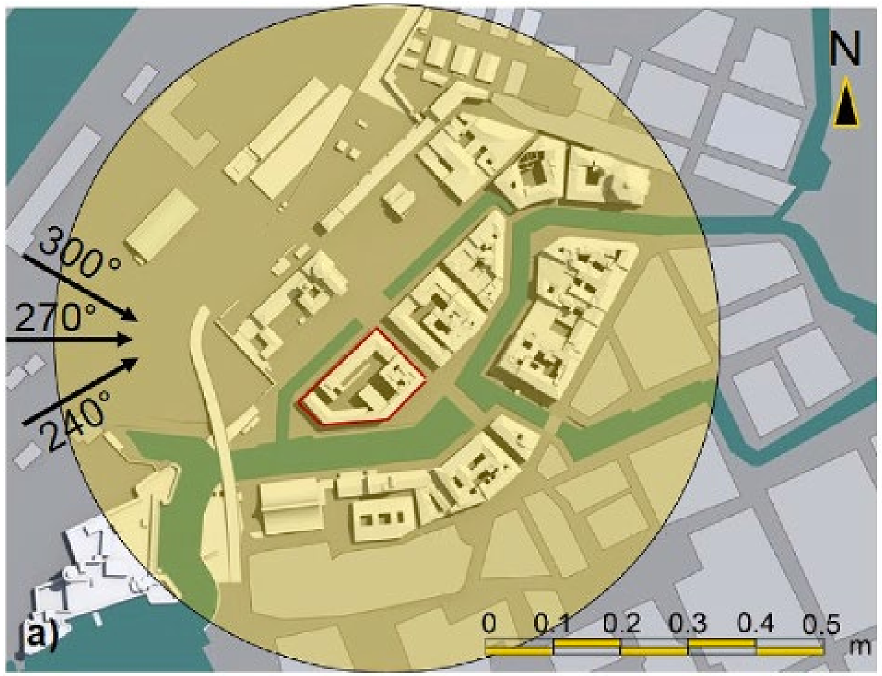
Goal 3
assess the magnitude of uncertainty effects on predicted wind flow patterns

Goal 2
improve the understanding of uncertainty in CFD simulations

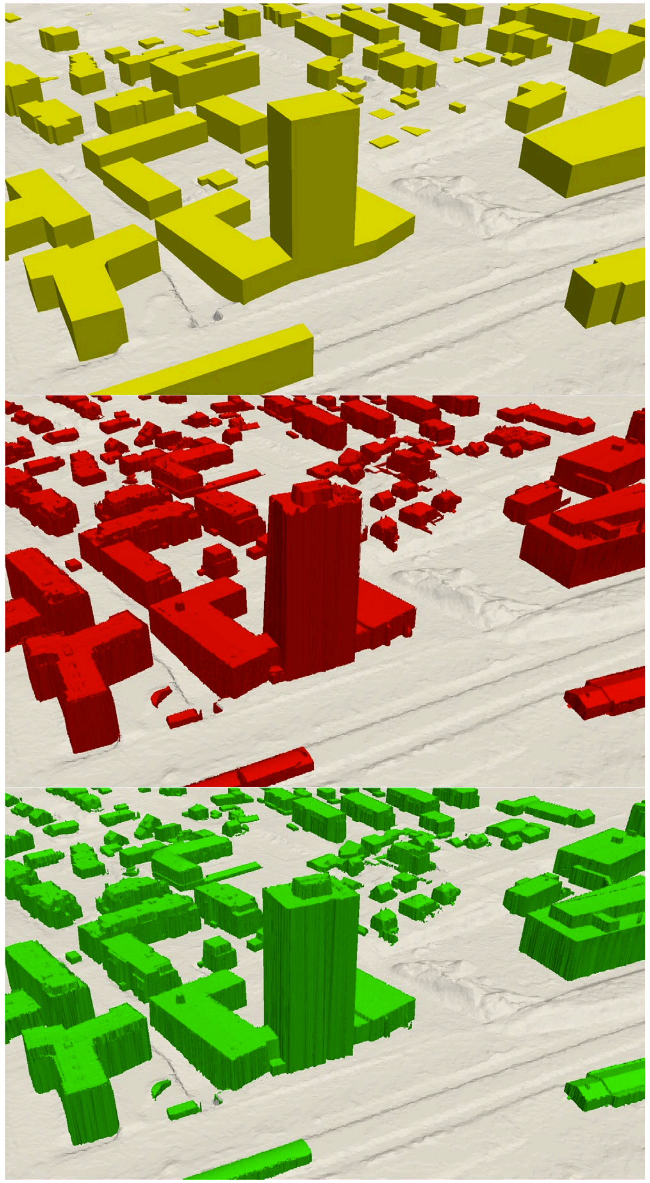
Goal 1
validation of CFD results against wind tunnel measurements



Uncertainties and CFD



Geometry (Digital model) and different wind angles (Ricci et al., 2017)



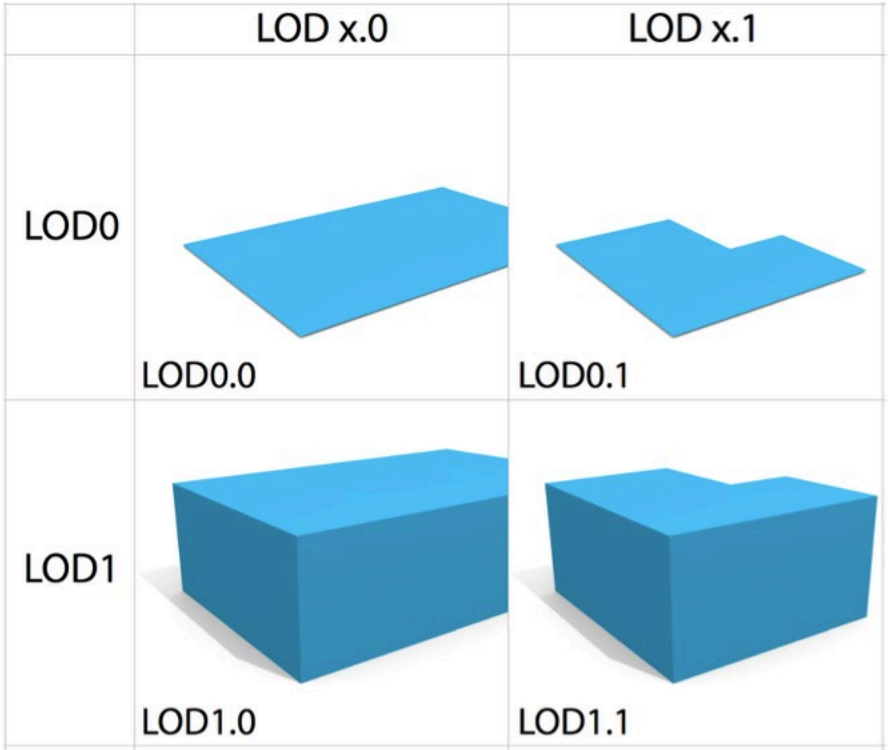
(a) Footprint extrusion model

(b) Drone photogrammetry model

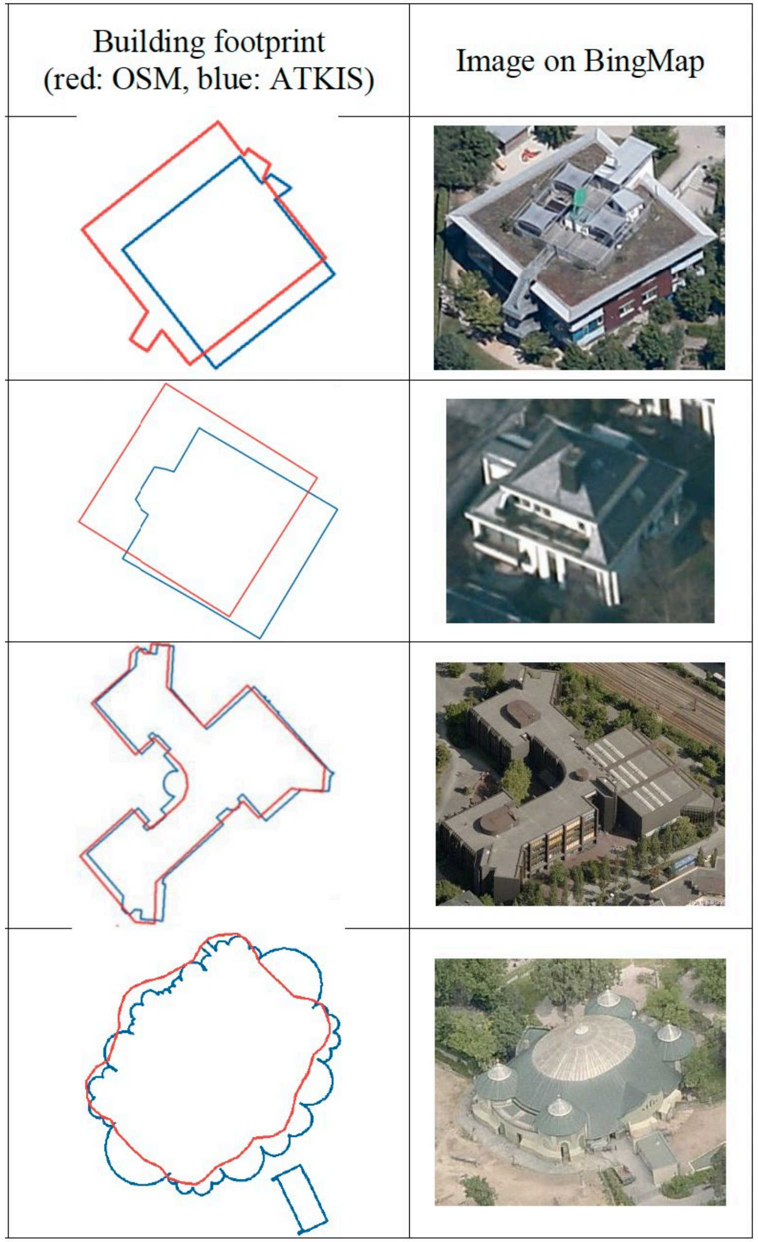
(c) Airborne LiDAR model

Comparison of different building model types (Hagbo et al., 2021)

Building Footprints

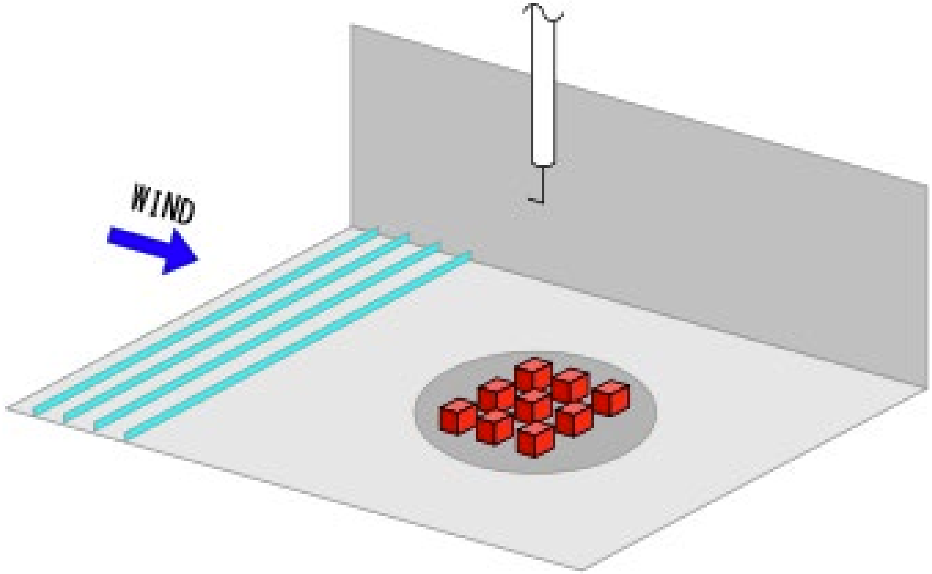


Visual example of the LoDs for a Building, (Biljecki et al., 2016)



Examples of building footprints in OSM and ATKIS, (Fan et al., 2014)

Our Case Study

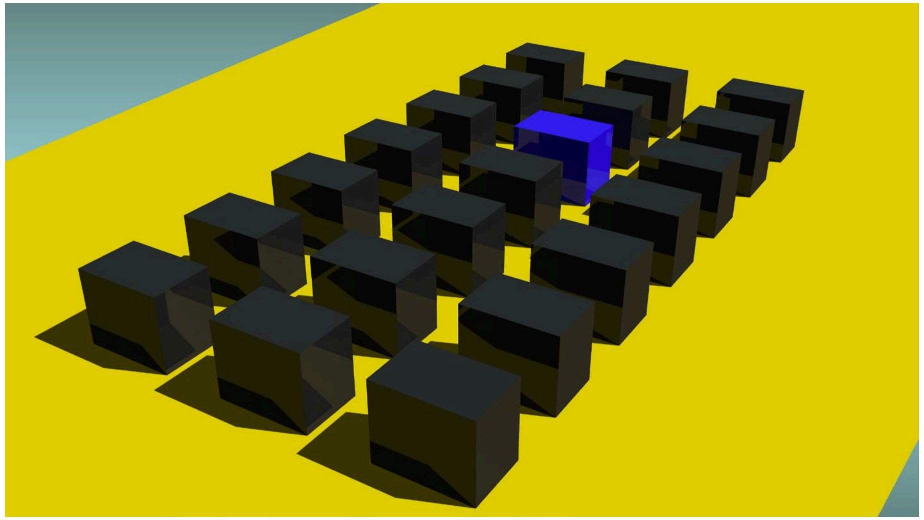


Among multiple benchmark cases, this study focuses exclusively on the **Case C** provided by the **Architectural Institute of Japan** because of:

- its well-documented geometry
- high-quality wind tunnel measurements
- and its widespread acceptance

Similar Geometrical Cases 1/3
CEDVAL Database

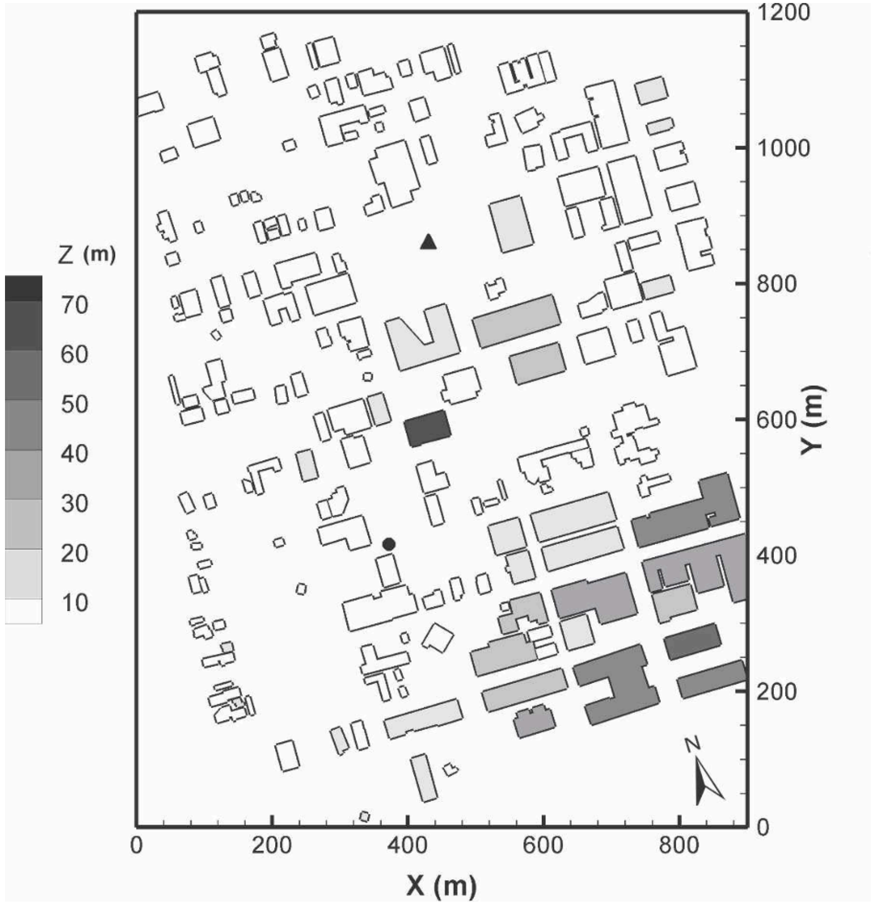
- An essential resource for validating CFD models in urban wind flow and dispersion studies
- Developed by the **Environmental Wind Tunnel Laboratory** at the **University of Hamburg**
- Contains a collection of high-quality wind tunnel measurements designed to evaluate numerical simulations



CEDVAL B1-1 case (Longo et al., 2017)

Similar Geometrical Cases 2/3

Joint Urban 2003 Field Study



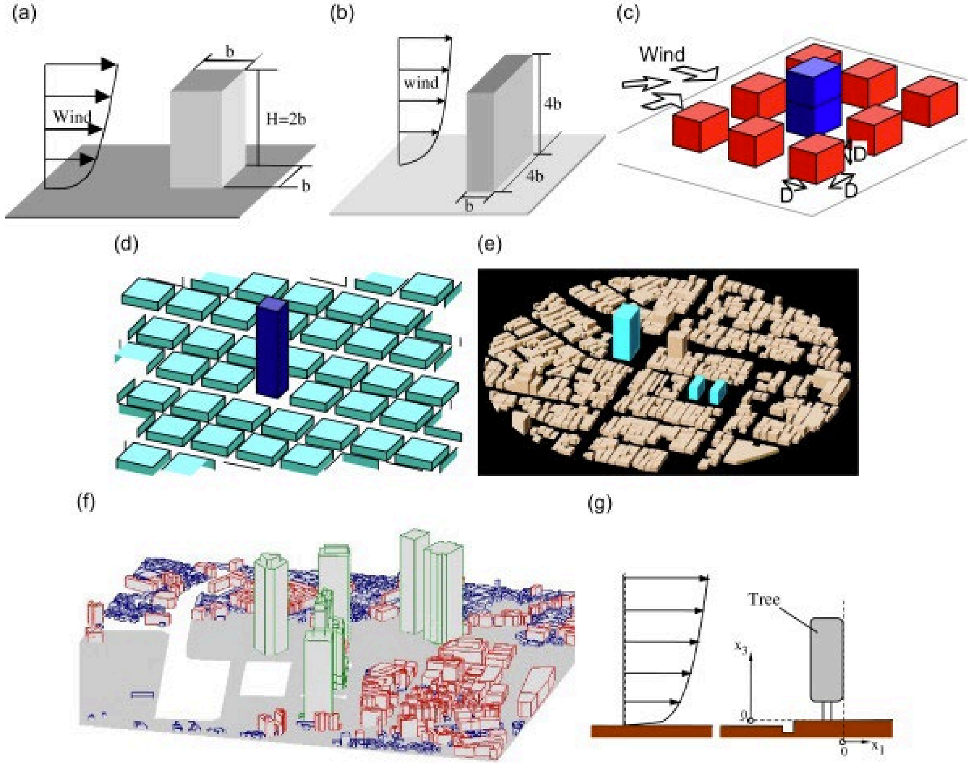
Part of JU2003, (Flaherty et al., 2007)

- Conducted in Oklahoma City to investigate wind flow and pollutant transport in a realistic urban environment
- It proves that accurately modelling of the buildings is crucial
- Several studies (e.g. Flaherty et al.(2007), Garcia-Sanchez et al. (2014)) used JU2003 data to evaluate CFD predictions over observed measurements and discrepancies were found

Similar Geometrical Cases 3/3

Guidebook for Urban CFD Predictions – Architectural Institute of Japan

- Extensive cross-comparisons between CFD simulation results and high-quality wind-tunnel measurements were conducted
- Seven test cases were used to investigate the influence of different computational conditions for various flow fields and geometries
- A set of guidelines was created to investigate the influence of the **computational conditions** on the prediction accuracy (grid discretization, domain sizes, boundary conditions, etc.)



