Modeling tree topology effects on wind

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Supervisors:

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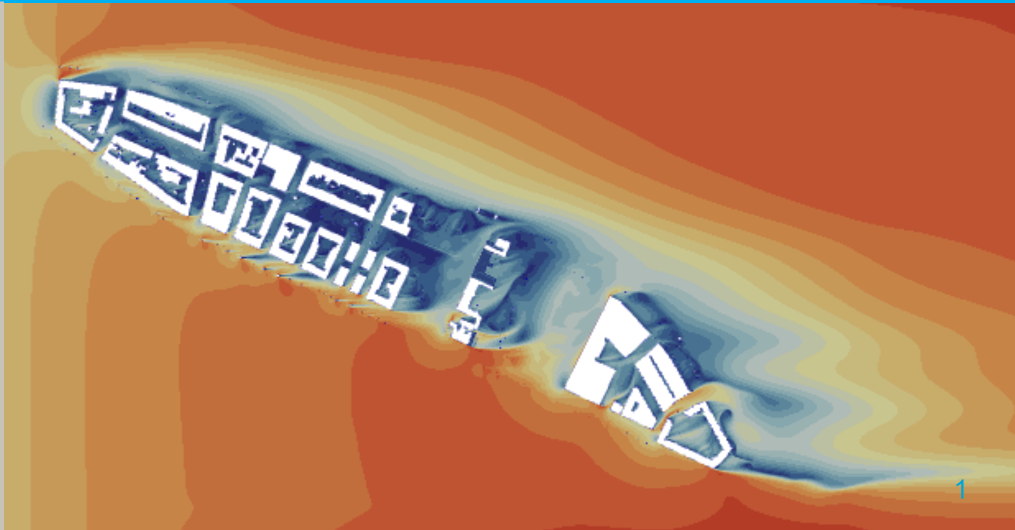
Ivan Pađen



Contents

- Motivation
- Research questions
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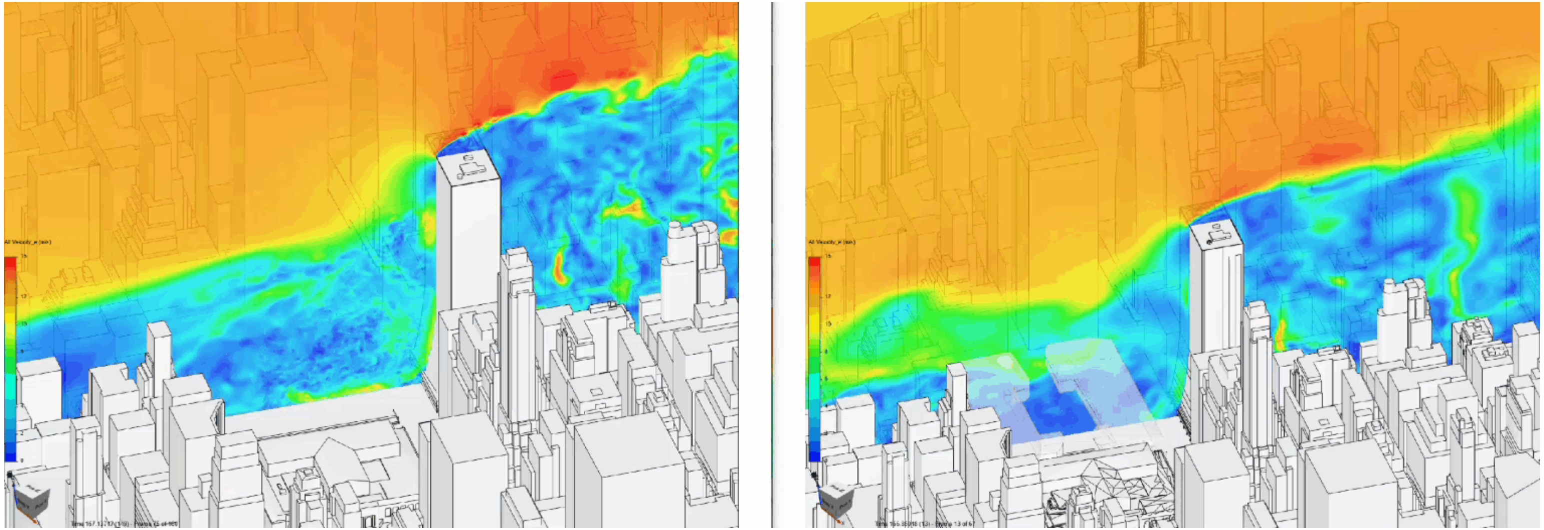
Trees effect and Computational Fluid Dynamics (CFD)

Improve/or negatively affect air quality,

Mitigate urban heat island effects,

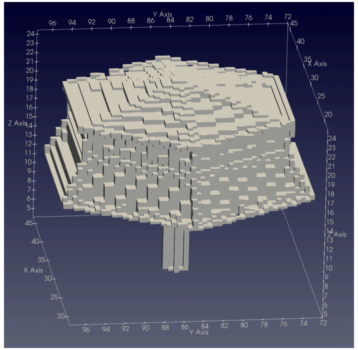
Improve pedestrian wind comfort

Reduce buildings energy consumption



CFD simulations: wind effects around buildings, before and after trees are modeled.
(Source: https://www.simscale.com/blog/2020/03/march-product-update-simscale/)

Implicit tree modeling approach



Implicit tree modeling approach: porous zones

- Mark finite volume cells that roughly account for trees as porous zones.
- Tree drag is defined as a source and/or sink term in the momentum equation and turbulence equations.

$$S_{ui} = -\rho C_d \, LAD \, U_i \mathbf{U} \left[\frac{N}{m^3}\right]$$

$$S_k = \rho C_d \, LAD \, (\beta_p \mathbf{U}^3 - \beta_d \mathbf{U} k) \left[\frac{W}{m^3}\right]$$

$$S_\varepsilon = \rho C_d \, LAD \, \frac{\varepsilon}{k} (C_{\varepsilon 4} \beta_p \mathbf{U}^3 - C_{\varepsilon 5} \beta_d \mathbf{U} k) \left[\frac{W}{m^3}\right]$$

C_d *(leaf drag coefficient): Values vary between 0.1～0.3, with 0.2 being the most commonly used.*

LAD *(leaf area density): Depends on tree species and varies with height over the tree crown;*

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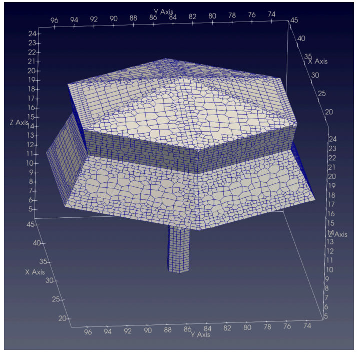
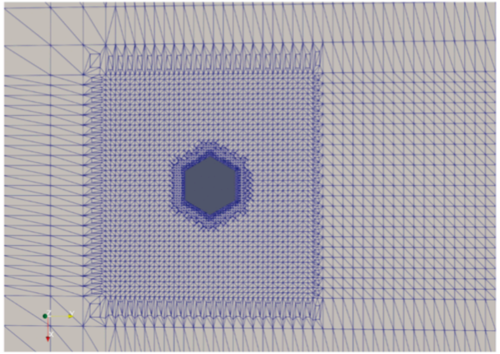
Explicit tree modeling approach



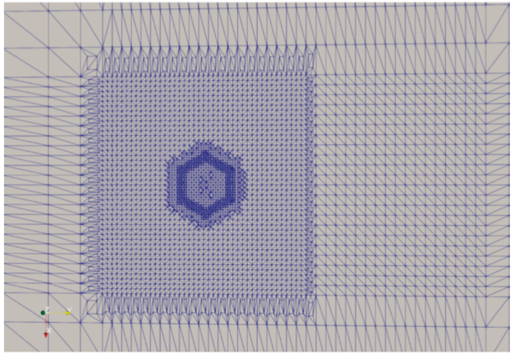
Explicit tree modeling approach: geometric modeling

- Trees are geometrically modeled as objects.
- Wind will be blocked by the surface of the tree model.

Explicit:
has no cells within the tree model



Implicit:
cells are still present but marked as porous medium



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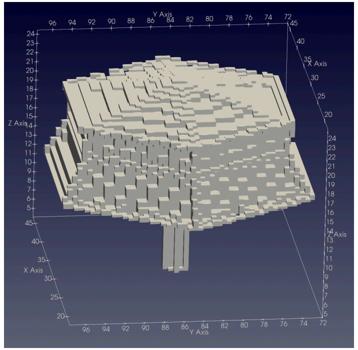
Explicit VS Implicit? Tree shapes & LoDs?

Explicit VS Implicit?



+

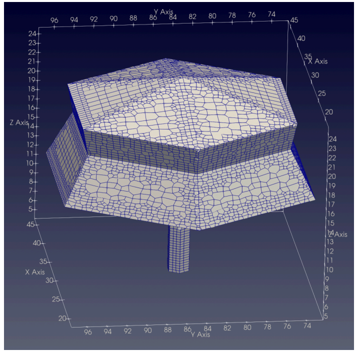
Very high values of

$$S_{ui} = -\rho\, C_d\, LAD\, U_i\, \mathbf{U}\, \left[\frac{N}{m^3}\right]$$

$$S_k = \rho\, C_d\, LAD\, (\beta_p \mathbf{U}^3 - \beta_d \mathbf{U} k)\, \left[\frac{W}{m^3}\right]$$

$$S_\varepsilon = \rho\, C_d\, LAD\, \frac{\varepsilon}{k}\, (C_{\varepsilon 4} \beta_p \mathbf{U}^3 - C_{\varepsilon 5} \beta_d \mathbf{U} k)\, \left[\frac{W}{m^3}\right]$$

= ?