AIJ cases, (Tominaga et al., 2008)

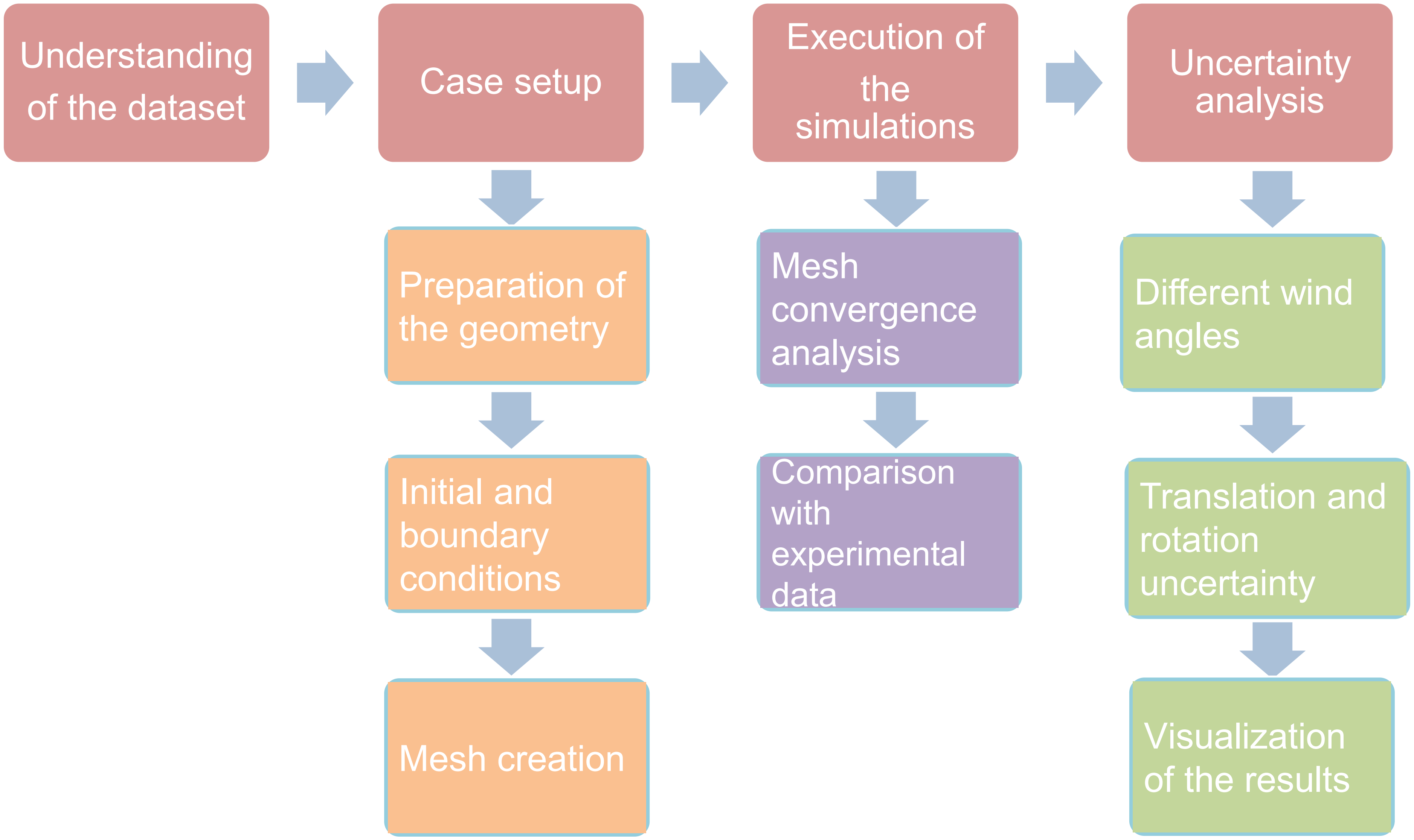
Some Useful Outcomes Derived From Literature Review

The uncertainty in CFD simulations of urban flow is inevitable and multifaceted.

Geometric uncertainty is a particularly influential factor for urban wind and dispersion predictions.

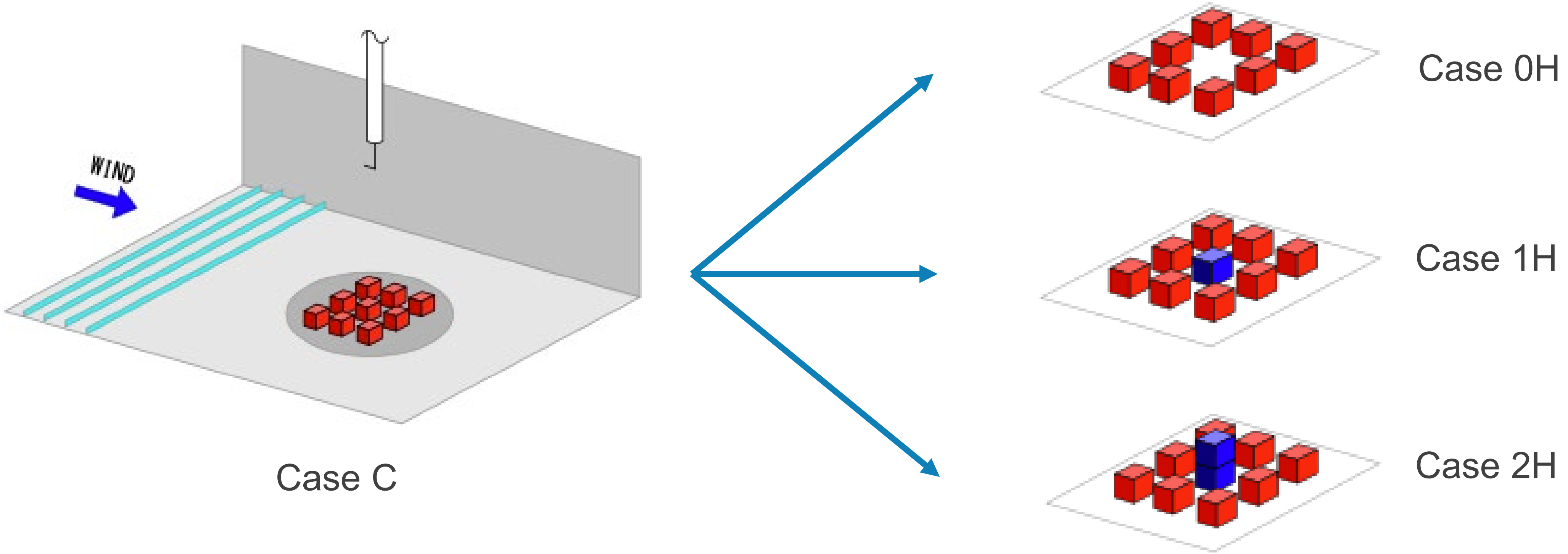
Numerous validation efforts (wind-tunnel and field studies) have helped quantify these uncertainties, showing where and by how much CFD results might deviate.

Methodology



Dataset

Architectural Institute of Japan – Case C (Simple Building Blocks)

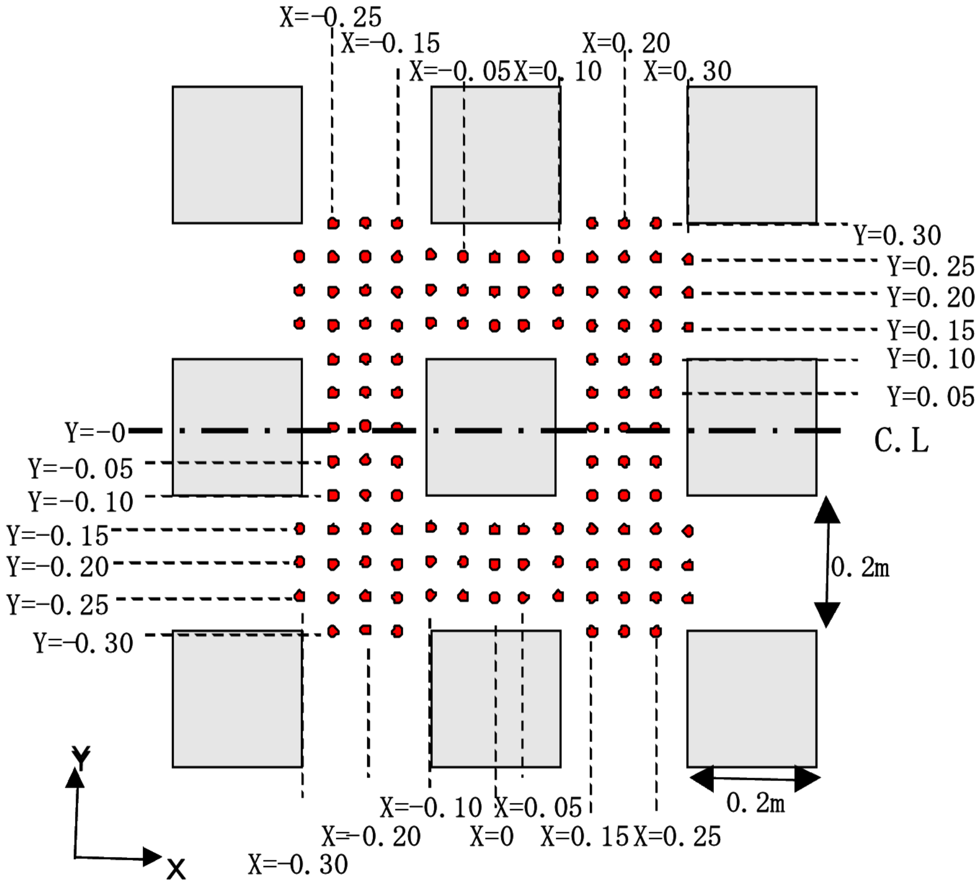


Source: https://www.aij.or.jp/jpn/publish/cfdguide/index_e.htm

Dataset

Architectural Institute of Japan – Case C (Simple Building Blocks)

- 0.2m cubes' size and distance from each other
- 0.02m probes' height distance from each other
- 120 probes (testing points)

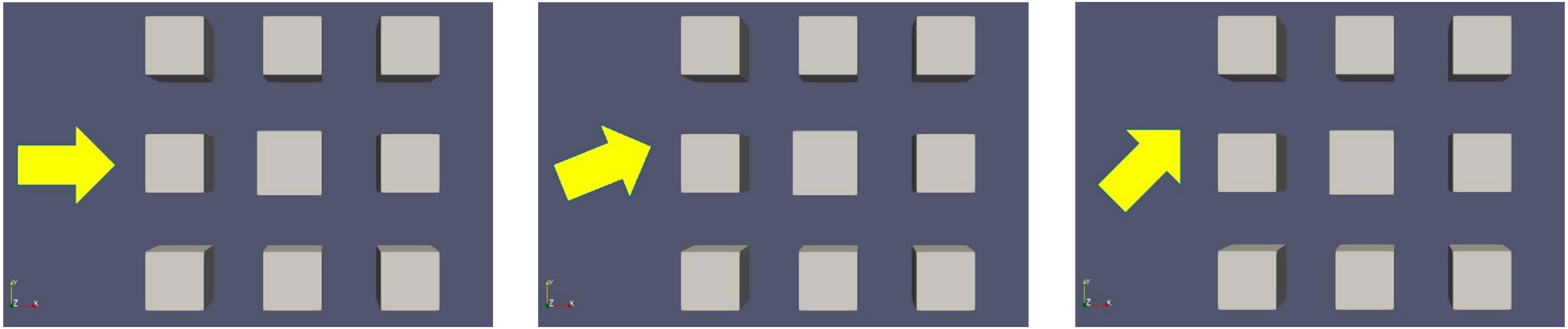


Top view and probes

Source: https://www.aij.or.jp/jpn/publish/cfdguide/index_e.htm

Dataset

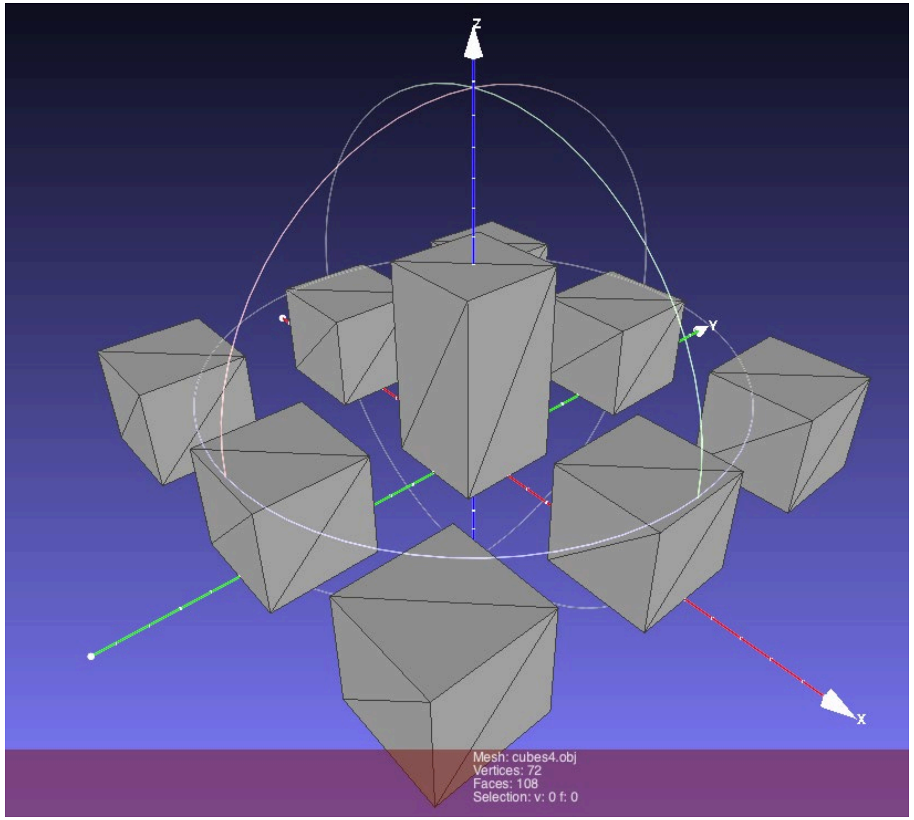
Architectural Institute of Japan – Case C (Simple Building Blocks)