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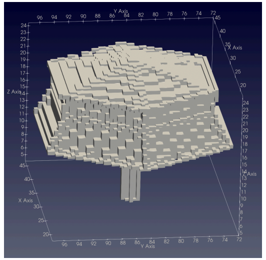
Explicit VS Implicit? Tree shapes & LoDs?

Explicit VS Implicit?



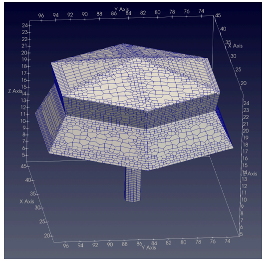
Very high values of

$$S_{ui} = -\rho C_d \, LAD \, U_i \mathbf{U} \left[\frac{N}{m^3}\right]$$

$$S_k = \rho C_d \, LAD \left(\beta_p \mathbf{U}^3 - \beta_d \mathbf{U} k\right) \left[\frac{W}{m^3}\right]$$

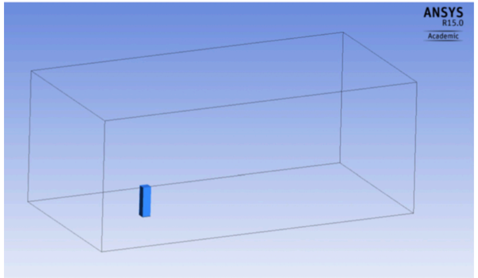
$$S_\varepsilon = \rho C_d \, LAD \, \frac{\varepsilon}{k} \left(C_{\varepsilon 4} \beta_p \mathbf{U}^3 - C_{\varepsilon 5} \beta_d \mathbf{U} k\right) \left[\frac{W}{m^3}\right]$$

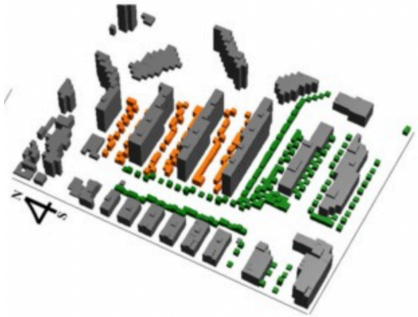
?

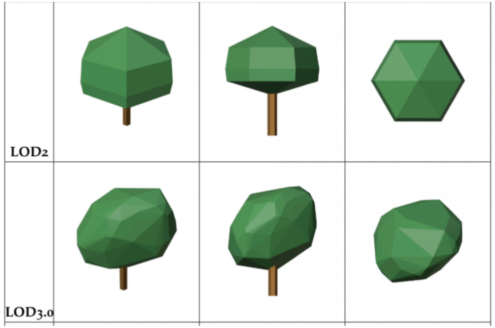


Tree LoDs & shapes?

Most studies use simple regular cylinders or prisms to represent trees, or assume that all trees within the study area are of the same shape







Research questions

Motivation

Research questions

Methodology

Implementation & Verification

Results & Analysis

Conclusion

The main research question for this thesis is:

what is the impact of tree topology modeling for urban flow simulations?

To answer this, the following sub-questions will be relevant:

- How to obtain implicit tree models and explicit tree models from point cloud?
- What is the difference between simulation results using implicit tree models and explicit tree models?
- What is the impact of tree LoDs on urban wind flow simulations?
- Does changing the tree shapes (broadleaf or conifer) make any difference to the impact of tree LoDs?
- Does changing the LAD value or wind direction make any difference to the impact of tree LoDs?

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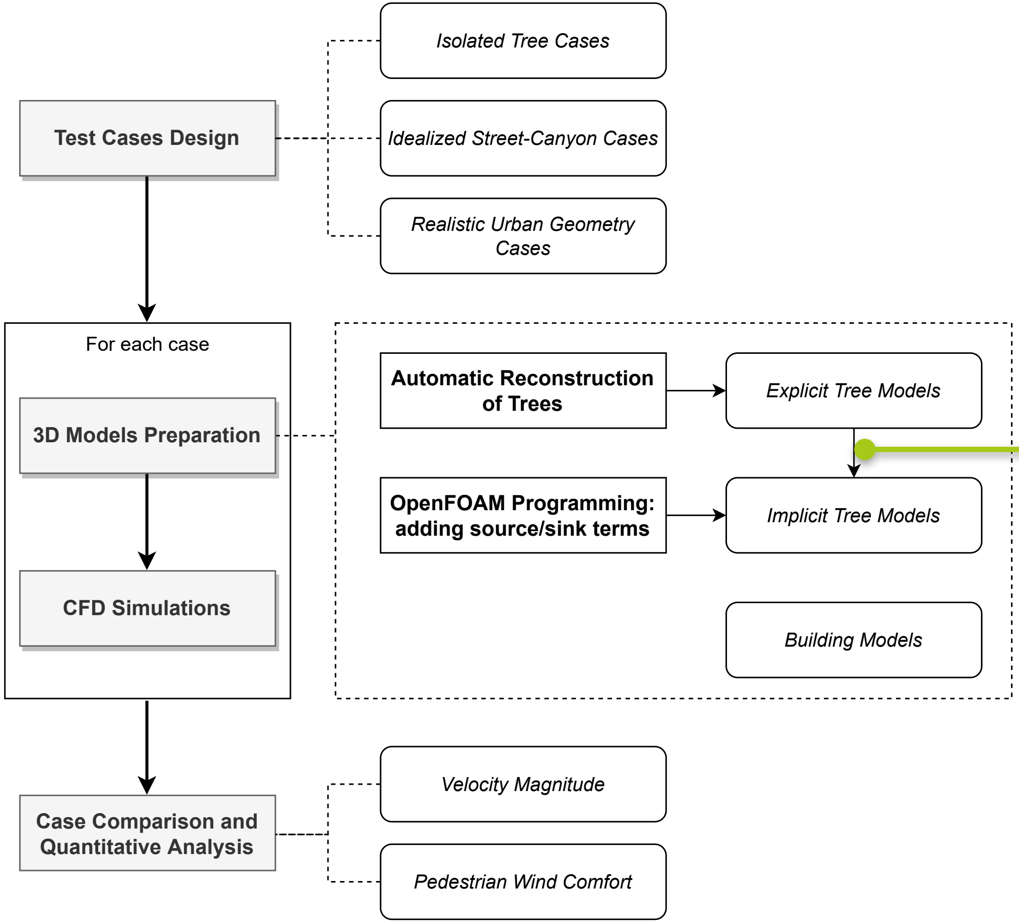
A general workflow of this thesis



marking the volume cells that roughly account for the explicit tree models as porous medium

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Test cases design and set up: Isolated tree

Motivation

Research questions

Methodology

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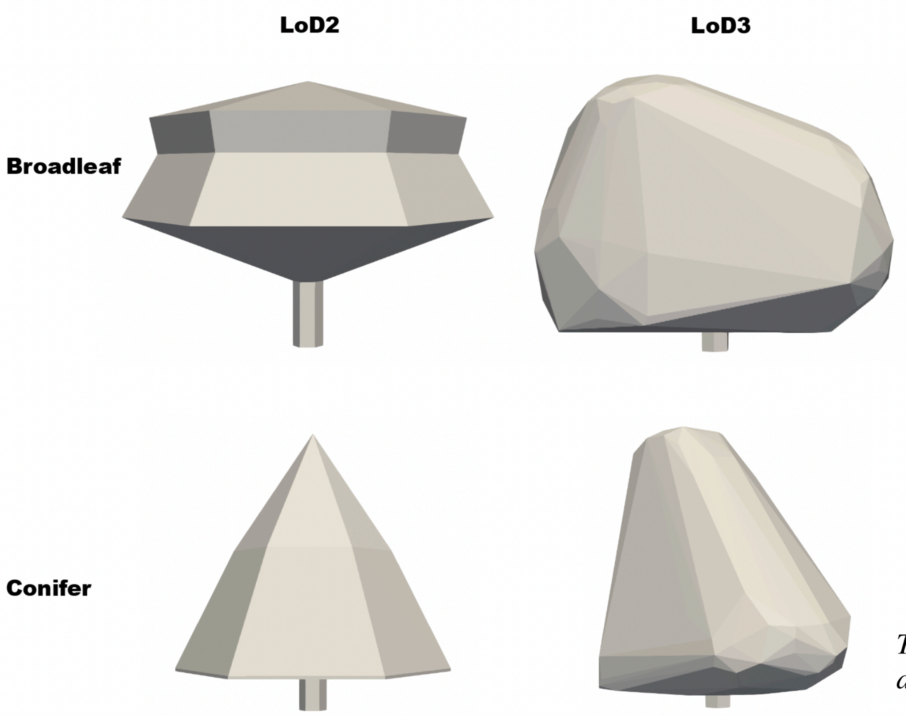
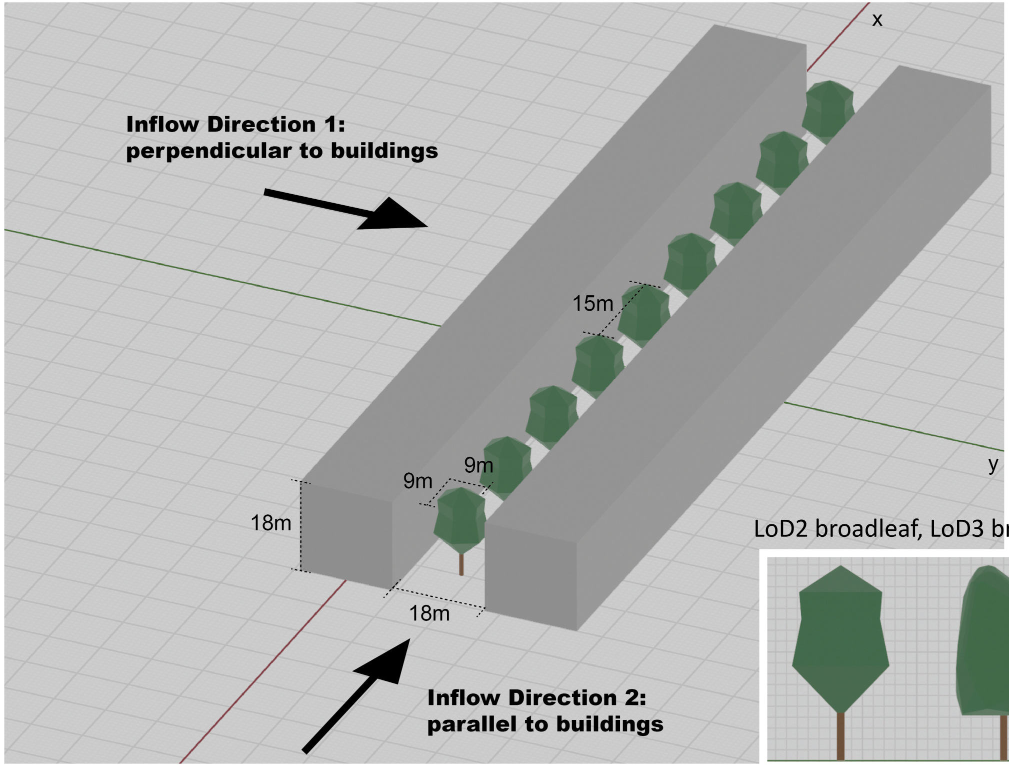
Two LoDs : LoD 2 and LoD 3

Two tree shapes: Broadleaf and Conifer

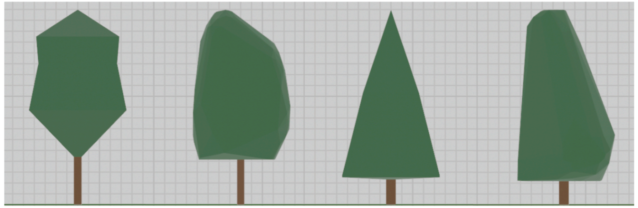


Tree models are obtained using the reconstruction algorithm introduced by [de Groot, 2020]

Test cases design and set up: Idealized street canyon



LoD2 broadleaf, LoD3 broadleaf, LoD2 conifer, and LoD3 conifer



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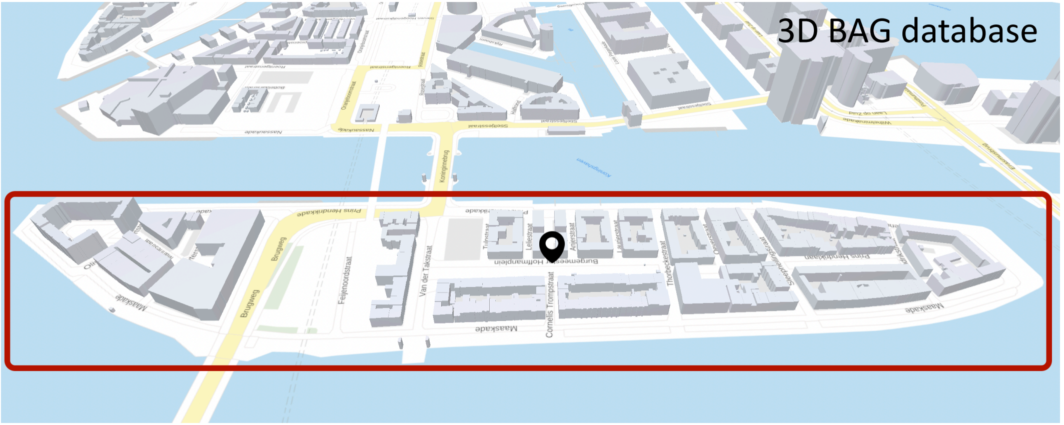
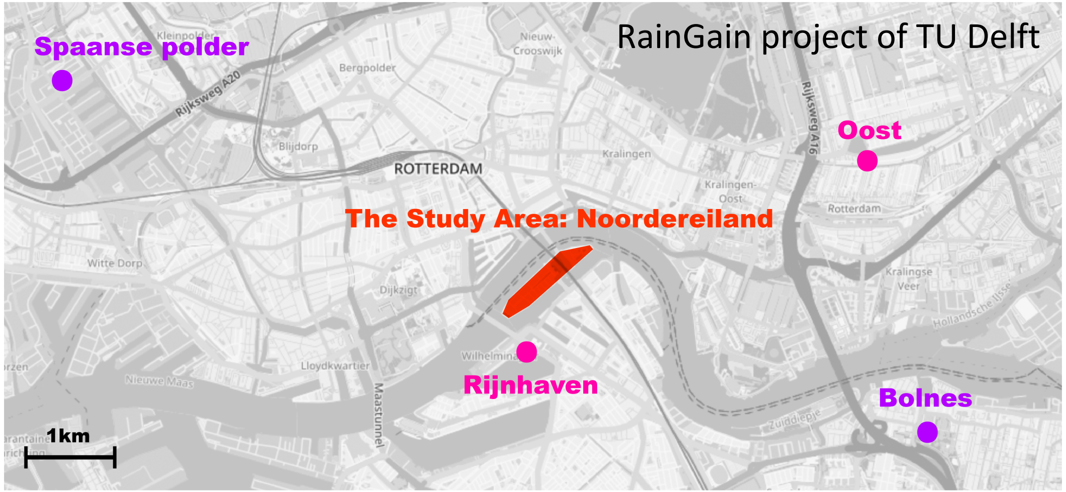
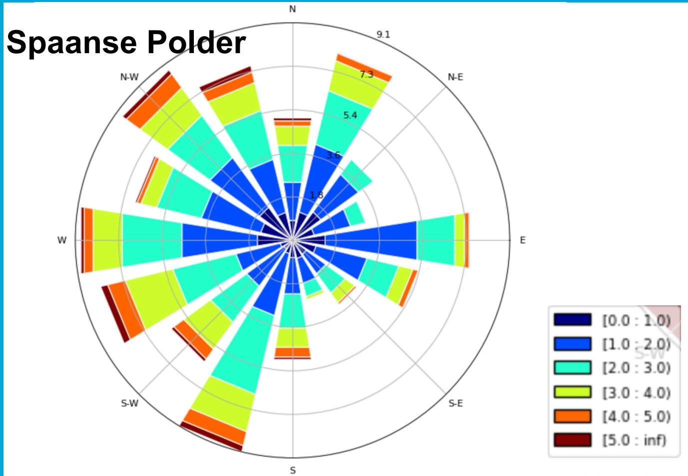
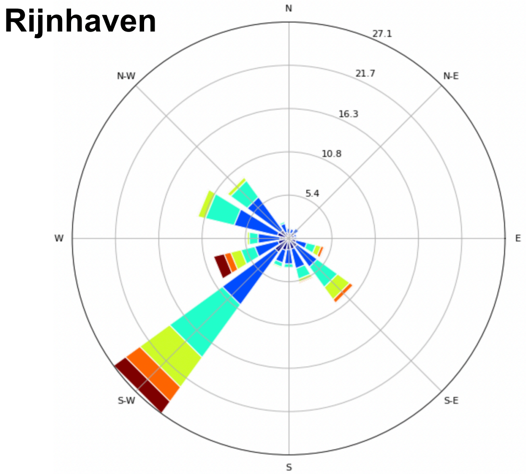
Test cases design and set up: Realistic urban geometry

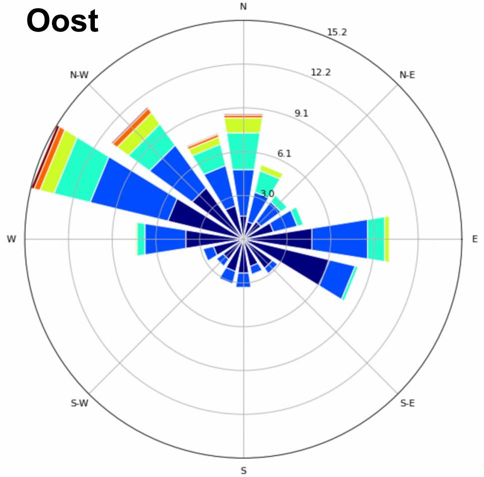


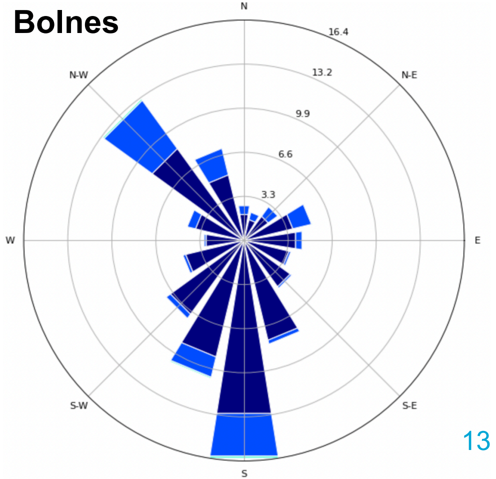


Test cases design and set up: Realistic urban geometry









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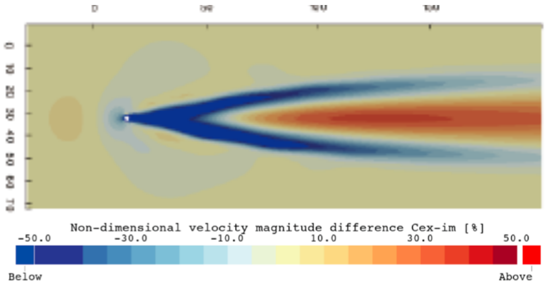
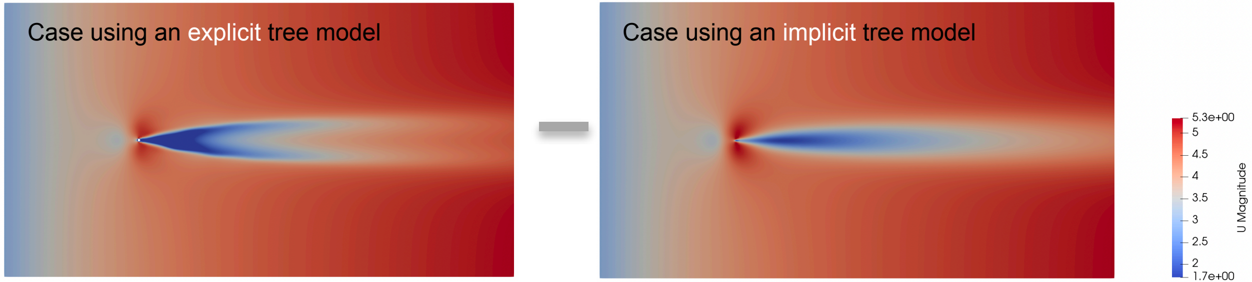
Measures for quantitative analysis