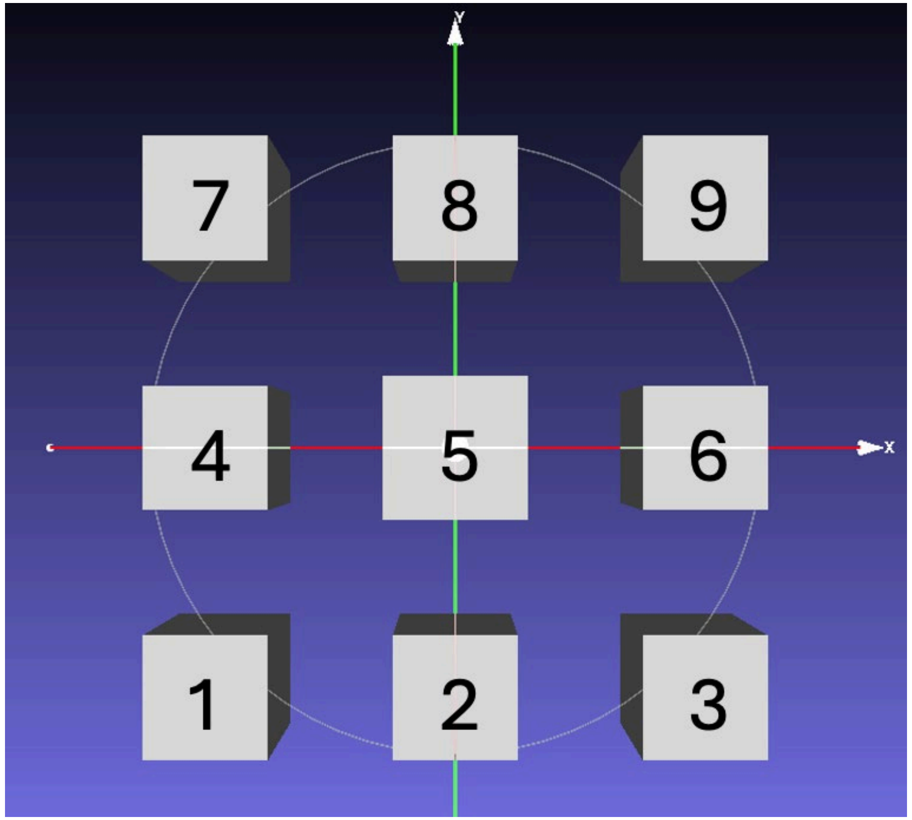
0º ***22.5º*** ***45º***

3 different wind angles

Preparation of Geometry



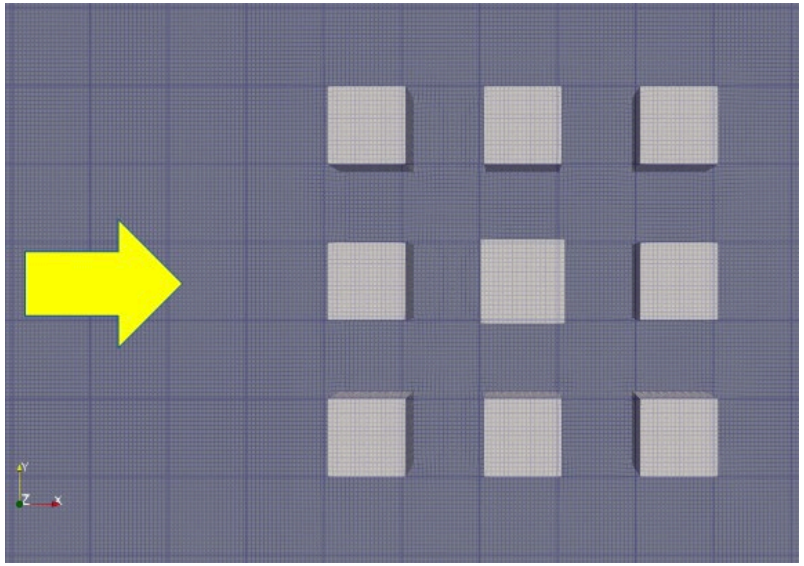
Case C - 2H obj (Meshlab)



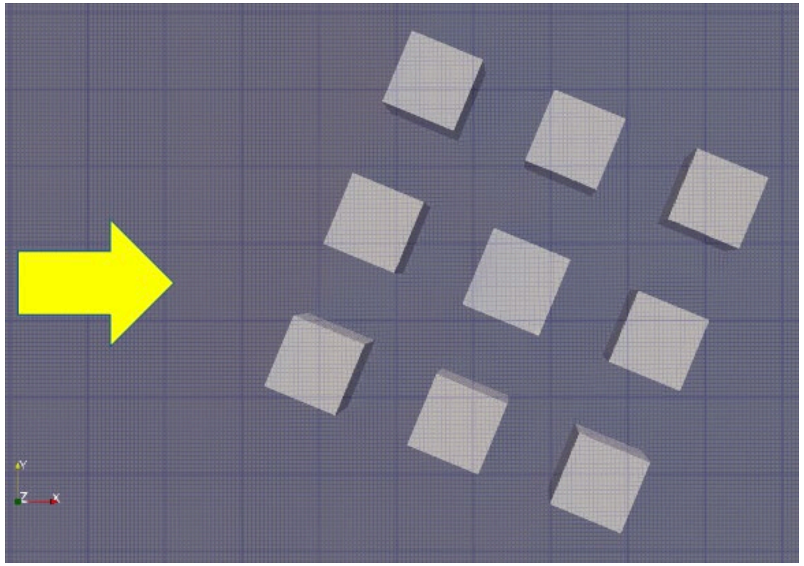
Case C - enumeration

3 .obj files were created: **0H, 1H, 2H**

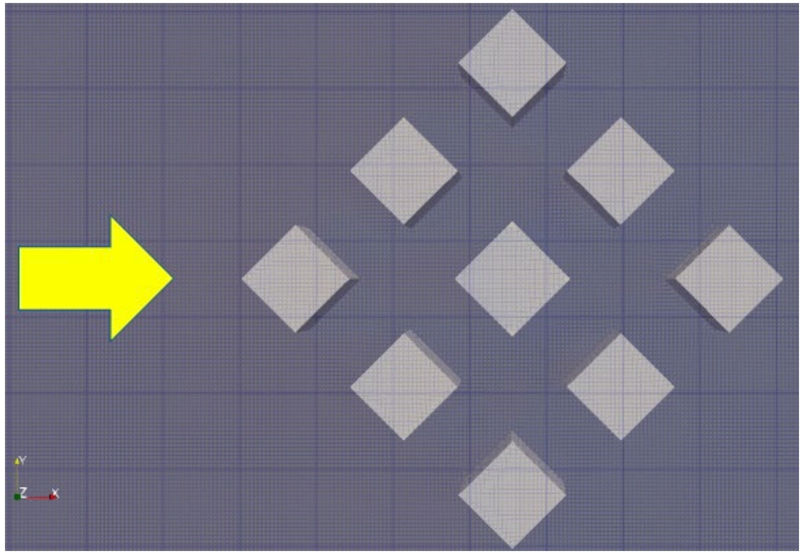
Preparation of Geometry



Rotation 0^{o}



Rotation 22.5^{o}



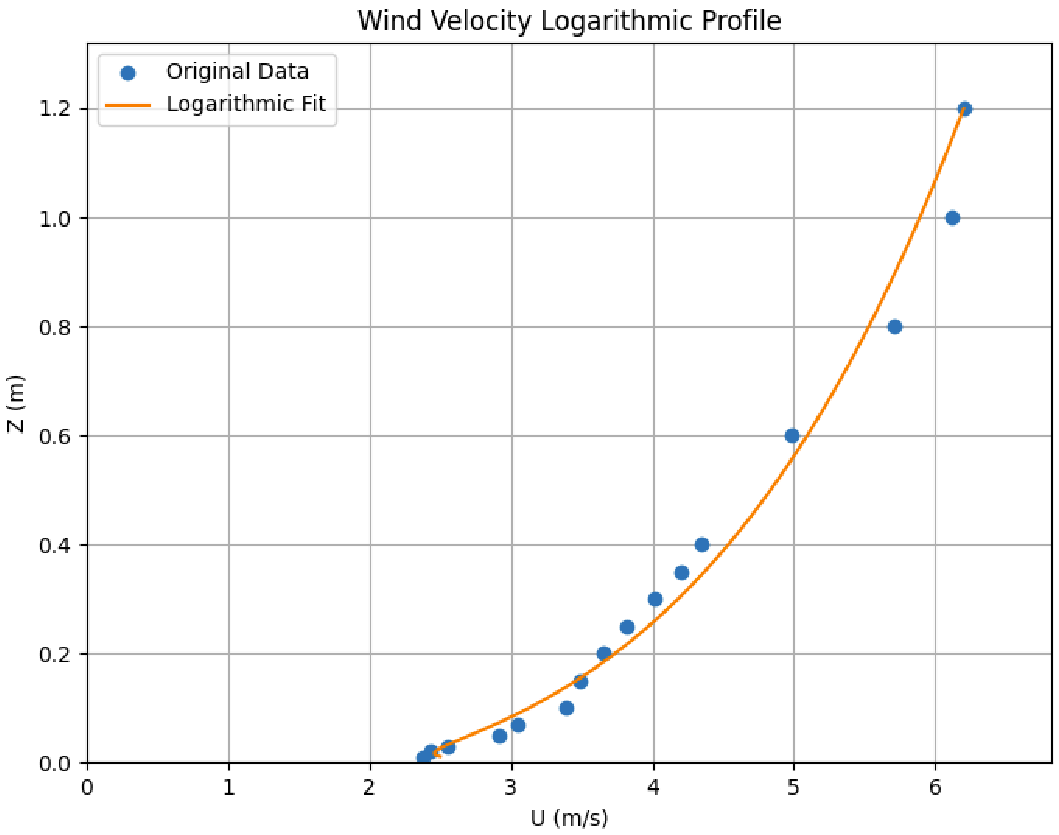
Rotation 45^{o}

To simulate different wind angles, we rotated our geometry clockwise

Initial and Boundary Conditions

Z(m)	U (m/s)
0,01	2,372
0,02	2,434
0,03	2,548
0,05	2,912
0,07	3,042
0,1	3,392
0,15	3,483
0,2	3,654
0,25	3,82
0,3	4,019
0,35	4,205
0,4	4,343
0,6	4,985
0,8	5,713
1	6,12
1,2	6,201

Inflow values



Logarithmic Wind velocity profile

Source: https://www.aij.or.jp/jpn/publish/cfdguide/index_e.htm

Initial and Boundary Conditions

$$(1)\ U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right)$$ → **u_* = 0.322 m/s** friction velocity

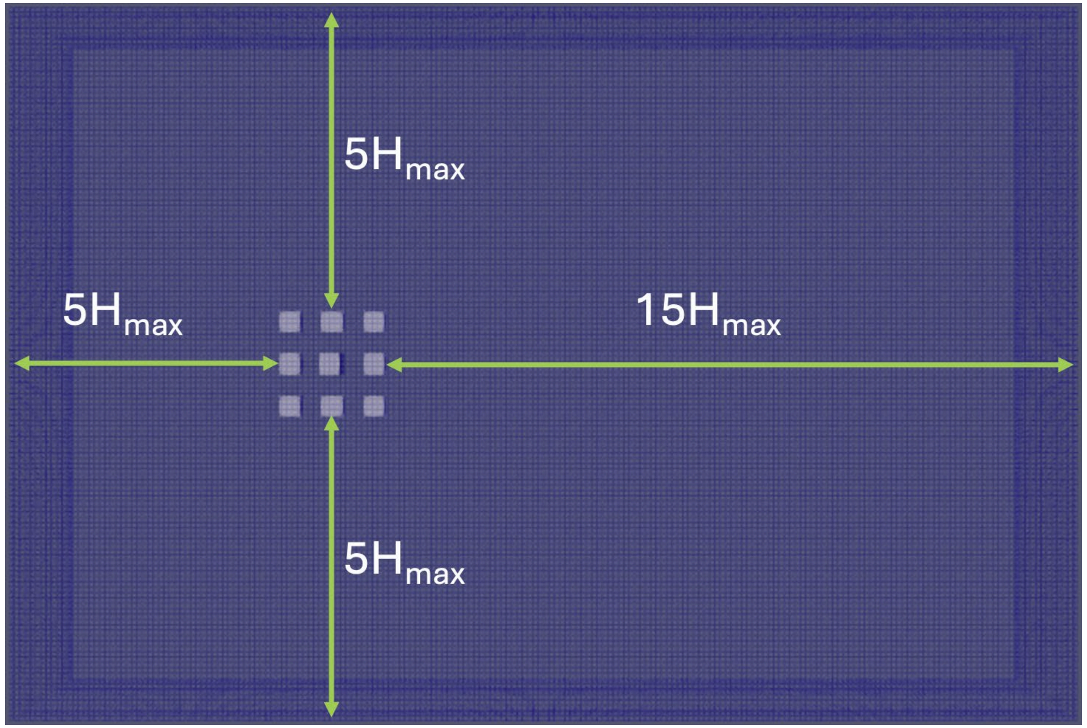
$$(2)\ k(z) = \frac{u_*^2}{\sqrt{C_\mu}}$$ → **k = 0.346 m^2/s^2** TKE

$$(3)\ \epsilon(z) = \frac{u_*^3}{\kappa(z+z_0)}$$ → **ε = 0.068 m^2/s^3** Turbulent Epsilon

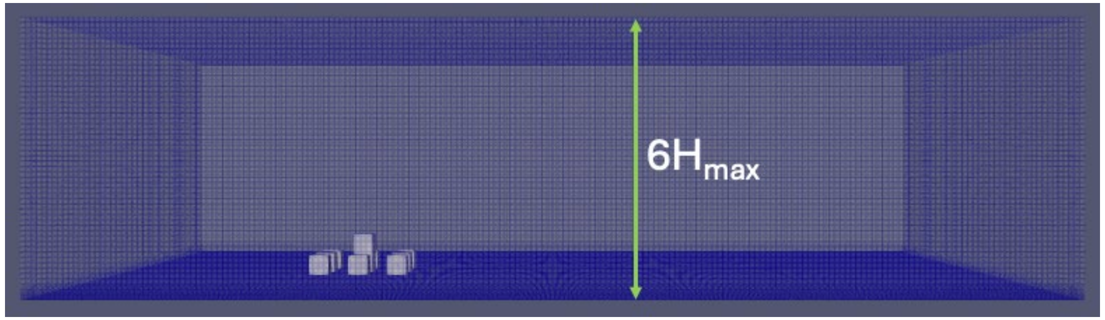
(Richards and Hoxey, 1993)

Mesh Creation

According to *Franke et al. (2007)* *guidelines the blockmesh dimensions are:*



Top view



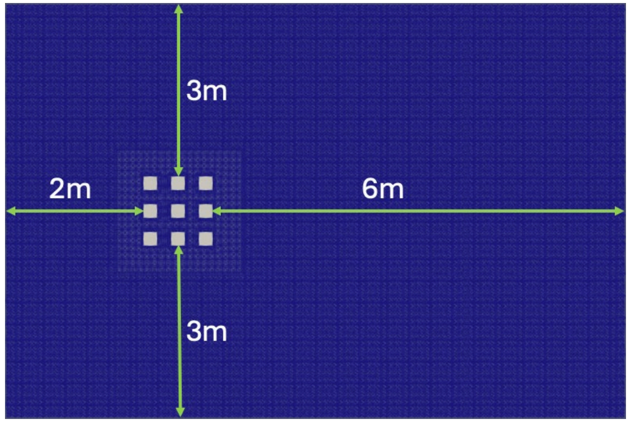
Side view

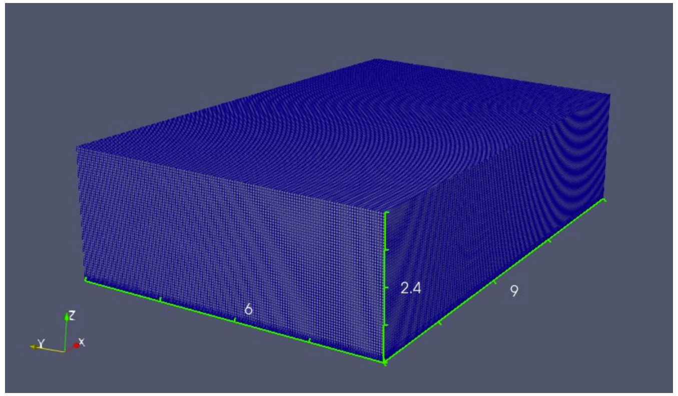
Directional Blockage Ratio:

Length: $BR_{\mathrm{L}} = \frac{L_{\mathrm{building}}}{L_{\mathrm{domain}}} < 17\%$

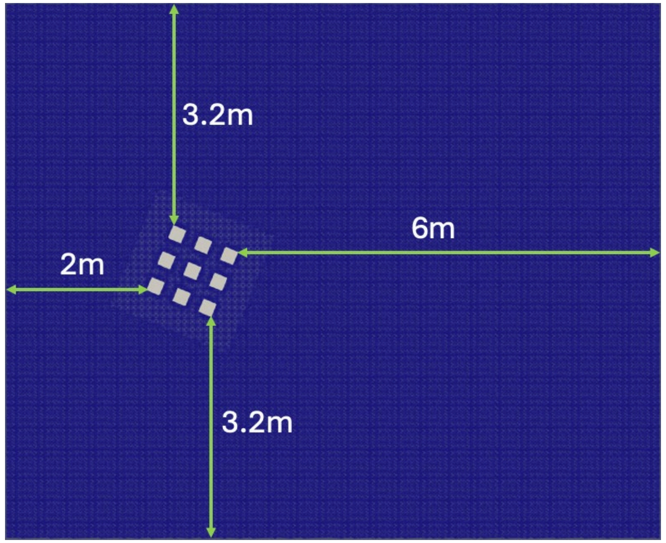
Height: $BR_{\mathrm{H}} = \frac{H_{\mathrm{building}}}{H_{\mathrm{domain}}} < 17\%$