Non-dimensional velocity magnitude difference

$$C_{ex-im} = \frac{(U_{ex} - U_{im})}{U_{ref}} \qquad C_{l2-l3} = \frac{(U_{lod2} - U_{lod3})}{U_{ref}}$$



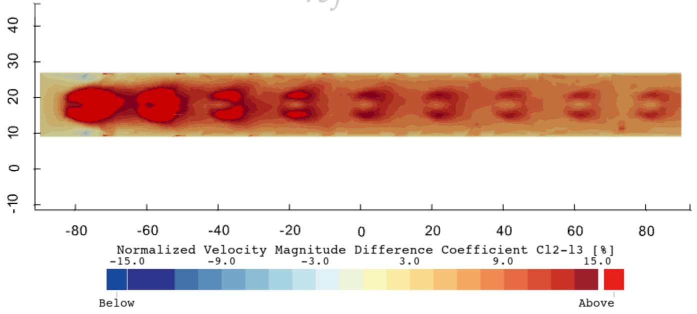


U_{ref}

Measures for quantitative analysis

Non-dimensional velocity magnitude difference

$$C_{ex-im} = \frac{(U_{ex} - U_{im})}{U_{ref}} \qquad C_{l2-l3} = \frac{(U_{lod2} - U_{lod3})}{U_{ref}}$$



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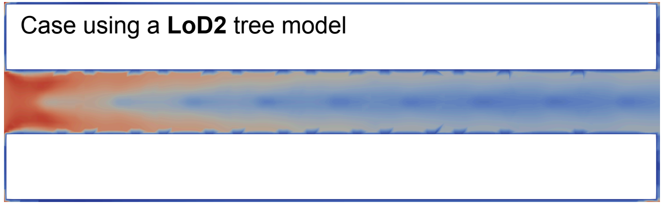

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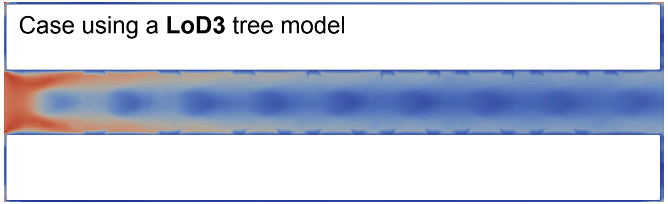

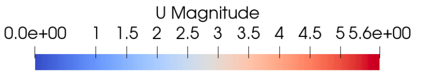

U_{ref}

Measures for quantitative analysis

Pedestrian wind comfort criteria

Category	*Description*	*Mean and GEM wind speed at 1.75 m height (m/s)*	*Effect*	*Acceptable activities*
A	Calm	0.0–0.1		Frequent outdoor sitting use, e.g. restaurant, café.
B	Light air	0.2–1.0	No noticeable wind	
C	Light breeze	1.1–2.3	Wind felt on face;	
D	Gentle breeze	2.4–3.8	Hair disturbed, clothing flaps, newspaper difficult to read;	Occasional outdoor seating, e.g. general public outdoor spaces, balconies and terraces intended for occasional use, etc.
E	Moderate breeze	3.9–5.5	Raises dust and loose paper, hair disarranged;	Entrances, bus stops, covered walkways or passageways beneath buildings.
F	Fresh breeze	5.6–7.5	Force of wind felt on body, danger of stumbling when entering a windy zone;	External pavements, walkways
G	Strong breeze	7.6–9.7	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forwards walking force, wind noise on ears unpleasant;	Not comfortable for regular pedestrian access

based on the work by [of London Corporation, 2019; Blocken and Carmeliet, 2004; Lawson, 1978]

$$\text{Gust Equivalent Mean (GEM) wind speed} = \frac{\text{Maximum mean wind speed}}{1.85}$$

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OpenFOAM programming to add source/sink terms

Modify the source code of the standard $k-\varepsilon$ turbulence model and the *simpleFoam* solver in OpenFOAM. Based on the work by [Haukur, 2009] and [Maldonado J, 2012].

```
// Turbulent kinetic energy equation
tmp<fvScalarMatrix> kEqn
(
    fvm::ddt(alpha, rho, k_)
  + fvm::div(alphaRhoPhi, k_)
  - fvm::laplacian(alpha*rho*DkEff(), k_)
 ==
    alpha()*rho()*G
  - fvm::SuSp((2.0/3.0)*alpha()*rho()*divU, k_)
  - fvm::Sp(alpha()*rho()*epsilon_()/k_(), k_)
  + fvm::Sp(plantCd_() *leafAreaDensity_() / k_()*(betaP_ * pow(mag(U()),3)- betaD_ * k_() * mag(U())), k_)//Source Term
  + kSource()
  + fvOptions(alpha, rho, k_)
);
```

The main modified parts of the standard $k-\varepsilon$ turbulence model

$$S_k = \rho\, C_d\, LAD\, (\beta_p \mathbf{U}^3 - \beta_d \mathbf{U} k)\ \left[\frac{W}{m^3}\right]$$

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OpenFOAM programming to add source/sink terms

Modify the source code of the standard $k-\varepsilon$ turbulence model and the *simpleFoam* solver in OpenFOAM. Based on the work by [Haukur, 2009] and [Maldonado J, 2012].

```
// Dissipation equation
tmp<fvScalarMatrix> epsEqn
(
    fvm::ddt(alpha, rho, epsilon_)
  + fvm::div(alphaRhoPhi, epsilon_)
  - fvm::laplacian(alpha*rho*DepsilonEff(), epsilon_)
 ==
    C1_*alpha()*rho()*G*epsilon_()/k_()
  - fvm::SuSp(((2.0/3.0)*C1_ - C3_)*alpha()*rho()*divU, epsilon_)
  - fvm::Sp(C2_*alpha()*rho()*epsilon_()/k_(), epsilon_)
  + fvm::Sp(plantCd_()*leafAreaDensity_()/k_()*(C4_*betaP_*pow(mag(U()),3)- C5_*betaD_*k_()*mag(U())), epsilon_) //Source Term
  + epsilonSource()
  + fvOptions(alpha, rho, epsilon_)
);
```

The main modified parts of the standard $k-\varepsilon$ turbulence model

$$= \quad S_\varepsilon = \rho\, C_d\, LAD\, \frac{\varepsilon}{k}\left(C_{\varepsilon 4}\beta_p \mathbf{U}^3 - C_{\varepsilon 5}\beta_d \mathbf{U} k\right)\left[\frac{W}{m^3}\right]$$

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OpenFOAM programming to add source/sink terms

Modify the source code of the standard $k-\varepsilon$ turbulence model and the *simpleFoam* solver in OpenFOAM. Based on the work by [Haukur, 2009] and [Maldonado J, 2012].

The main modified parts of the *simpleFoam* solver

```
tmp<fvVectorMatrix> tUEqn
(
    fvm::div(phi, U)
  + MRF.DDt(U)
  + turbulence->divDevReff(U)
 ==
    fvOptions(U)
  - fvm::Sp(plantCd * leafAreaDensity * mag(U), U)
);
```

$$= \quad S_{ui} = -\rho\, C_d\, LAD\, U_i\, \mathbf{U} \left[\frac{N}{m^3}\right]$$

Isolated tree

Isolated tree test cases

Case ID	*Tree shape*	*Tree modeling approach*	*LoD of tree*	*LAD value* ($m^2\ m^{-3}$)
1	Broadleaf	Explicit	2	-
2			3	-
3		Implicit	2	1.4
4			3	1.4
5			2	5e10
6			3	5e10
7	Conifer	Explicit	2	-
8			3	-
9		Implicit	2	1.4
10			3	1.4
11			2	5e10
12			3	5e10

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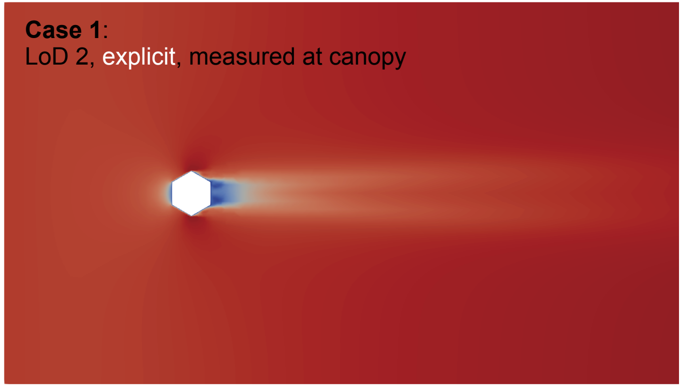
Isolated tree

ID	Tree Shapes	Tree modeling approach	LoD	LAD
1	Broadleaf	EX	2	-
2			3	-
3		IM	2	1.4
4			3	1.4
5			2	5e10
6			3	5e10
7	Conifer	EX	2	-
8			3	-
9		IM	2	1.4
10			3	1.4
11			2	5e10
12			3	5e10

Cases need to be compared in pairs to get C_{ex-im}

$$C_{ex-im} = \frac{(U_{ex} - U_{im})}{U_{ref}}$$

For example: (Case 1 (LEFT) minus Case 5 (RIGHT) / U_{ref}



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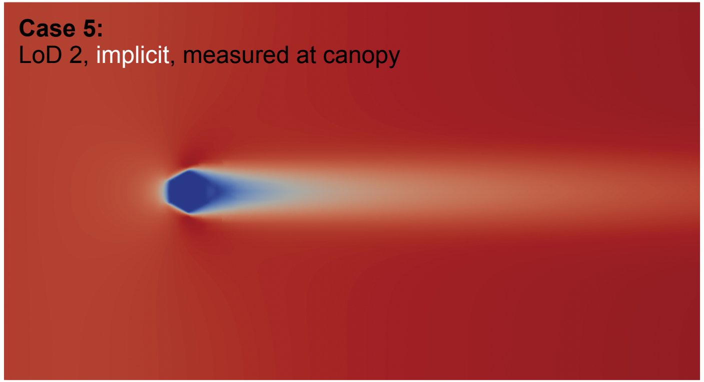


U_{ref}

Isolated tree

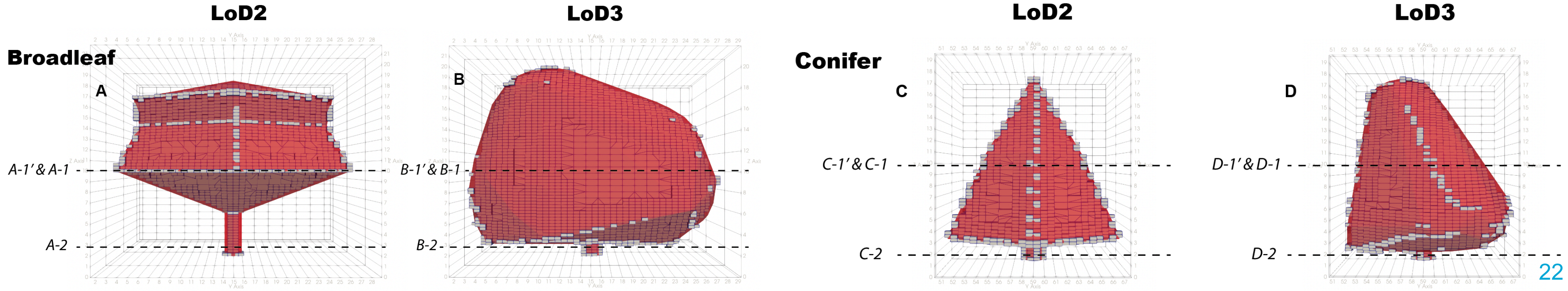
Isolated tree test cases

ID	Tree Shapes	Tree modeling approach	LoD	LAD
1	Broadleaf	EX	2	-
2			3	-
3		IM	2	1.4
4			3	1.4
5			2	5e10
6			3	5e10
7	Conifer	EX	2	-
8			3	-
9		IM	2	1.4
10			3	1.4
11			2	5e10
12			3	5e10

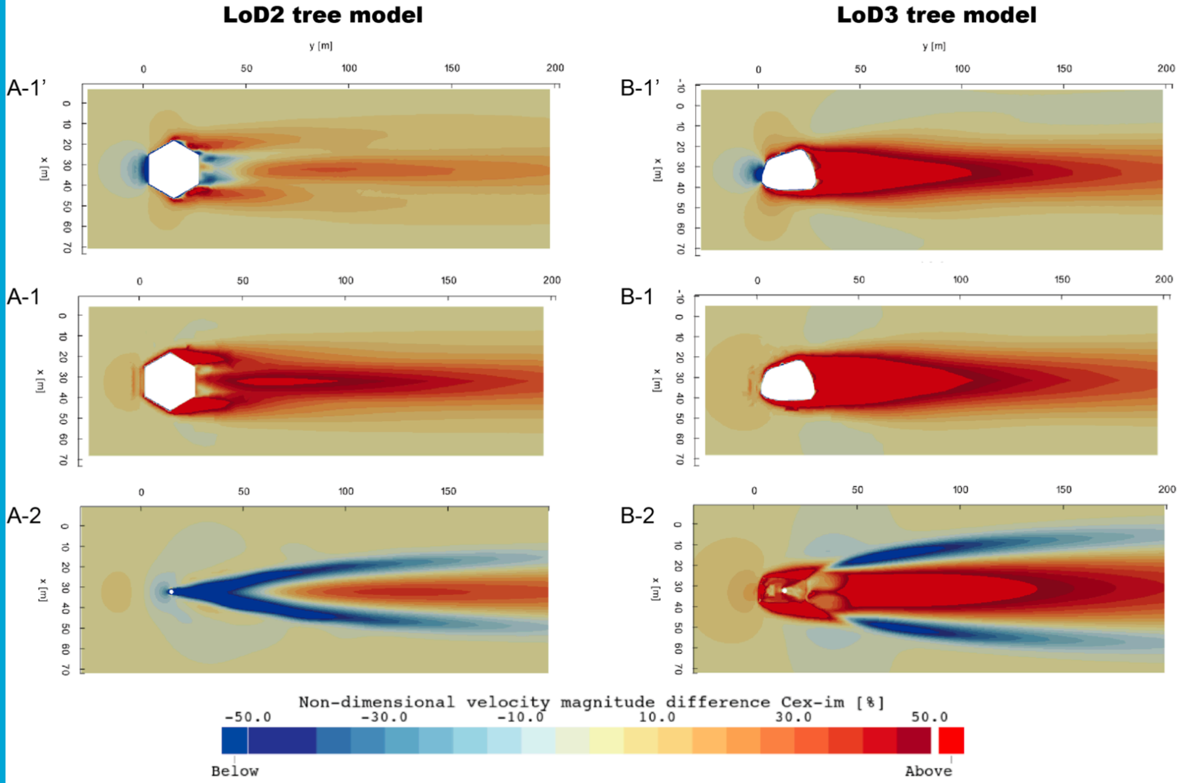
12 U_{ex-im} plots in total. 6 for broadleaf and 6 for conifer.

C_{ex-im} ID	*Tree shape*	*LoD of tree*	*Explicit case (U_{ex})*	*Implicit case (U_{im})*	*Measurement Height*
A-1′	Broadleaf	2	Case 1	Case 3 (LAD = 1.4)	Canopy
A-1				Case 5 (LAD = 5e10)	
A-2					Trunk
B-1′		3	Case 2	Case 4 (LAD = 1.4)	Canopy
B-1				Case 6 (LAD = 5e10)	
B-2					Trunk
C-1′	Conifer	2	Case 7	Case 9 (LAD = 1.4)	Canopy
C-1				Case 11 (LAD = 5e10)	
C-2					Trunk
D-1′		3	Case 8	Case 10 (LAD = 1.4)	Canopy
D-1				Case 12 (LAD = 5e10)	
D-2					Trunk

The explicit tree models (meshes in red color) and the corresponding implicit tree models (porous cells in white color)



Isolated tree: broadleaf tree



ID	*Tree shapes*	*LoD*	*Explicit Case* (U_{ex})	*Implicit Case* (U_{im})	*Measurement Height*
A-1'	Broadleaf	2	Case 1	Case 3 *(LAD = 1.4)*	Canopy
A-1			Case 1	Case 5 *(LAD = 5e10)*	Canopy
A-2			Case 1	Case 5 *(LAD = 5e10)*	Trunk
B-1'		3	Case 2	Case 4 *(LAD = 1.4)*	Canopy
B-1			Case 2	Case 6 *(LAD = 5e10)*	Canopy
B-2			Case 2	Case 6 *(LAD = 5e10)*	Trunk

(A-1') difference between LoD2 explict broadleaf & LoD2 implicit broadleaf with LAD = 1.4, measured at canopy;
(A-1) difference between LoD2 explict broadleaf & LoD2 implicit broadleaf with LAD = 5e10, measured at canopy;
(A-2) difference between LoD2 explict broadleaf & LoD2 implicit broadleaf with LAD = 5e10, measured at trunk;