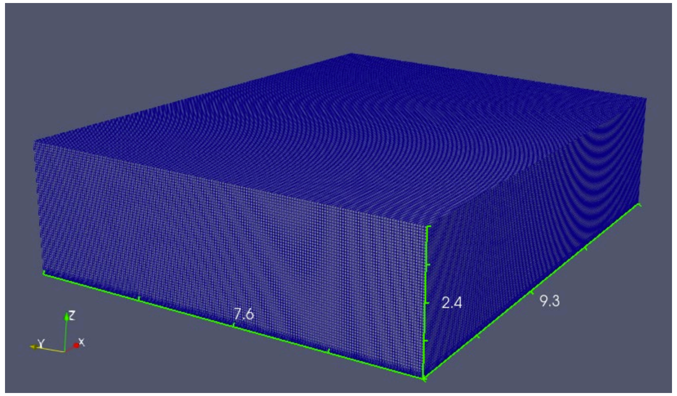
Blockmeshes



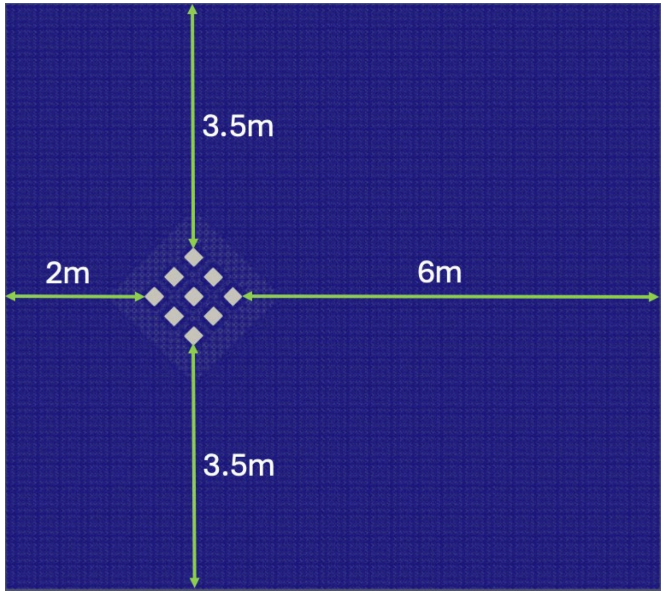


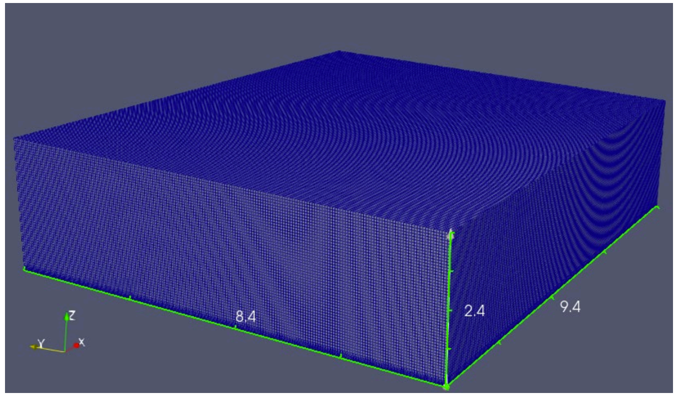
Wind angle 0^o





Wind angle 22.5^o





Wind angle 45^o

Blockmesh dimensions:

- Wind angle 0^o: 9 x 6 x 2.4 m (for all three cases: 0H, 1H, 2H)
- Wind angle 22.5^o: 9.3 x 7.6 x 2.4 m
- Wind angle 45^o: 9.4 x 8.4 x 2.4 m

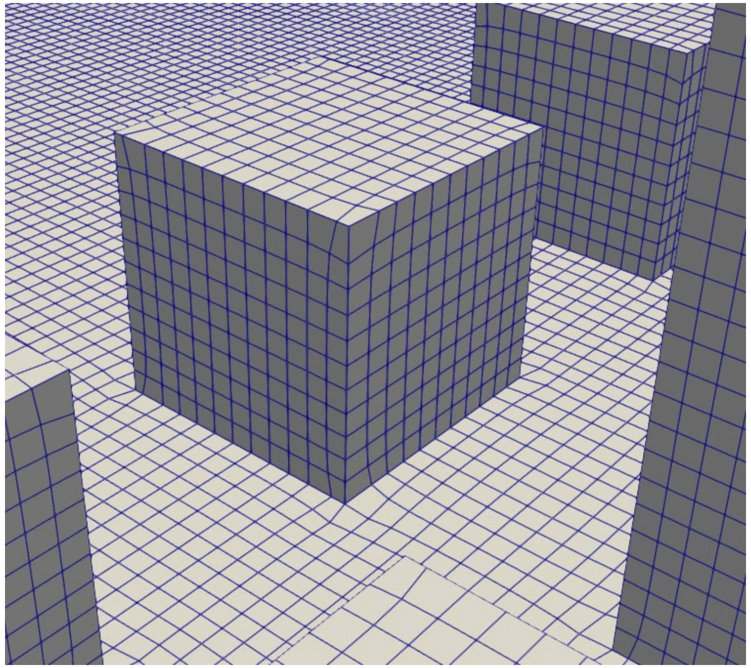
Grid Resolution

Requirements:

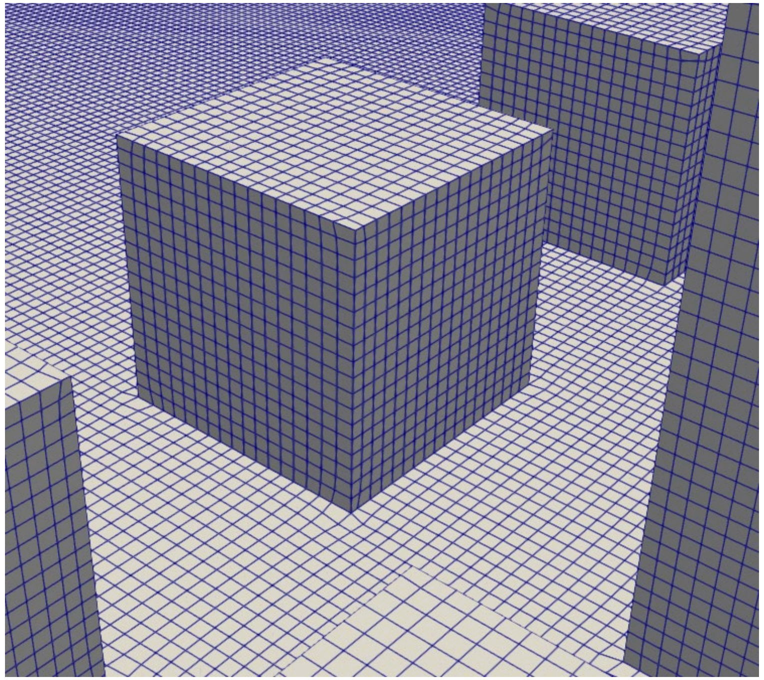
- 10 cells per cube root of the building volume and between buildings
- Cell size > z_0
- $3^{rd}/4^{th}$ cell should reach the height of the probes
- Stretching ratio per cell < 1.3

So, with refinement factor r = 1.5, our fine mesh was set to 0.03m grid resolution

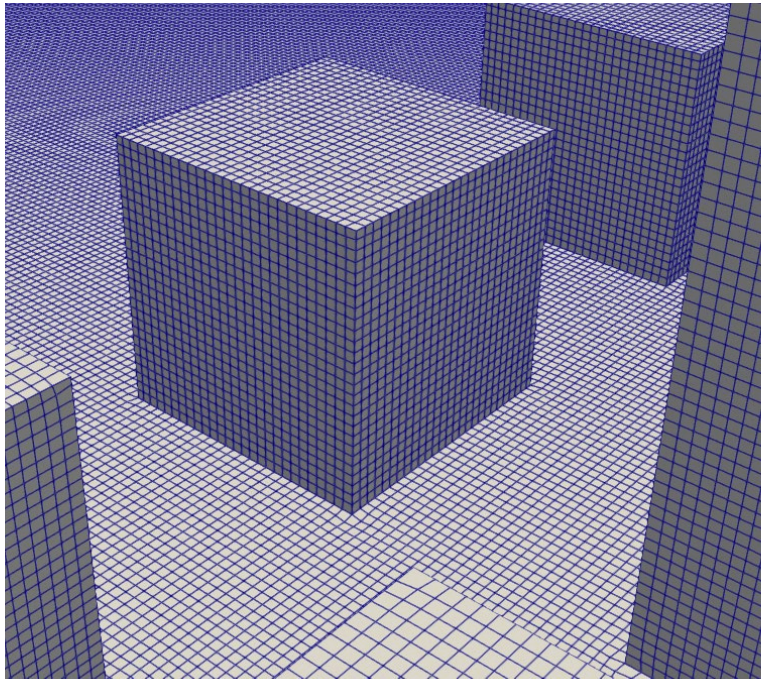
Grid Resolution



Coarse Mesh: 0,07m Resolution



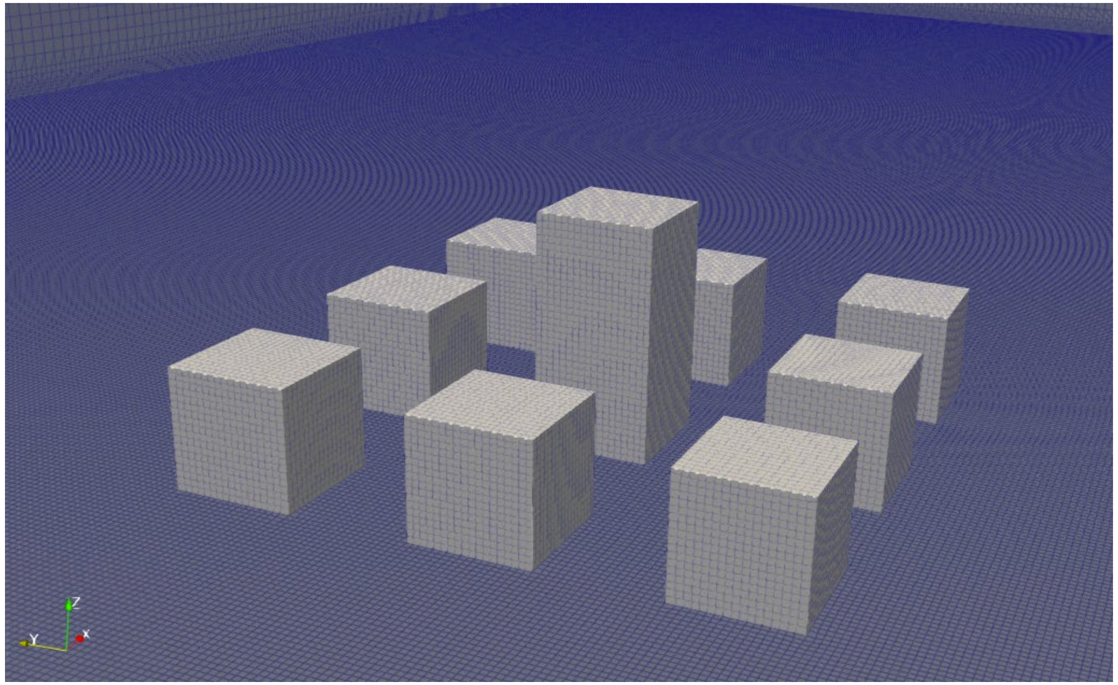
Medium Mesh: 0,045m Resolution

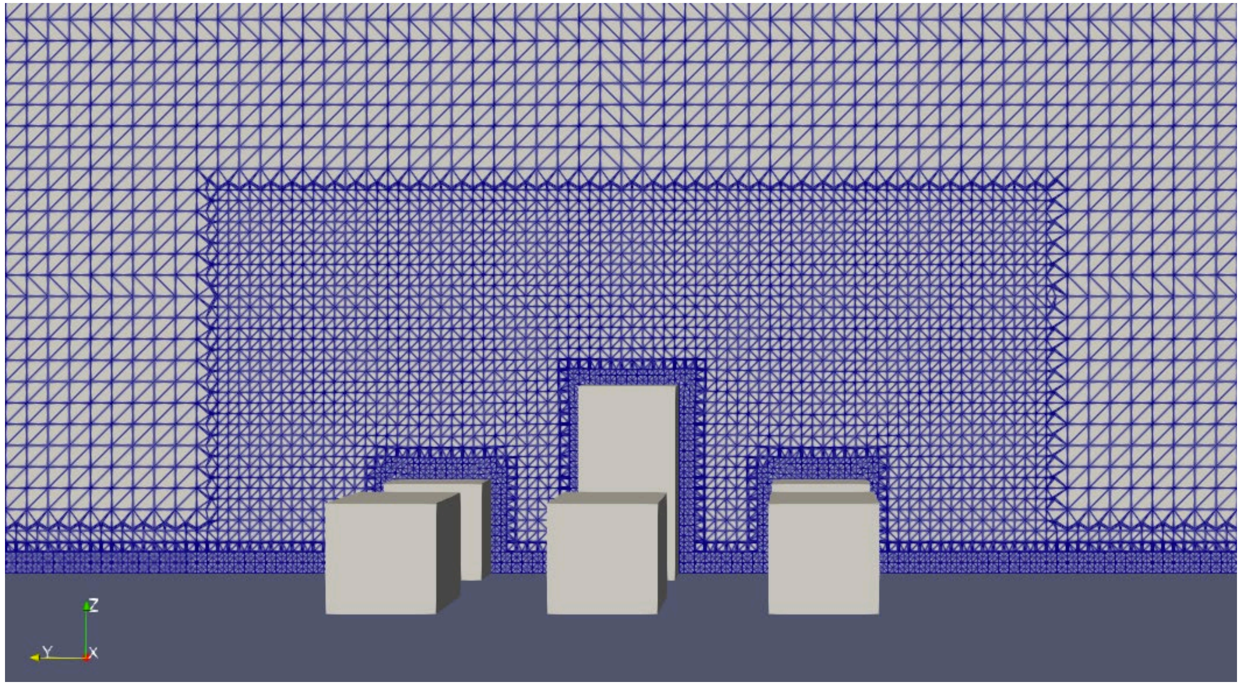


Fine Mesh: 0,03m Resolution

Mesh type	Cell size (m)	nCells x	nCells y	nCells z	Total cells
Coarse Mesh	0,07 x 0,07 x 0,07	128	86	34	374.272
Medium Mesh	0,045 x 0,045 x 0,045	200	133	53	1.409.800
Fine Mesh	0,03 x 0,03 x 0,03	300	200	80	4.800.000

SnappyHexMesh

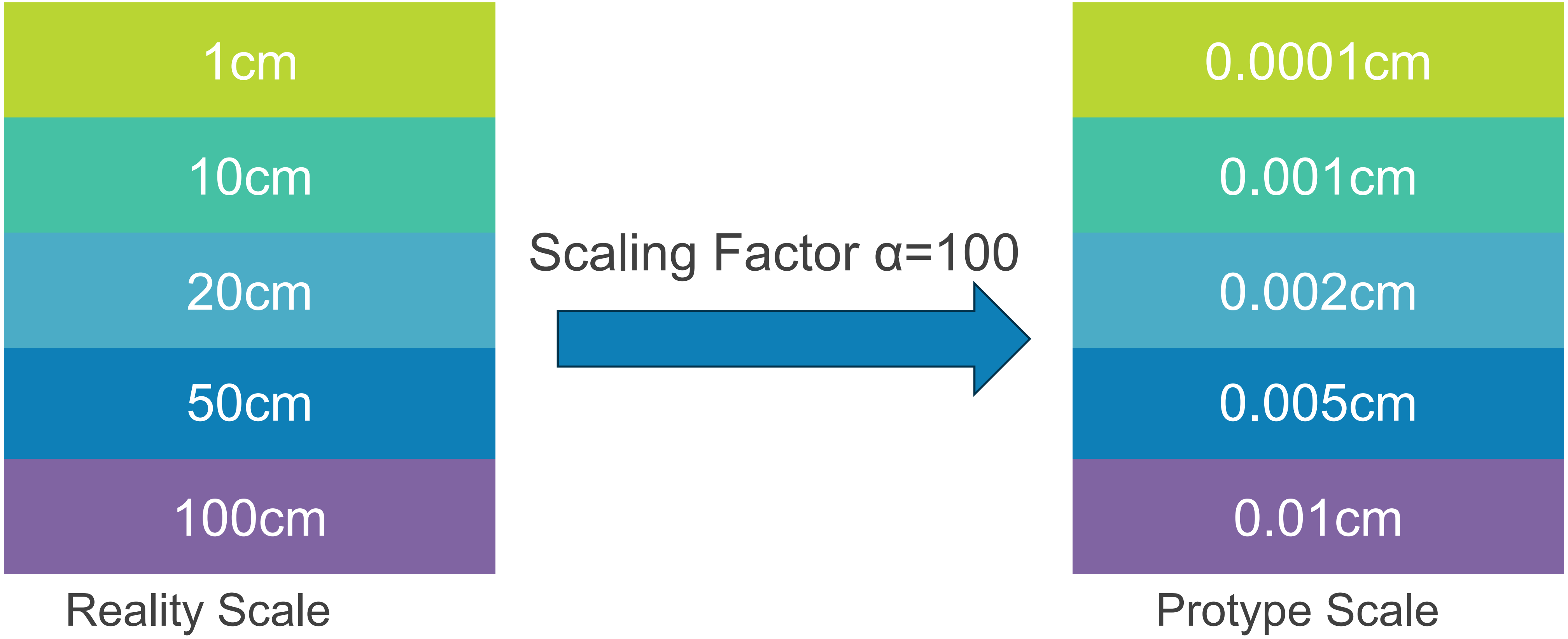




Refinement Boxes (Case 2H, medium mesh)

- 2 level of refinement
- 2 refinement boxes

Introduction to Uncertainty



Methodology Created for Translation

A The uncertainty will be represented as an offset

B The offset is radial (could take place towards any direction)

C There is one translational uncertainty value per building

D Each sample contains the translation values of the buildings, following the normal distribution N[μ, σ]

- ☑ The mean (μ) is centred around the translation value t_i
- ☑ The coefficient of variation is CV = 10% = 0.1
- ☑ The standard deviation is $\sigma = t_i * CV$

Methodology Created for Rotation

A B C D

- The mean (μ) is centred around the translation value r_i
- The coefficient of variation is CV = 10% = 0.1
- The standard deviation is $\sigma = r_i * CV$

Based on 1º ≈ 0.0025m offset, five uncertainty levels were created: **0.5º, 1º, 2º, 3º, 5º**

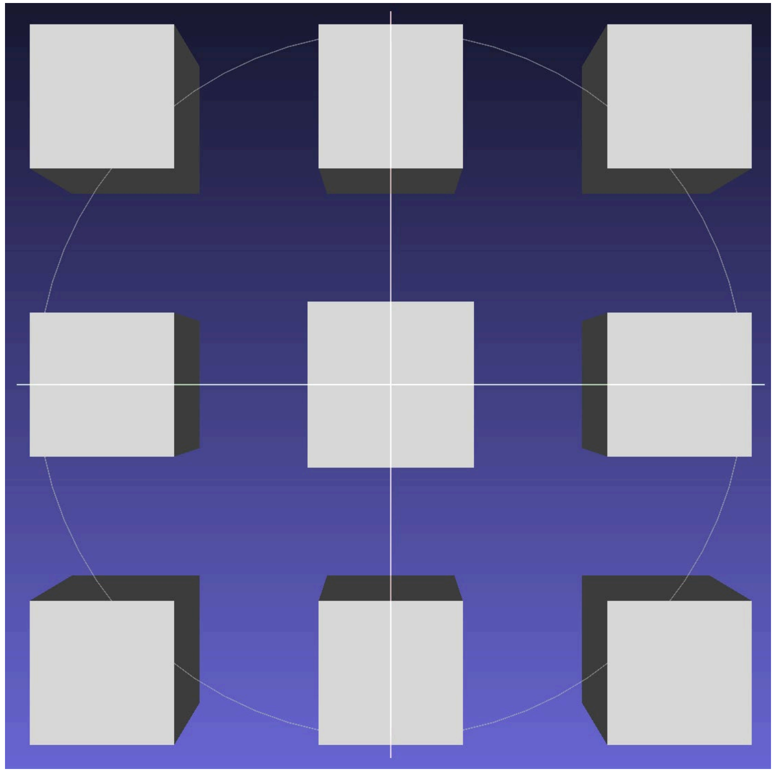
A The uncertainty will be represented as a rotation

B The rotation takes place either in the clockwise or counterclockwise direction

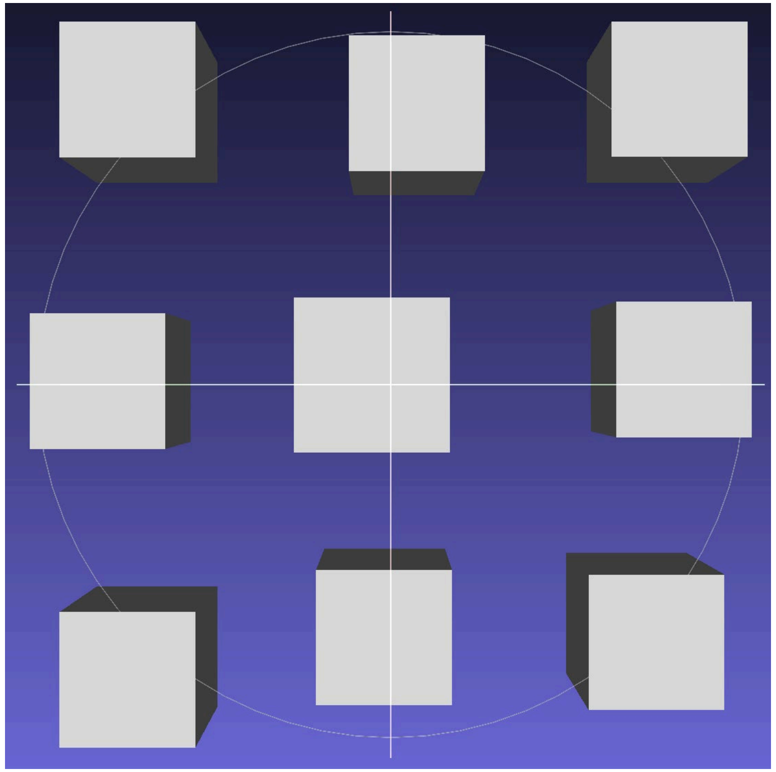
C There is one rotational uncertainty value per building

D Each sample containing the rotation values of the buildings, follows the normal distribution N[μ, σ]

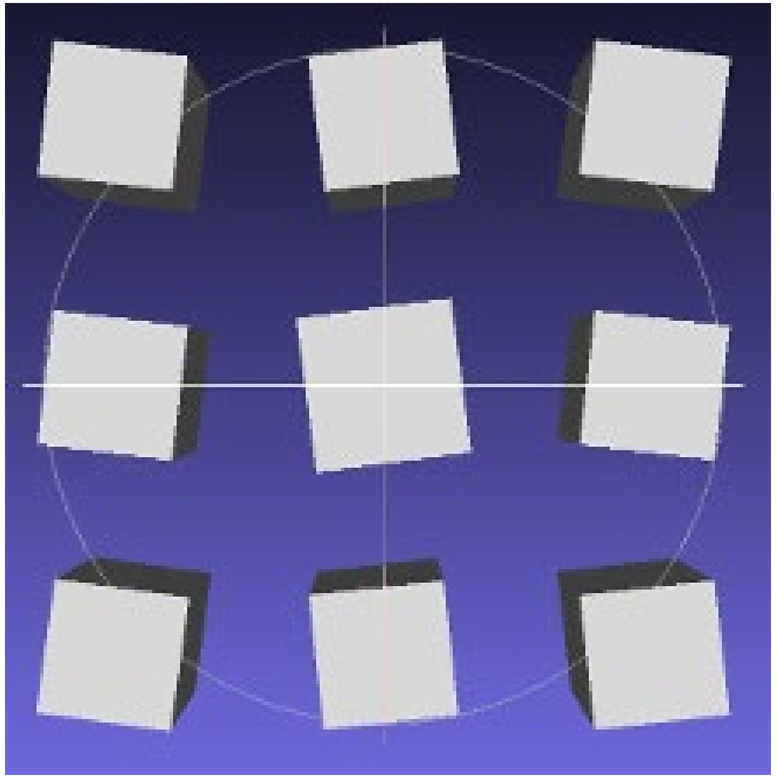
Visualization of Uncertainty



Initial Model



Translated Model (0.01m)

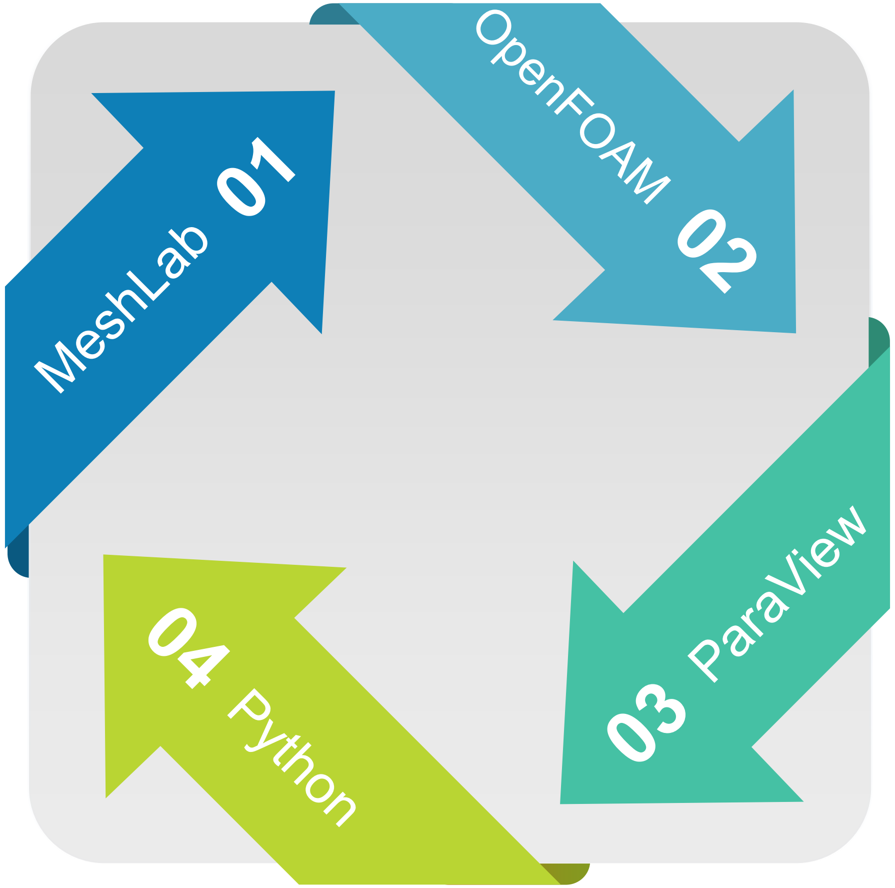


Rotated Model (10^o)

Implementation

Visualisation of geometry

Processing, plotting and statistical analysis



OpenFOAM

Open source software running CFD Simulations, connecting to TU Delft's server Gilfoyle

ParaView

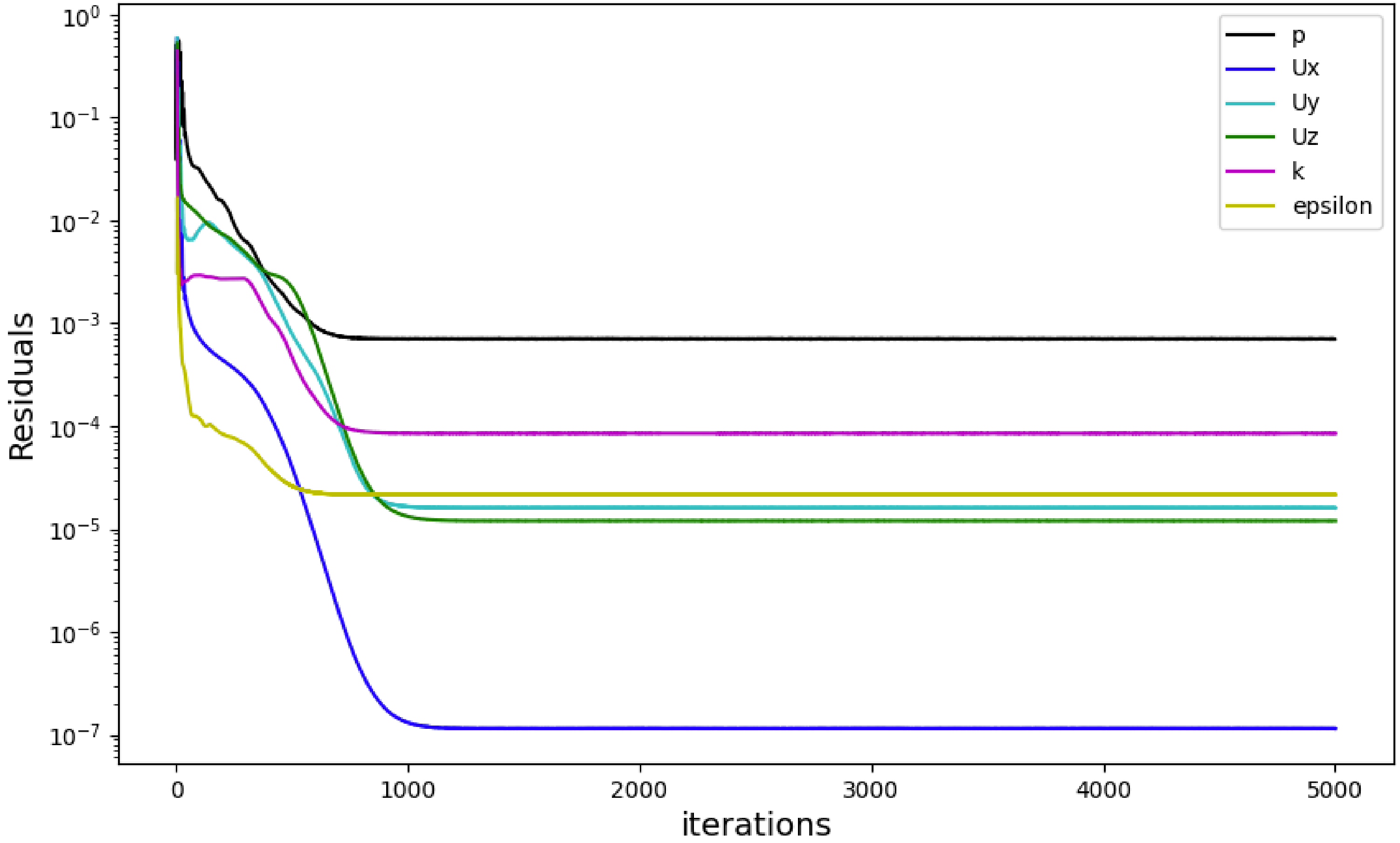
Post processing and visualisation of geometry

Simulation Times

Mesh type	Running times		
	Case 0H	Case 1H	Case 2H
Coarse	14min 36 sec	14min 21 sec	13min 24 sec
Medium	1h 14min 1sec	1h 14min 0sec	1h 8min 40sec
Fine	4h 49min 20sec	4h 46min 27sec	4h 16min 16sec

Number of iterations: **5000**

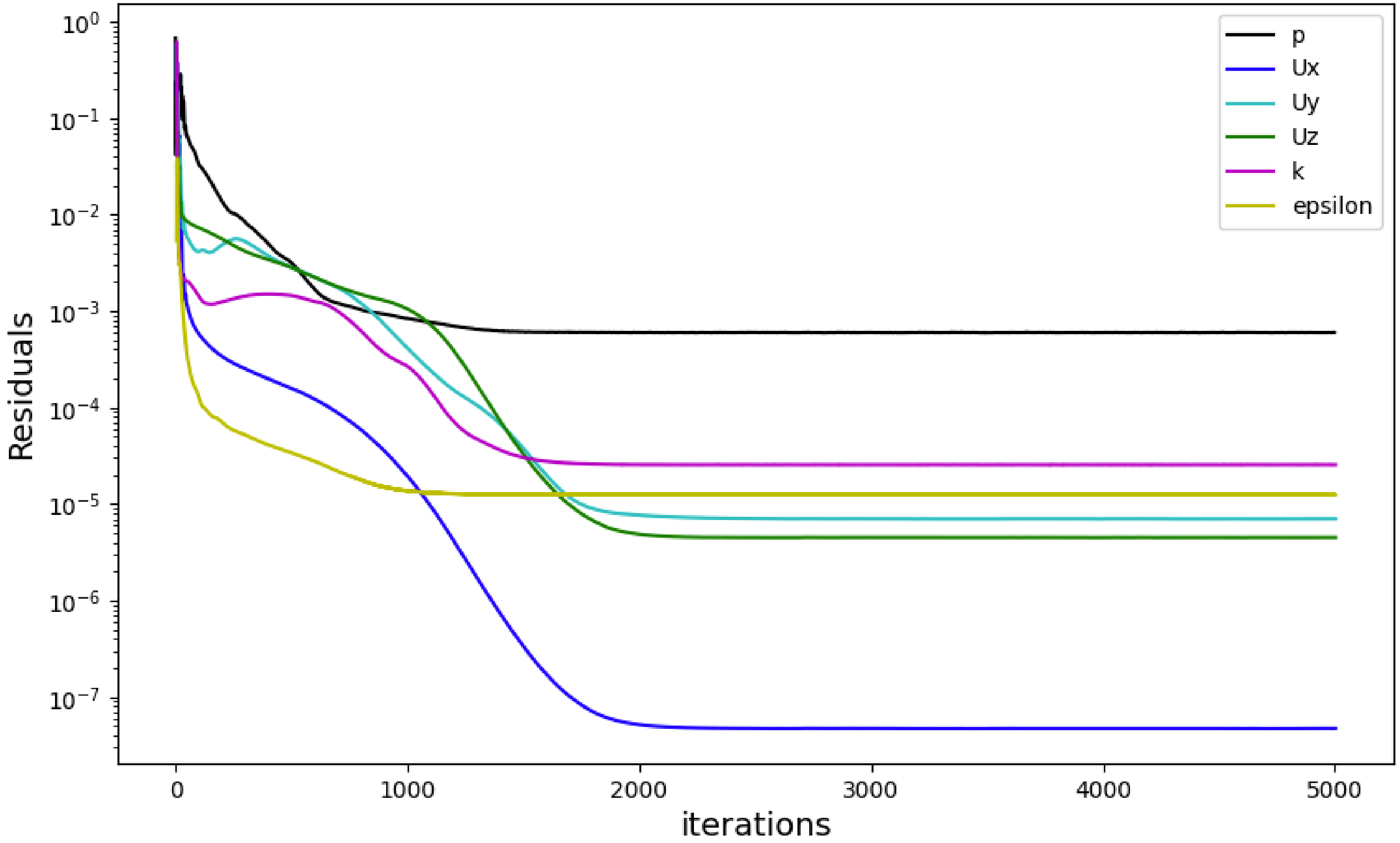
Residuals (Coarse Mesh)