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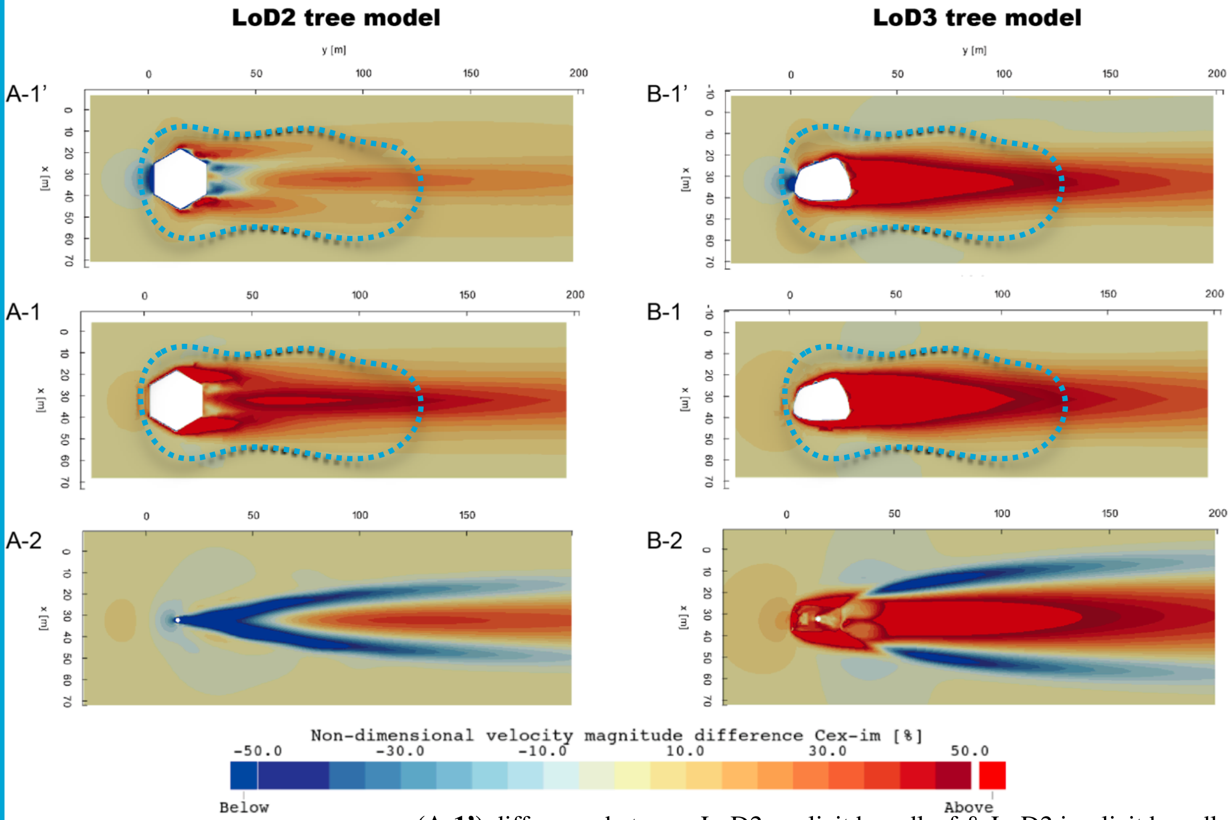
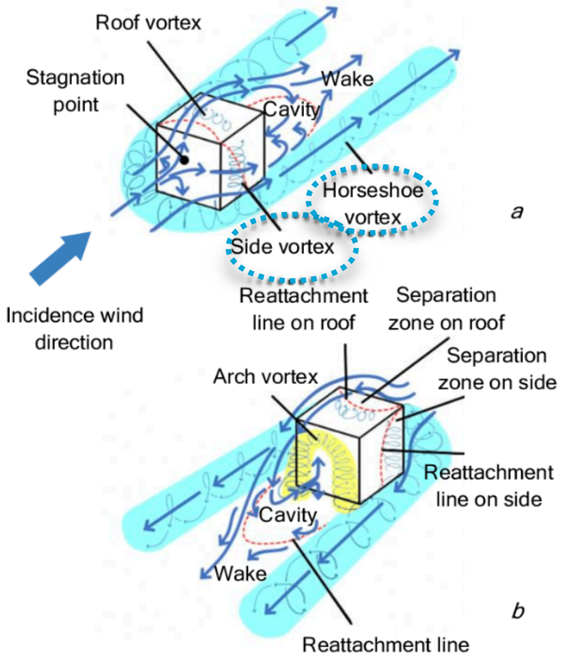
Isolated tree: broadleaf tree





(A-1') difference between LoD2 explicit broadleaf & LoD2 implicit broadleaf with LAD = 1.4, measured at canopy;
(A-1) difference between LoD2 explicit broadleaf & LoD2 implicit broadleaf with LAD = 5e10, measured at canopy;
(B-1') difference between LoD3 explicit broadleaf & LoD3 implicit broadleaf with LAD = 1.4, measured at canopy;
(B-1) difference between LoD3 explicit broadleaf & LoD3 implicit broadleaf with LAD = 5e10, measured at canopy;

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Isolated tree: broadleaf tree

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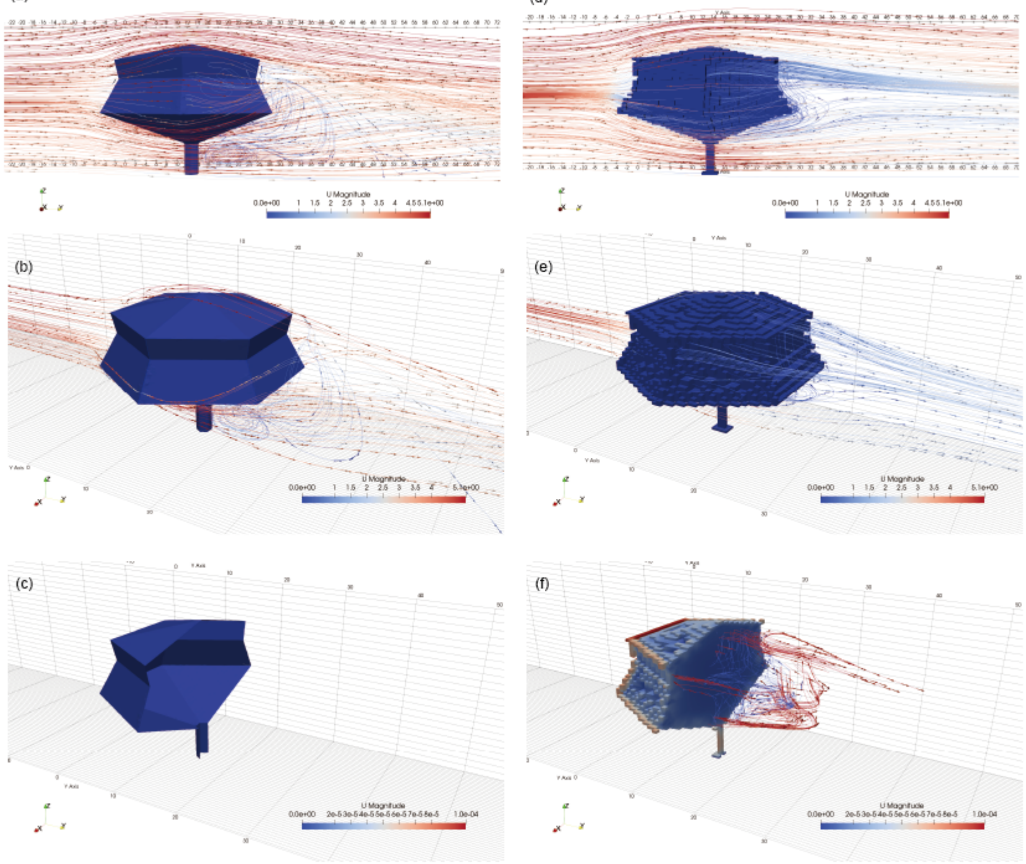
Explicit Tree Modeling Approach (Case 1)

LoD2 explicit broadleaf

Implicit Tree Modeling Approach (Case 5)

LoD2 implicit broadleaf with LAD = 5e10



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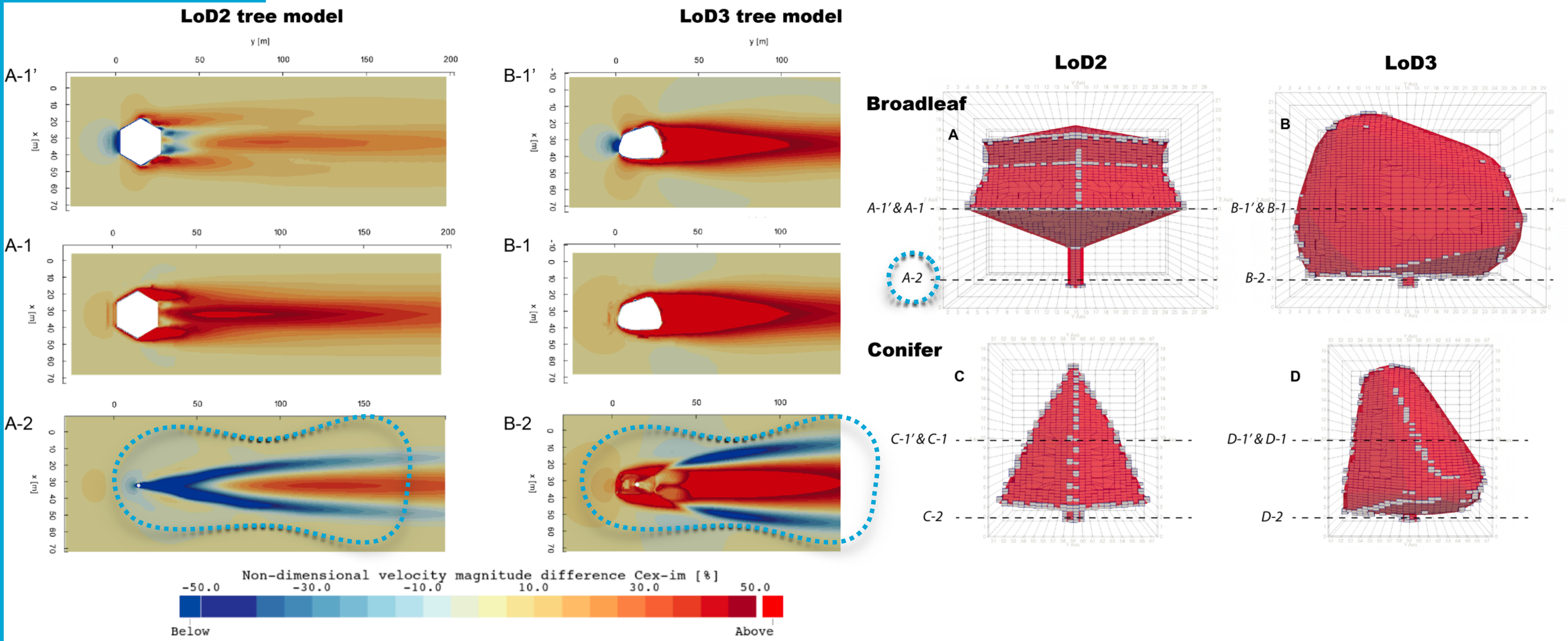
Isolated tree: broadleaf tree



(A-2) difference between LoD2 explicit broadleaf & LoD2 implicit broadleaf with LAD = 5e10, measured at trunk;

(B-2) difference between LoD3 explicit broadleaf & LoD3 implicit broadleaf with LAD = 5e10, measured at trunk;

Isolated tree: broadleaf tree

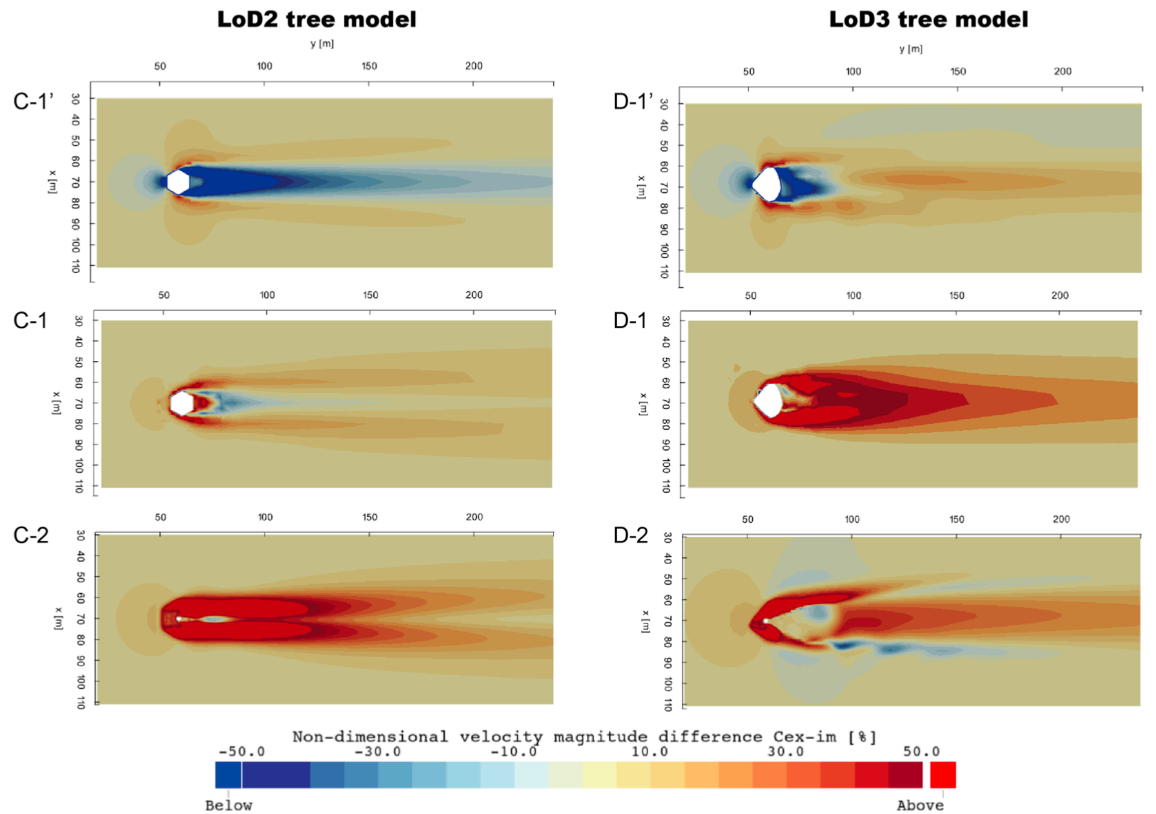
It is not recommended to model tree trunks, branches or even buildings implicitly rather than explicitly in order to reduce the time spent on designing a good CFD grid/mesh.

- The implicit models always allow some of the wind flow into the porous cells no matter how high the LAD values are.
- For relatively small objects, such as tree trunks, insufficiently refined CFD grid/mesh may lead to abnormal simulation results.

However, the conclusion hold **only for the porosity model used in this thesis** (S_{u_i}, S_k and S_ε);

TUDelft

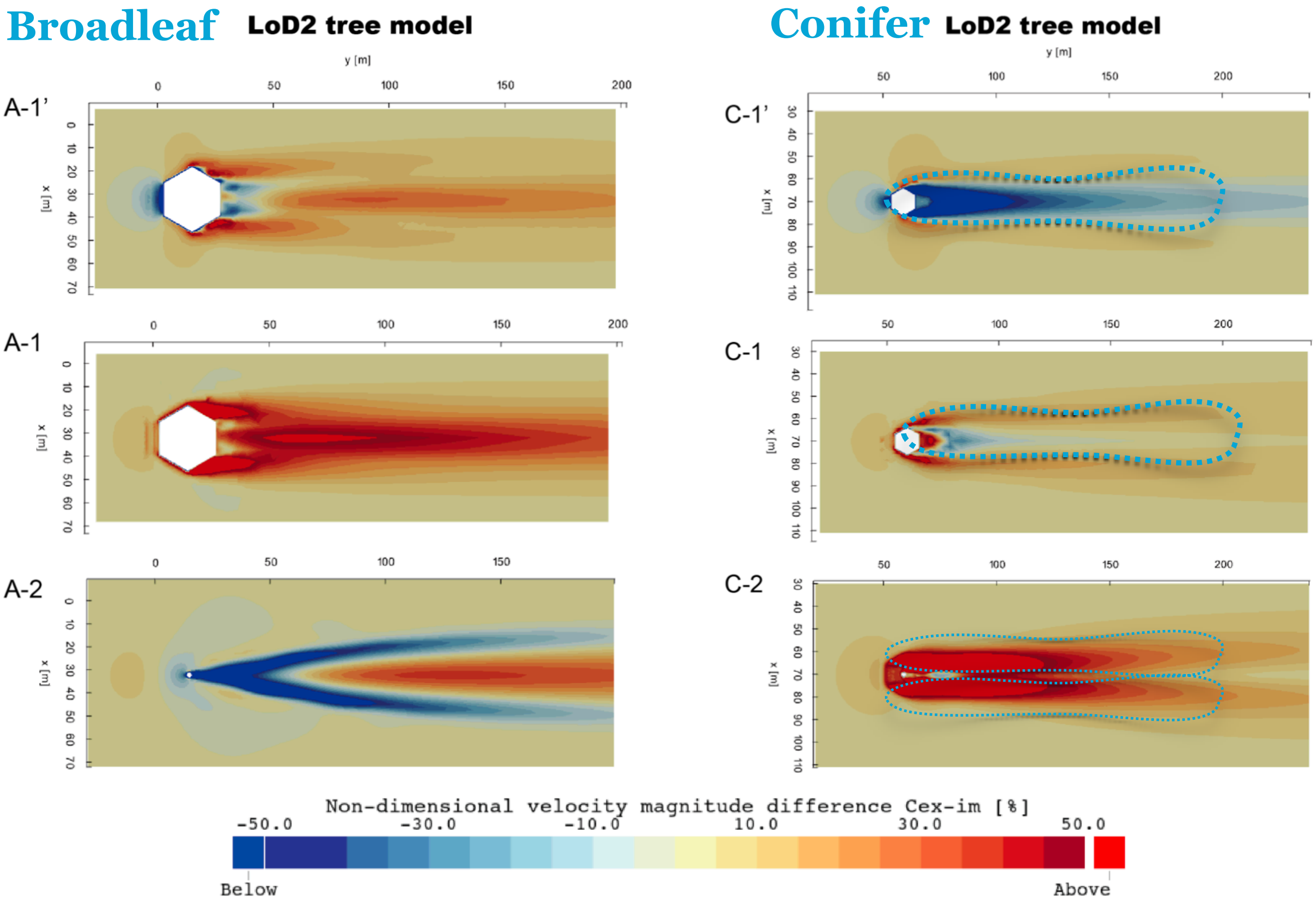
Isolated tree: conifer tree



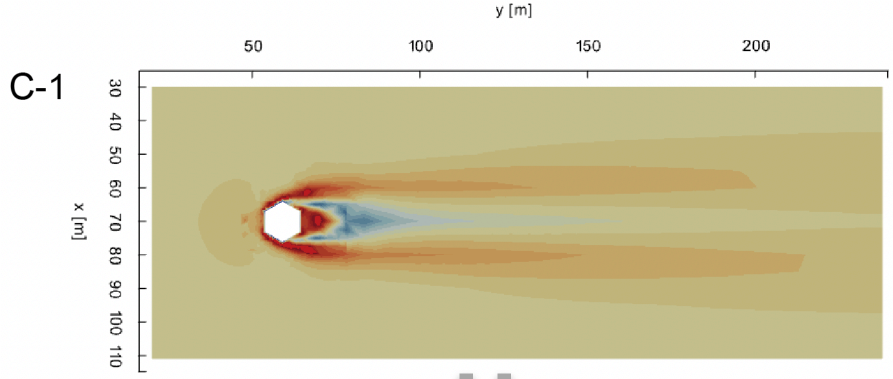
ID	Tree shapes	LoD	Explicit Case (U_{ex})	Implicit Case (U_{im})	Measurement Height
C-1'	Conifer	2	Case 7	Case 9 *(LAD = 1.4)*	Canopy
C-1			Case 7	Case 11 *(LAD = 5e10)*	Canopy
C-2			Case 7	Case 11 *(LAD = 5e10)*	Trunk
D-1'		3	Case 8	Case 10 *(LAD = 1.4)*	Canopy
D-1			Case 8	Case 12 *(LAD = 5e10)*	Canopy
D-2			Case 8	Case 12 *(LAD = 5e10)*	Trunk

(C-1') difference between LoD2 explicit conifer & LoD2 implicit conifer with LAD = 1.4, measured at canopy;
(C-1) difference between LoD2 explicit conifer & LoD2 implicit conifer with LAD = 5e10, measured at canopy;
(C-2) difference between LoD2 explicit conifer & LoD2 implicit conifer with LAD = 5e10, measured at trunk;