Residuals: Case 0H

Convergence achieved at 1000 iterations

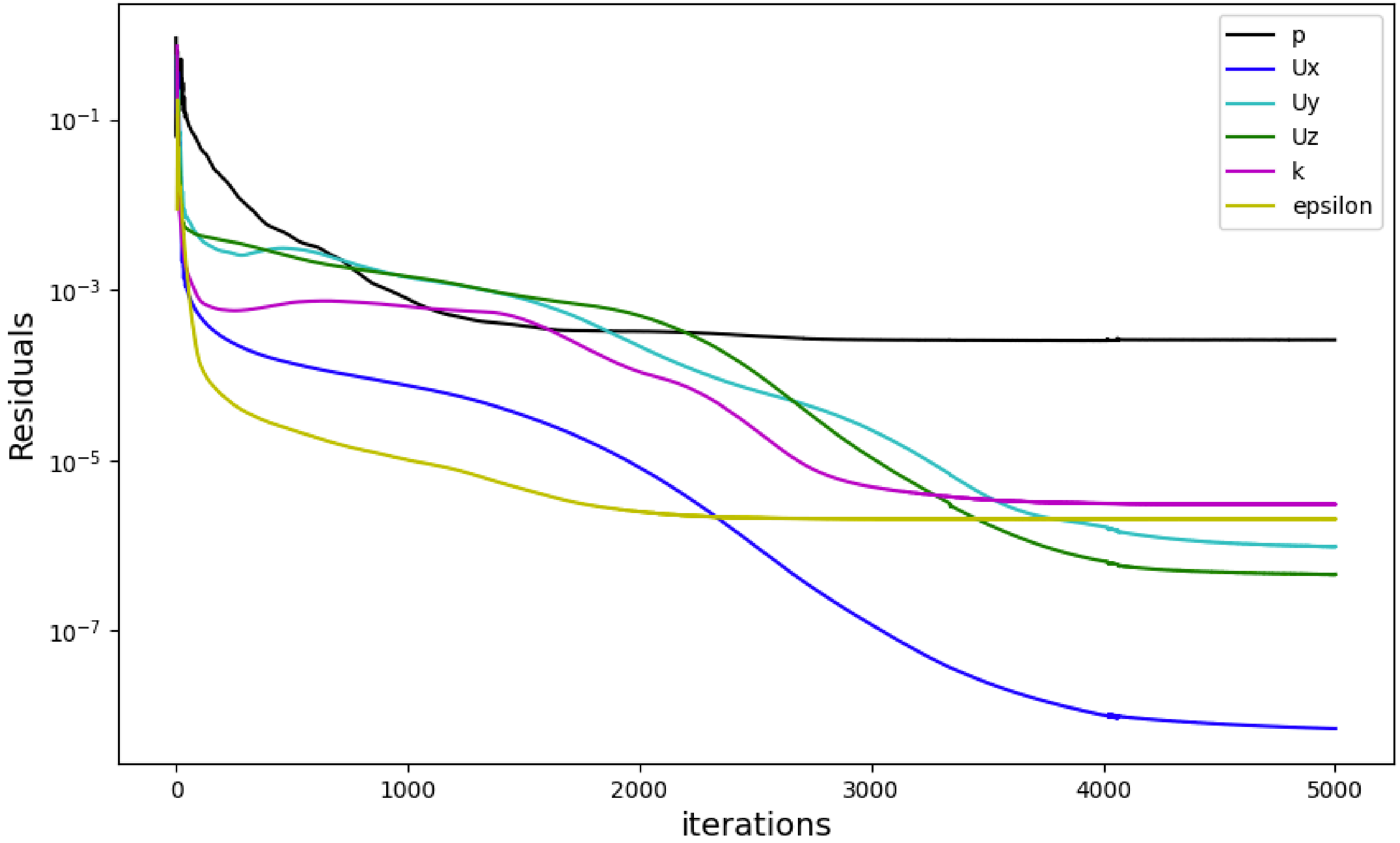
Residuals (Medium Mesh)



Residuals: Case 0H

Convergence achieved at 2000 iterations

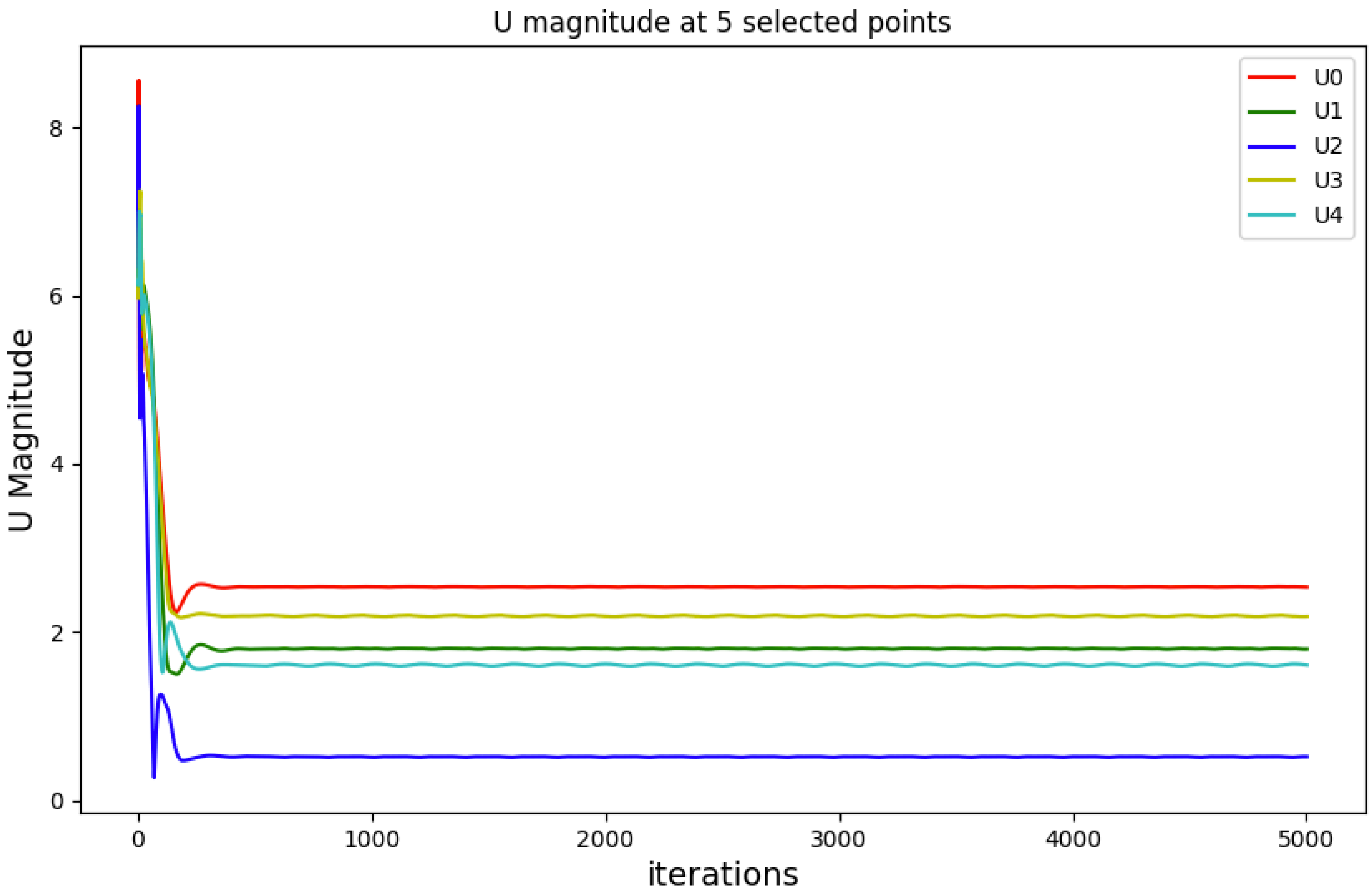
Residuals (Fine Mesh)



Residuals: Case 0H

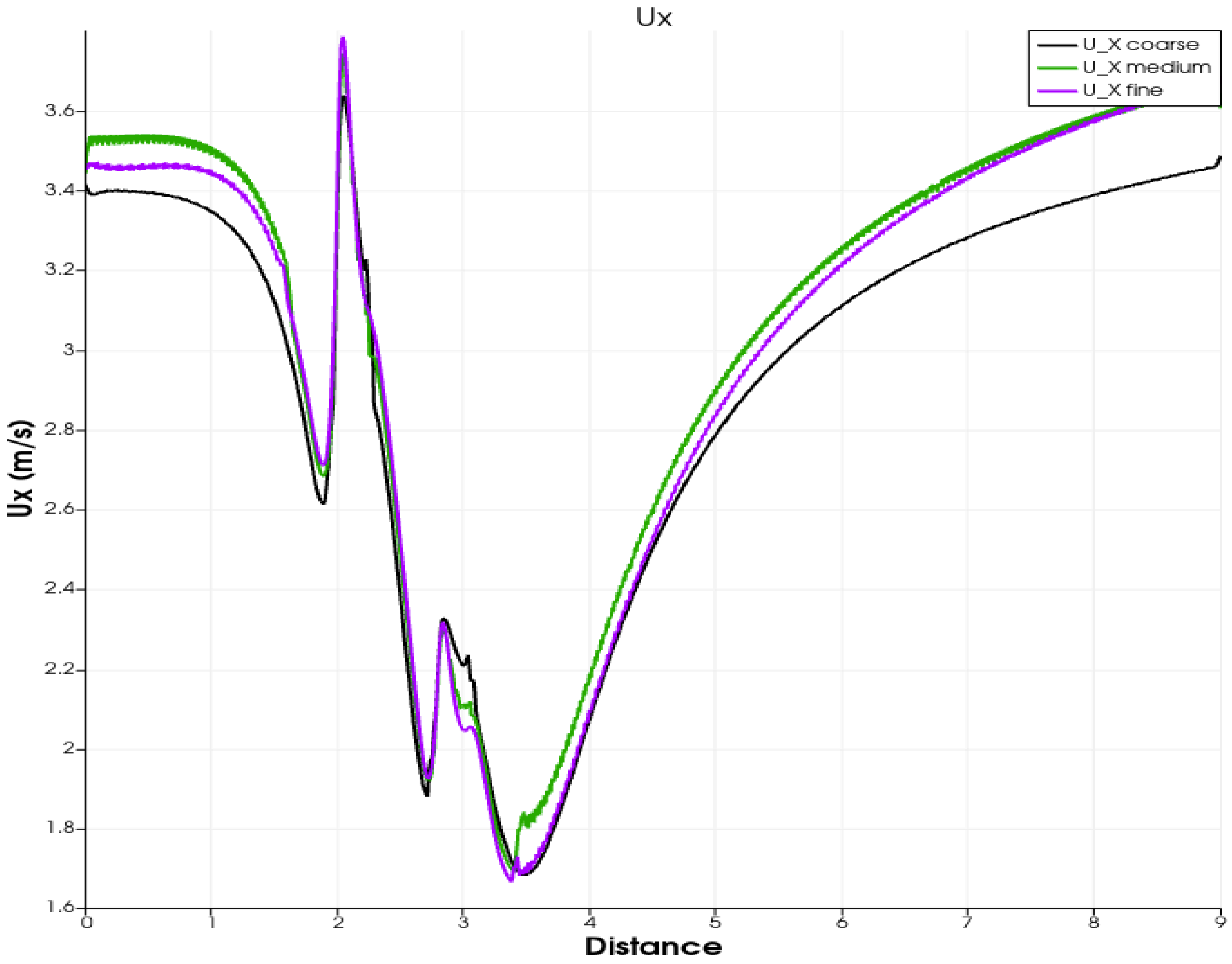
Convergence achieved at 4500 iterations

Velocity Stability at 5 Probes



Velocity magnitude over time for five testing points

Field Plots



Ux field plot for the three meshes: Case 0H

We plotted our field values through a chosen line: *(-2.5, 0.15, 0.1), (6, 0.15, 0.1)* across x-axis

Tool:
Plot over line (Paraview)

Grid Convergence Index (GCI)

Roache's formula was used: $$GCI_{21} = \frac{1.25\left|\frac{phi_2 - phi_1}{phi_1}\right|}{r_{21}^{p} - 1} \times 100\%$$

- GCI_{21}: Medium – Fine mesh
- GCI_{32}: Coarse – Medium mesh

	Case 0H	Case 1H	Case 2H
GCI_{21}:	2.612%,	1.314%,	2.553%
GCI_{32}:	3.069%,	4.518%,	5.640%

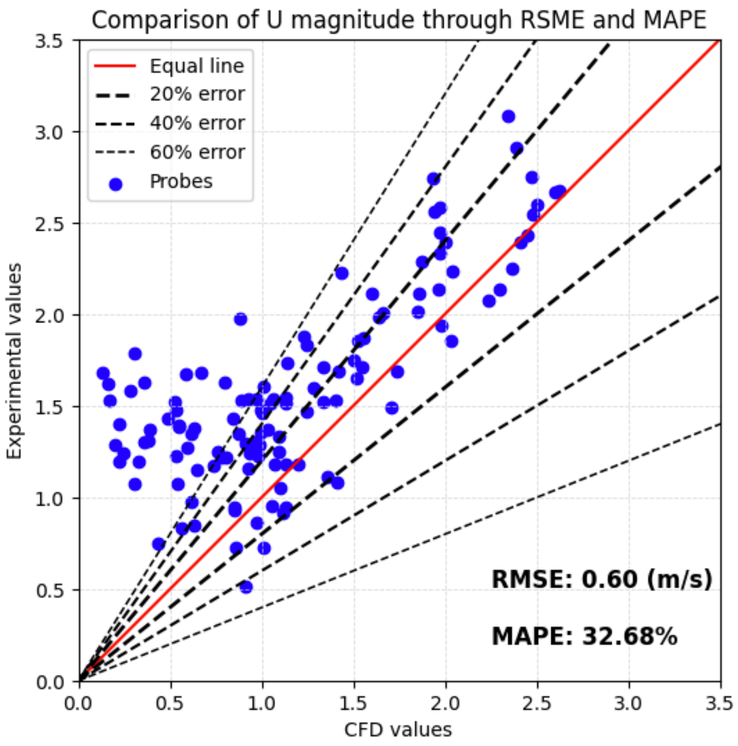
$GCI_{21} < GCI_{32}$ in all three cases

Mesh Convergence

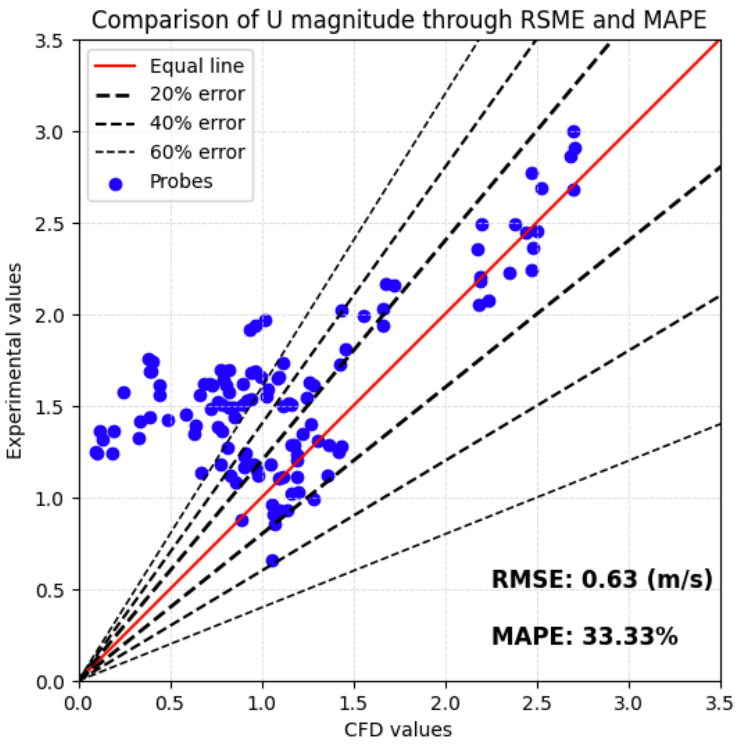
- Convergence time of the residuals
- Number of iterations needed
- Plots of the field values
- Grid Convergence Index (GCI)

According to these criteria, the **medium** mesh is chosen to perform the validation and analysis

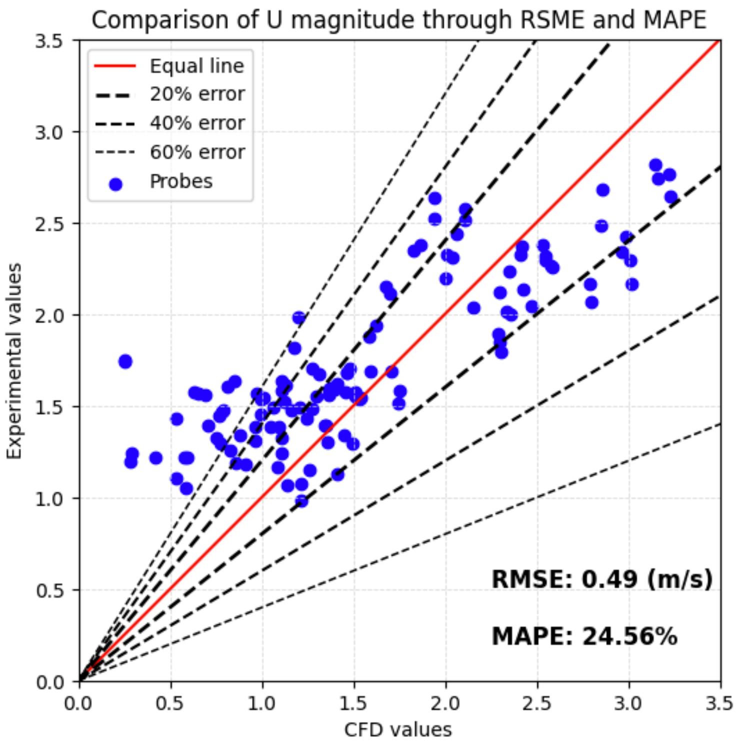
Validation: Scatter Plots (Point-by-Point comparison)



Case 0H



Case 1H



Case 2H

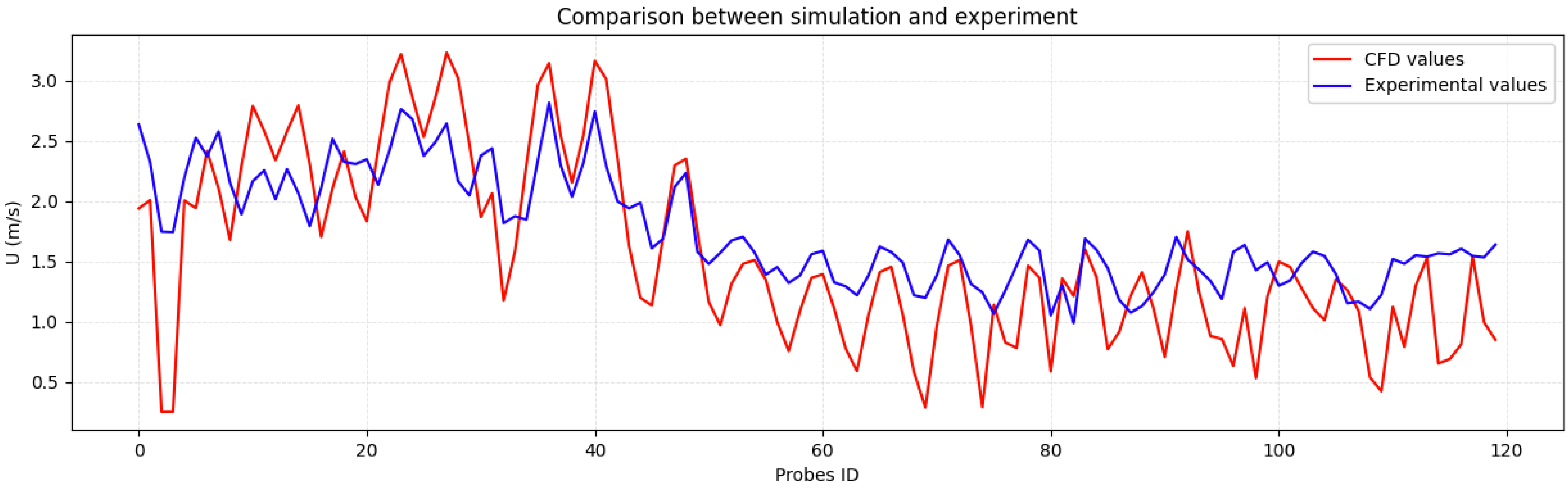
Validation metrics:

- Root Mean Squared Error **RMSE**
- Mean Absolute Percentage Error **MAPE**

- Pearson's correlation coefficient (r)

	Case 0H	**Case 1H**	**Case 2H**
r:	0.762	0.715	0.831

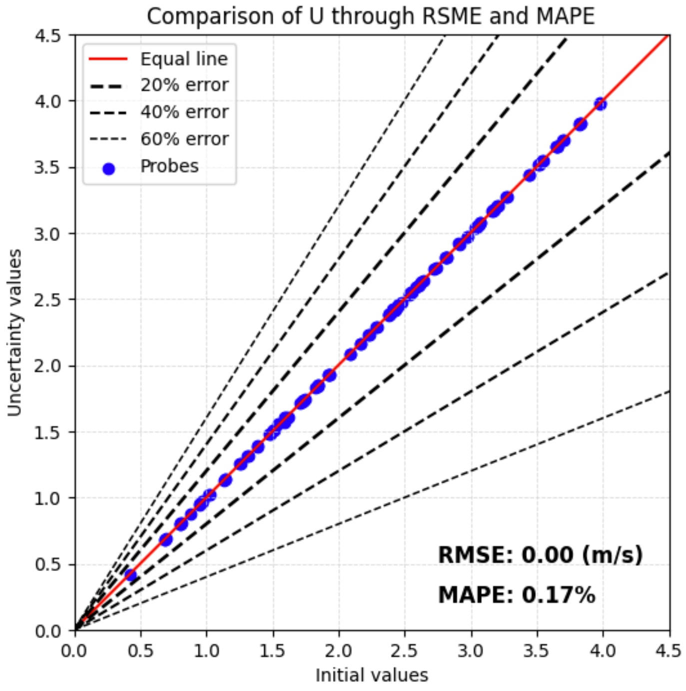
Validation: Velocity Graph



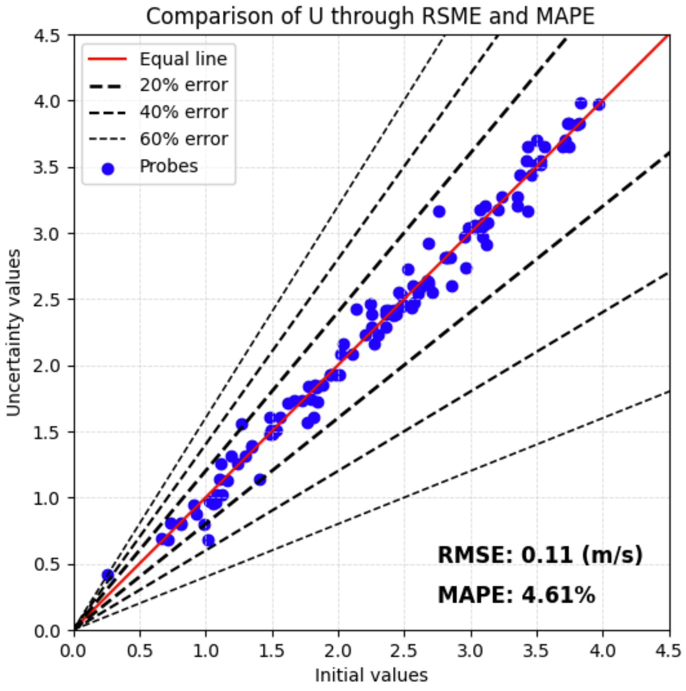
Velocity graph for the 120 probes

Results and Analysis

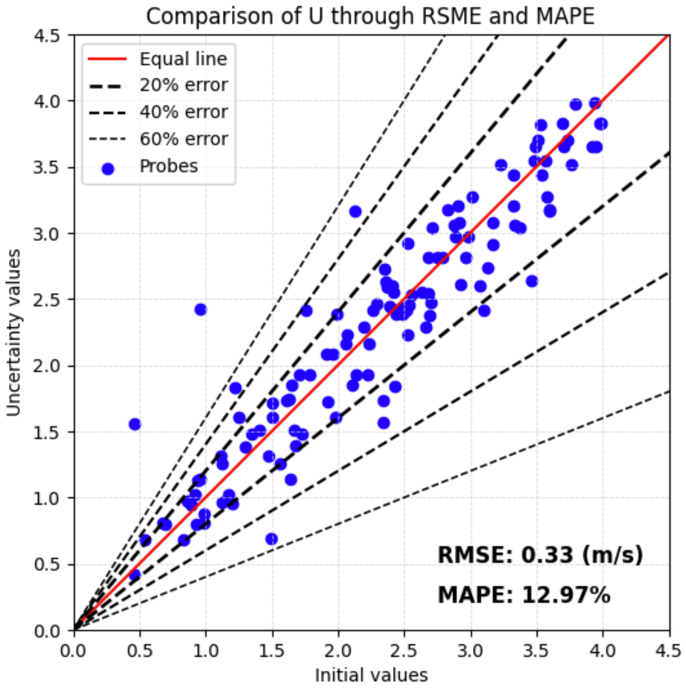
Point-by-Point Velocity Comparison



T1=0.0001m



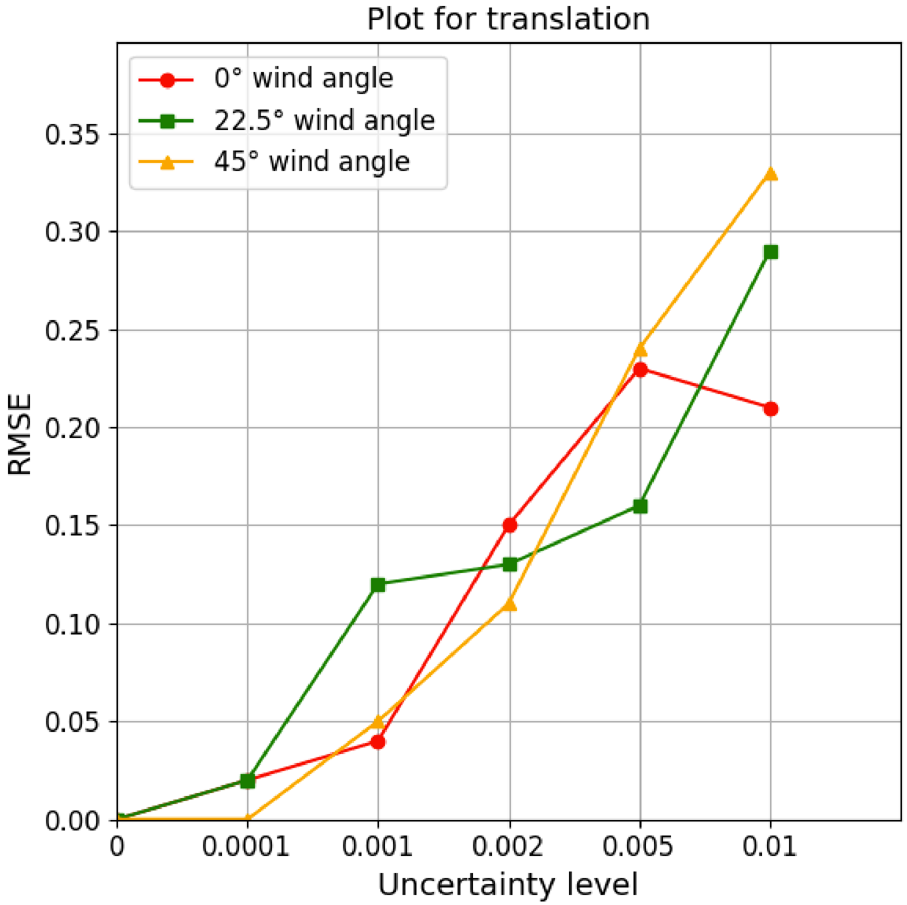
T3=0.002m



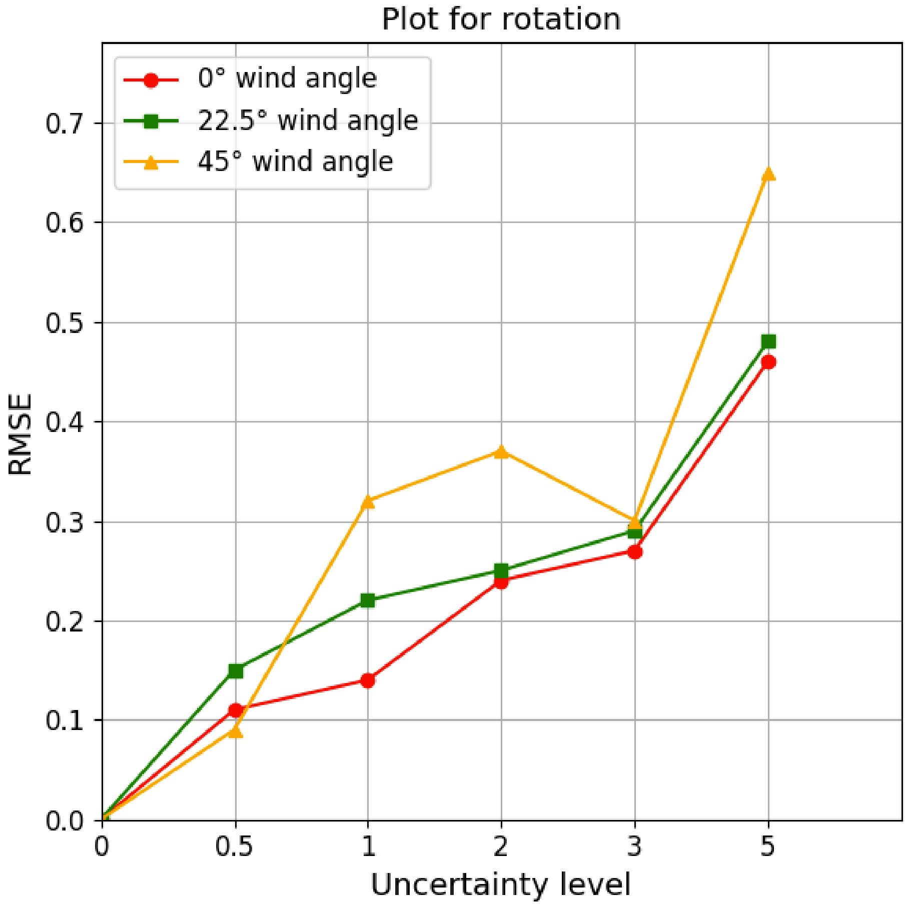
T5=0.01m

The metrics that were used are RMSE and MAPE

Point-by-Point Velocity Comparison: RMSE Graphs



Translation



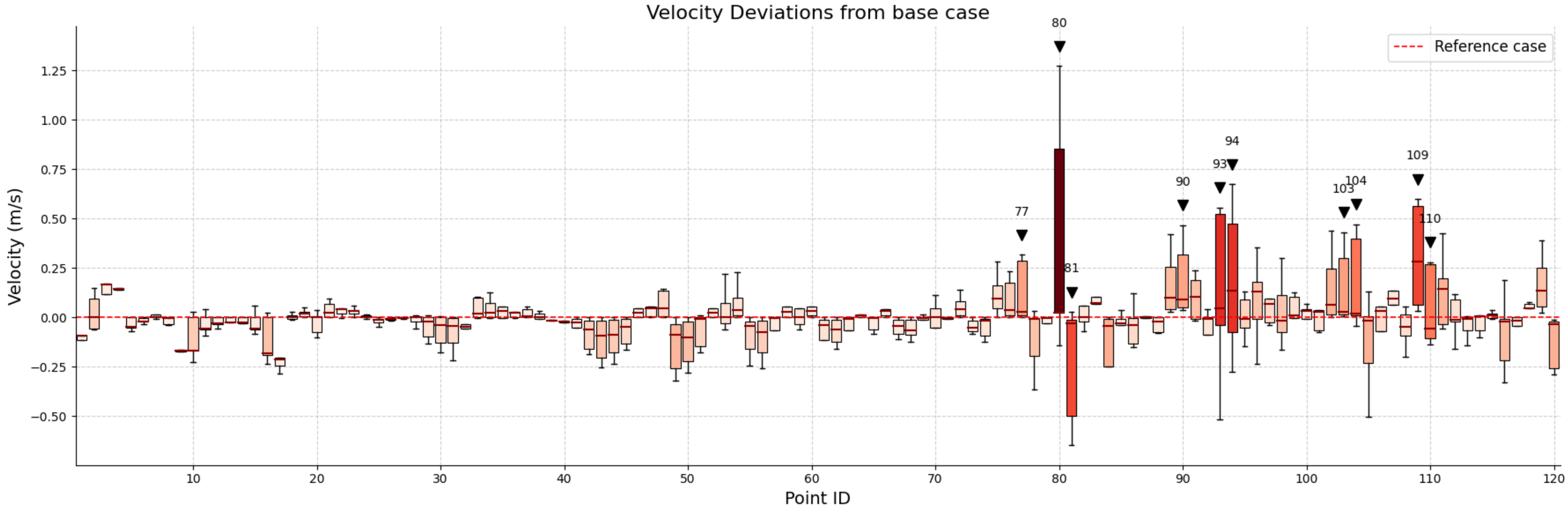
Rotation

Point-by-Point Velocity Comparison: RMSE Table

Uncertainty	Translation-RMSE (m/s)			Uncertainty	Rotation-RMSE (m/s)		
	0°	**22.5°**	**45°**		**0°**	**22.5°**	**45°**
T1	0.02	0.02	0.00	**R1**	0.11	0.15	0.09
T2	0.06	0.12	0.05	**R2**	0.14	0.22	0.32
T3	0.15	0.13	0.11	**R3**	0.24	0.25	0.37
T4	0.23	0.16	0.24	**R4**	0.27	0.29	0.30
T5	0.21	0.29	0.33	**R5**	0.46	0.48	0.65

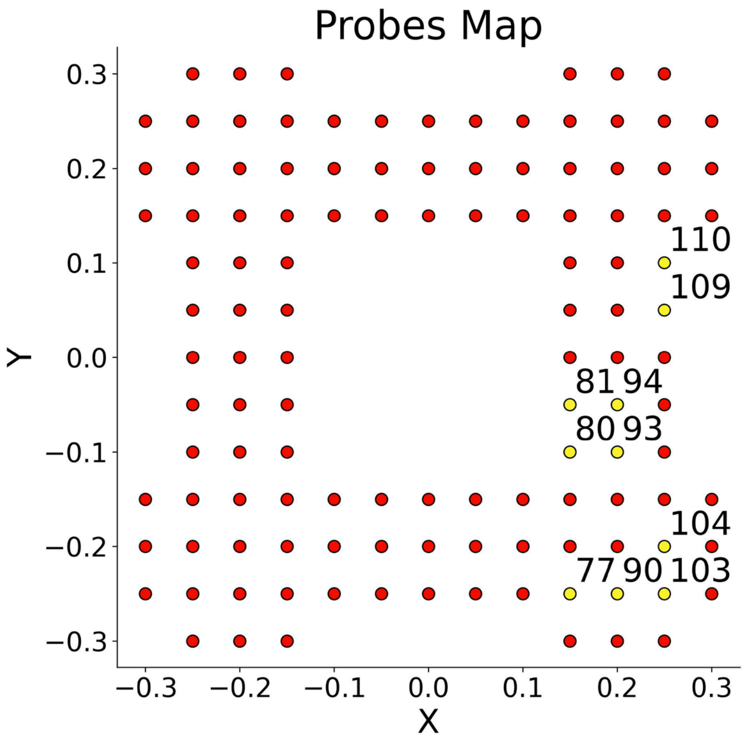
Uncertainties-RMSE

Box Plots

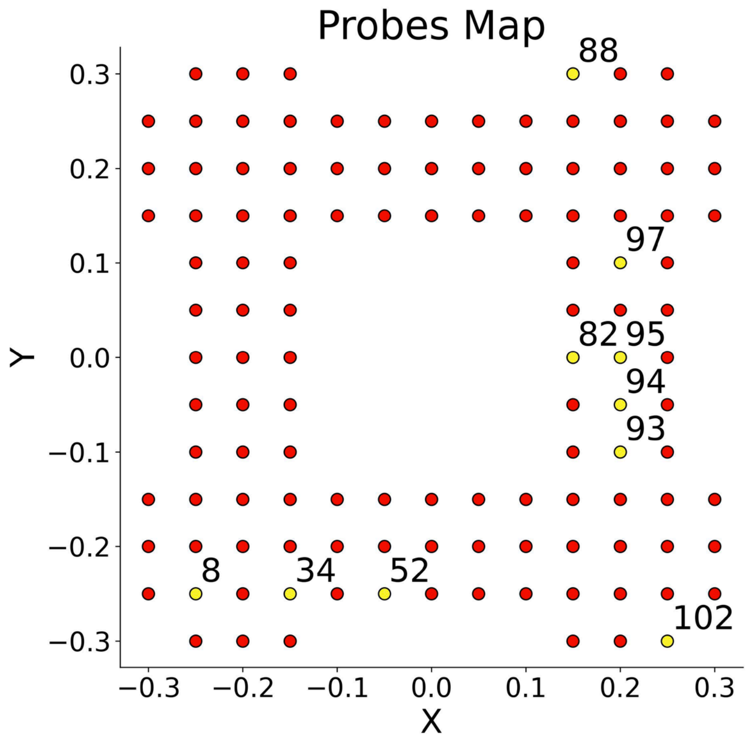


Box plot for translation and 0º wind angle

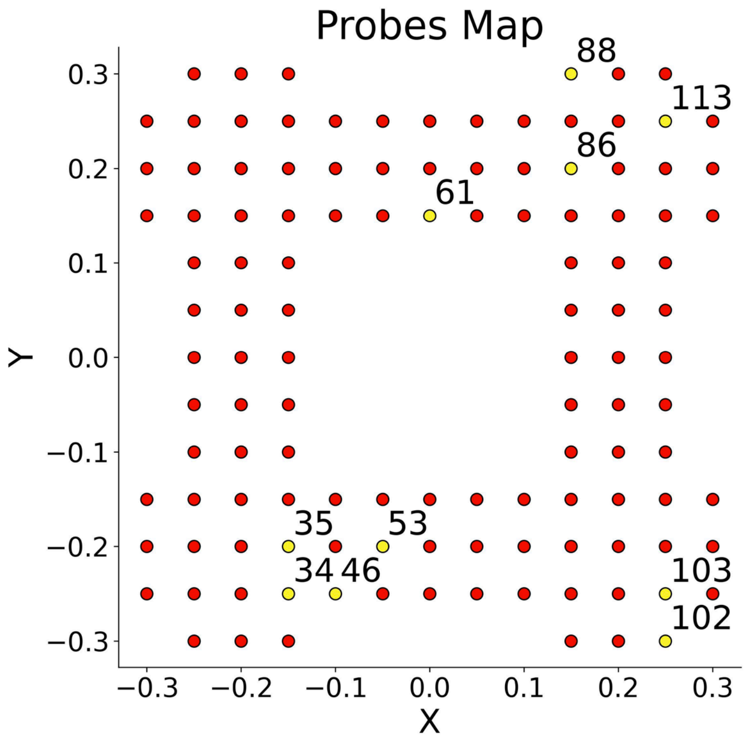
Box Plots (Probes' Map)



0º wind angle



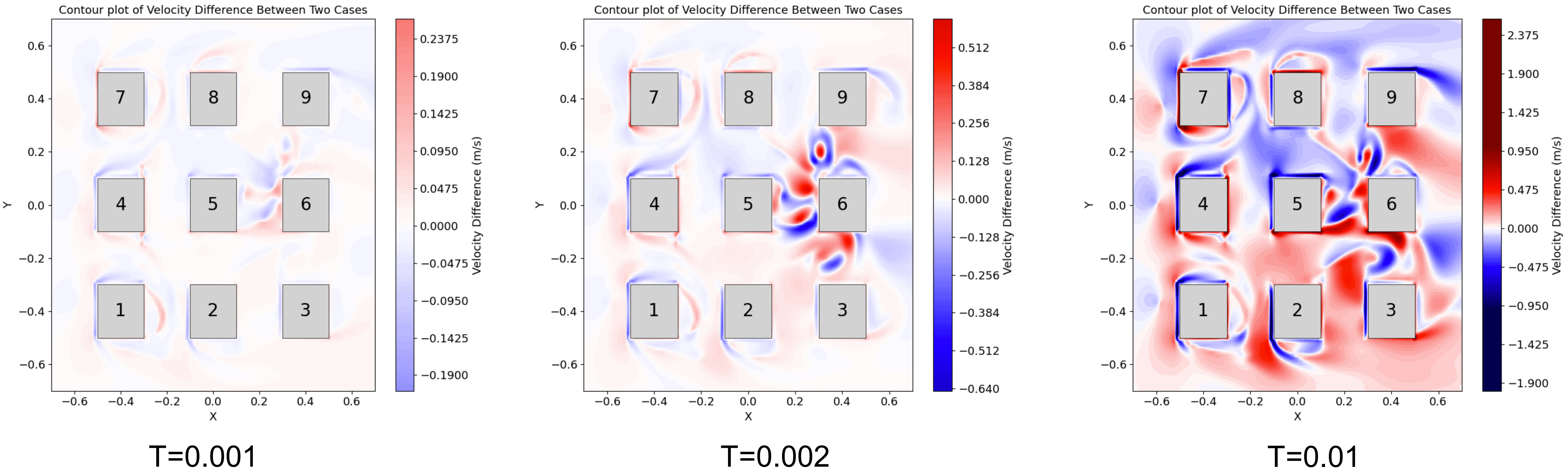
22.5º wind angle



45º wind angle

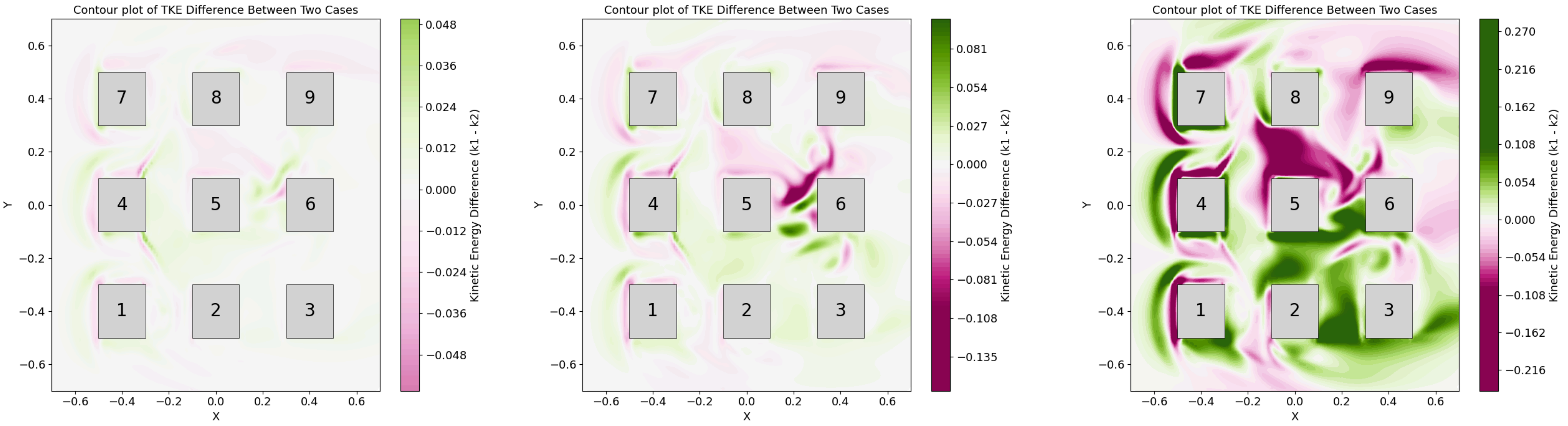
By using the probes' map it was easier to spot which 10 probes consistently show high deviation.

Contour Plots



U_{mag} difference contour plots

Contour Plots



T=0.001 T=0.002 T=0.01

TKE difference contour plots

Contour Plots

Uncertainty	Translation-RMSE (m/s)			Uncertainty	Rotation-RMSE (m/s)		
	0°	**22.5°**	**45°**		**0°**	**22.5°**	**45°**
T1	0.0089	0.0273	0.0054	**R1**	0.0620	0.0951	0.1291
T2	0.0255	0.0935	0.0626	**R2**	0.0856	0.1405	0.2402
T3	0.0719	0.1200	0.1121	**R3**	0.1873	0.1887	0.2897
T4	0.1600	0.1960	0.2323	**R4**	0.2175	0.2593	0.2411
T5	0.2376	0.3421	0.3860	**R5**	0.3864	0.3734	0.4933

RMSE of Umag difference from the contour plots

Contour Plots

Uncertainty	Translation-median (m/s)			Uncertainty	Rotation-median (m/s)		
	0°	**22.5°**	**45°**		**0°**	**22.5°**	**45°**
T1	0.0018	0.0025	0.0009	**R1**	0.0230	0.0294	0.0265
T2	0.0088	0.0296	0.0179	**R2**	0.0382	0.0443	0.0754
T3	0.0178	0.0372	0.0348	**R3**	0.0765	0.0550	0.0844
T4	0.0639	0.0592	0.0632	**R4**	0.0934	0.0809	0.0650
T5	0.0930	0.0884	0.0882	**R5**	0.1707	0.1329	0.1551

Median of Umag difference from the contour plots

Answering the Research Questions

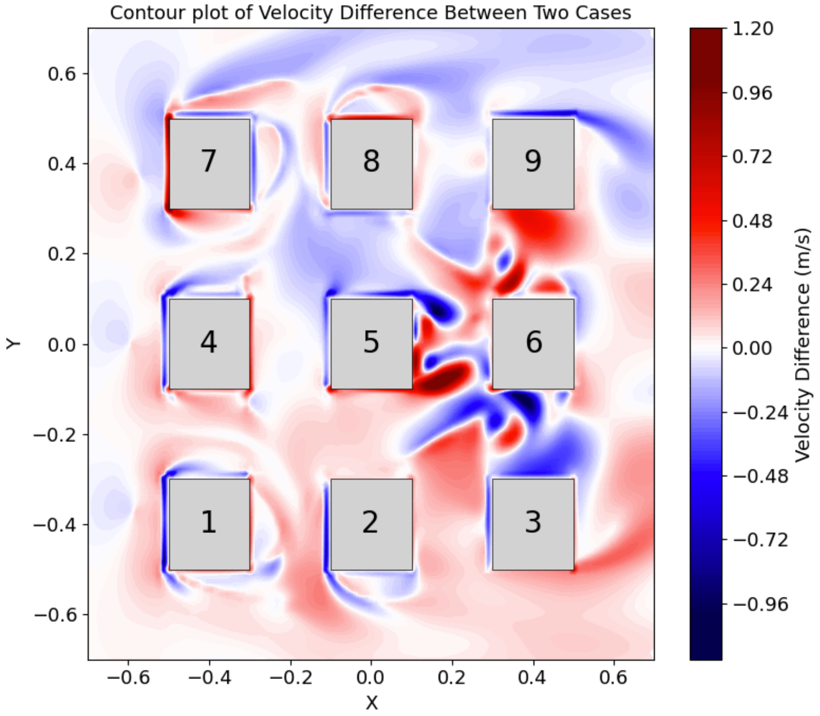
Validation with wind-tunnel data

The ***r* = 0.8** and ***MAPE* = 24%** indicate a correlation with the experimental data, with the 2H case presenting the best results, but:

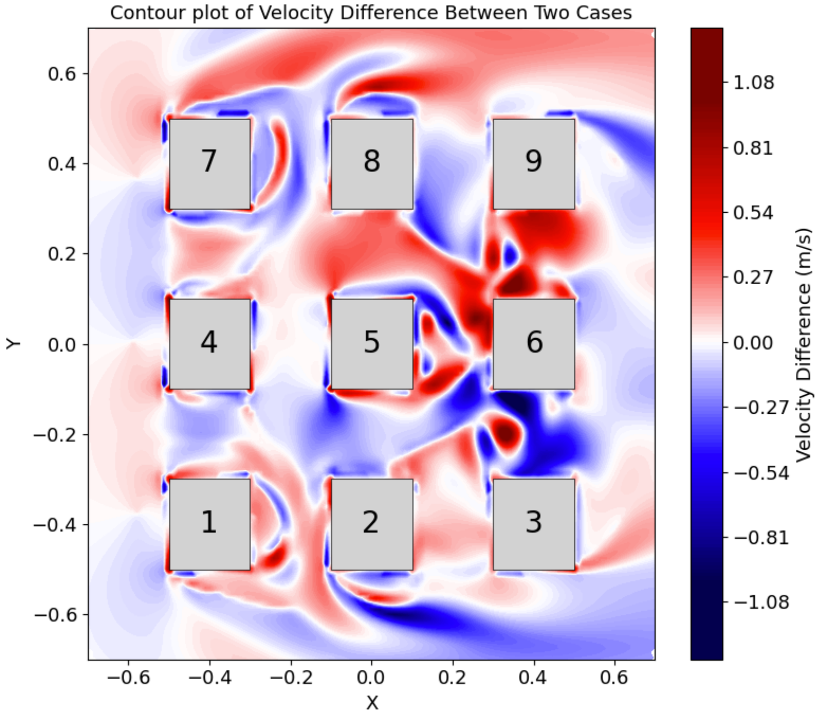
- A relative offset is observed in all three cases
- slightly higher experimental values
- Possibly z_0 underestimates the wind speed

Answering the Research Questions

Impact due to translation and rotation



Translation

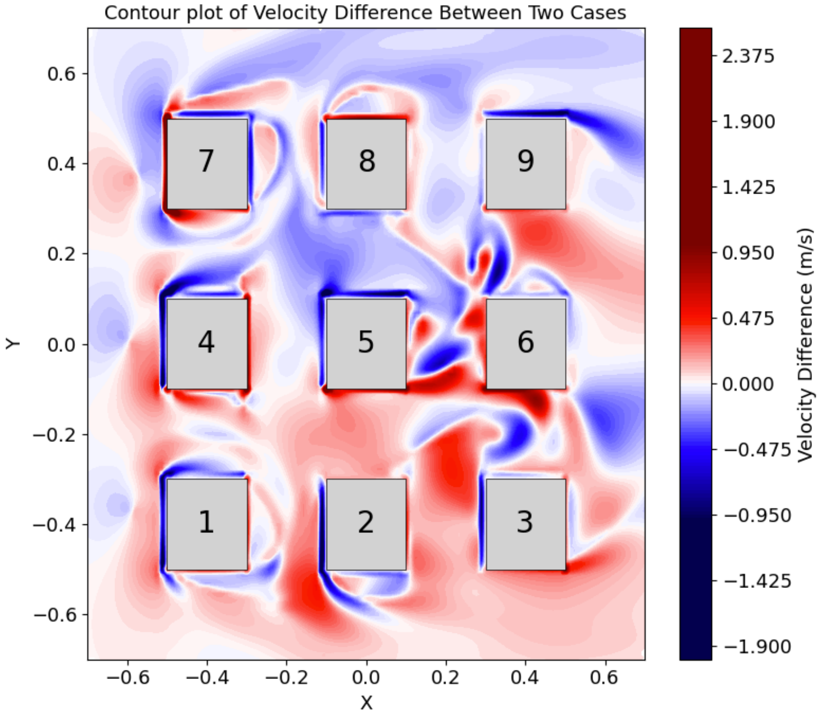


Rotation

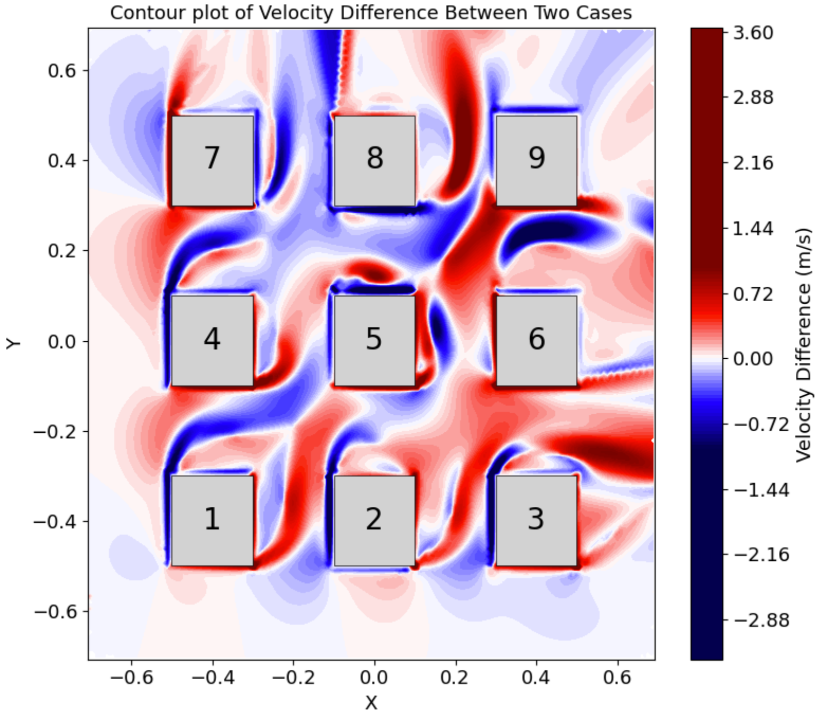
- Highly localized effect for translation
- Spatially distributed effect for rotation
- Clearly, higher impact of rotation

Answering the Research Questions

Impact due to different wind angle



Translation = 0.01m
0° wind angle



Translation = 0.01m
45° wind angle

- 45°, buildings go through asymmetric loading and more complex flows
- The impact of both translation and rotation uncertainties becomes more obvious as the wind direction shifts away from the orthogonal 0° case.

The Novelty of my Thesis

- An integrated approach to quantifying geometric uncertainty by combining spatial qualitative methods (plots) with statistical performance metrics (RMSE, MAPE, median) over multiple perturbed cases

- Isolates the effects of building footprint inaccuracy (translation, rotation), unlike other studies that focus on mesh or turbulence model sensitivity

The Final Conclusions

The effect of building footprint uncertainty on CFD simulations is:

- direction-dependent
- localized for translation
- spatially broader for rotation
- increases as the wind direction shifts away from the orthogonal 0° case

Limitations

- The conclusions are based on a single reference case (AIJ Case C) and a specific validation setup
- Limited scope of the uncertainty magnitude. Translation distances and rotation angles were discrete without covering the entire variety of possible geometric uncertainties

Recommendations for Future work and improvements

Application of this methodology to a more realistic urban geometry

Application of different uncertainty values and directions per vertex and not just per building.

Introduction and combination with other uncertainty sources (inflow conditions)

Is there a critical threshold beyond which geometric uncertainty leads to nonlinear flow divergence?

How does the combination of translation and rotation interact?

Recommendations for Future work and improvements

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Thank you for your attention!

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