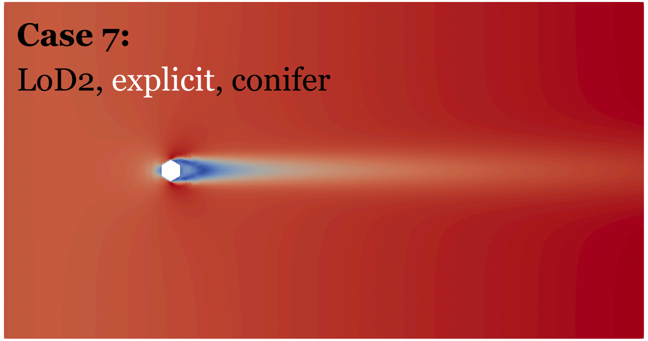
Isolated tree: conifer tree

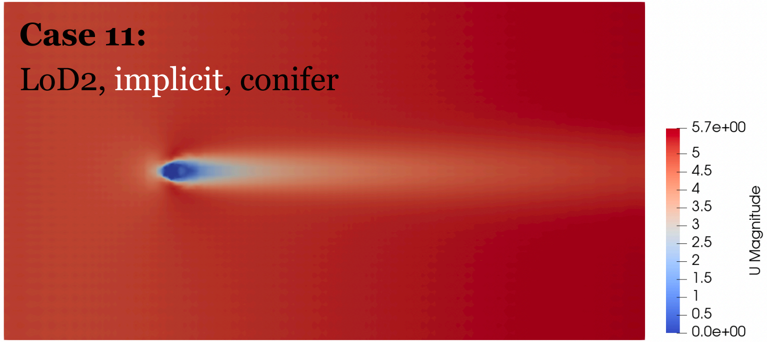


Isolated tree: conifer tree



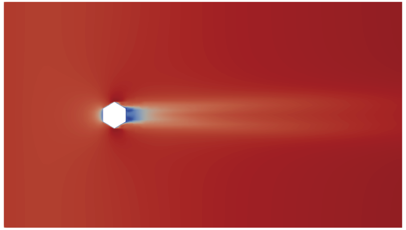
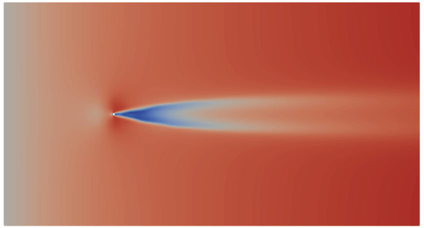
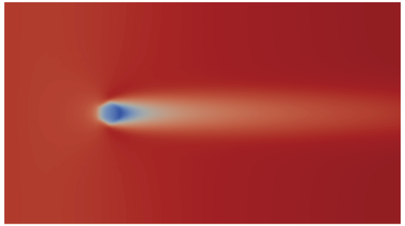
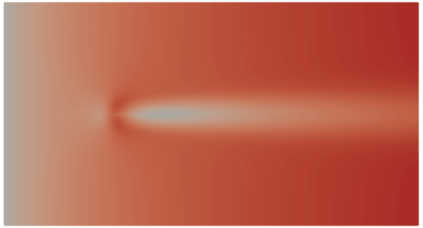
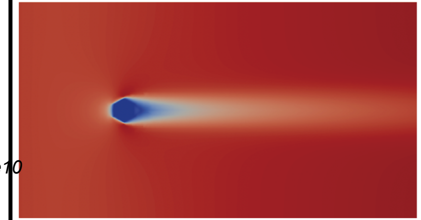
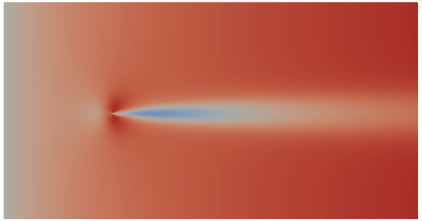
ID	Tree shapes	LoD	Explicit Case (U_{ex})	Implicit Case (U_{im})	Measurement Height
C-1	Conifer	2	Case 7	Case 11 *(LAD = 5e10)*	Canopy

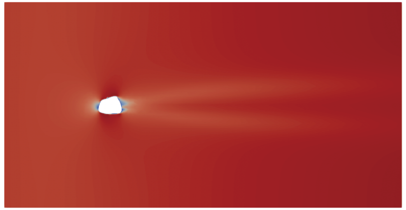
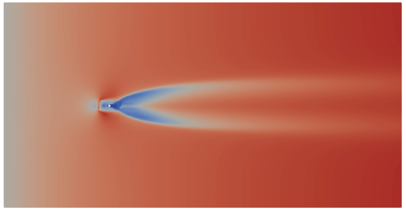
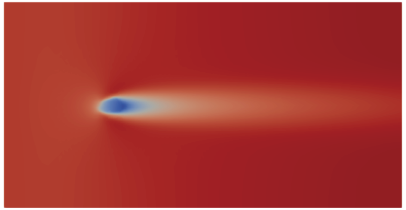
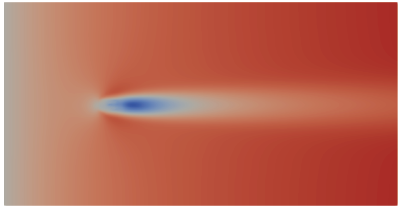
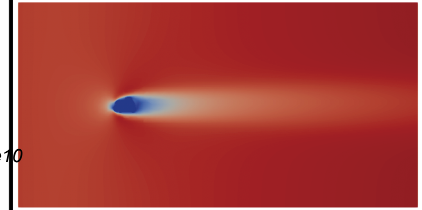
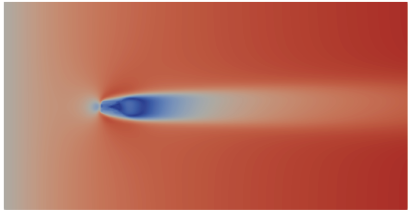




U_{ref}

Isolated tree: EX VS IM at wake

LoD2 broadleaf tree model		
	Measured at canopy	**Measured at trunk**
Case 1 *Explicit*		
Case 3 *Implicit LAD = 1.4*		
Case 5 *Implicit LAD = 5e10*		

LoD3 broadleaf tree model		
	Measured at canopy	**Measured at trunk**
Case 2 *Explicit*		
Case 4 *Implicit LAD = 1.4*		
Case 6 *Implicit LAD = 5e10*		

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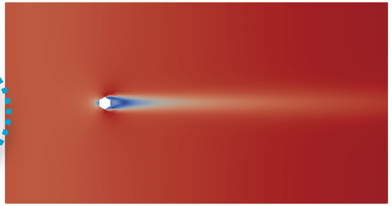
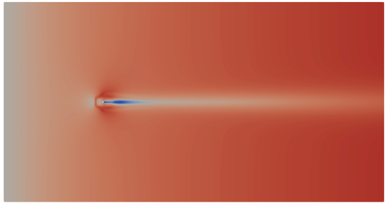
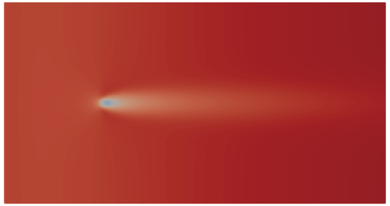
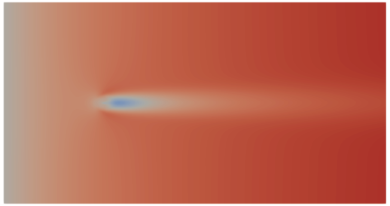
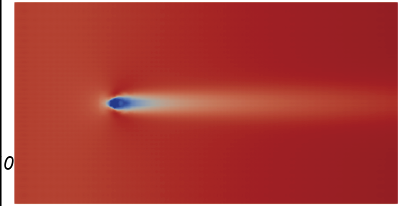
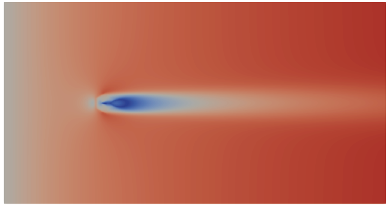
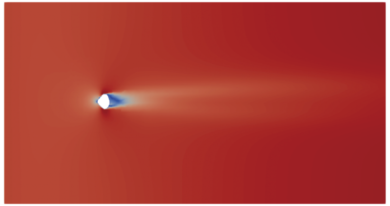
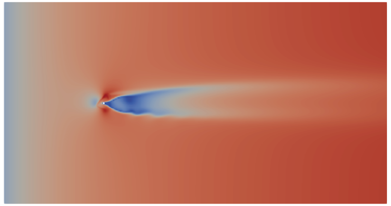
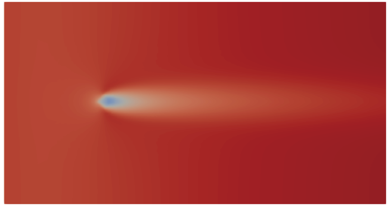
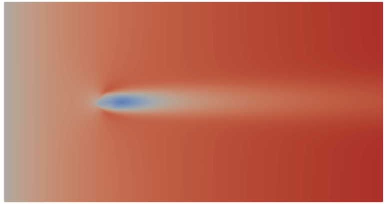
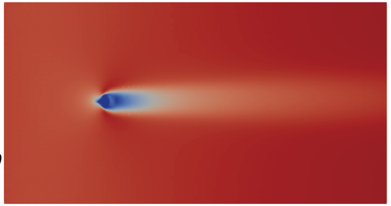
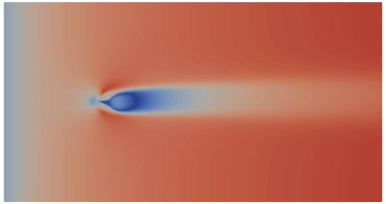
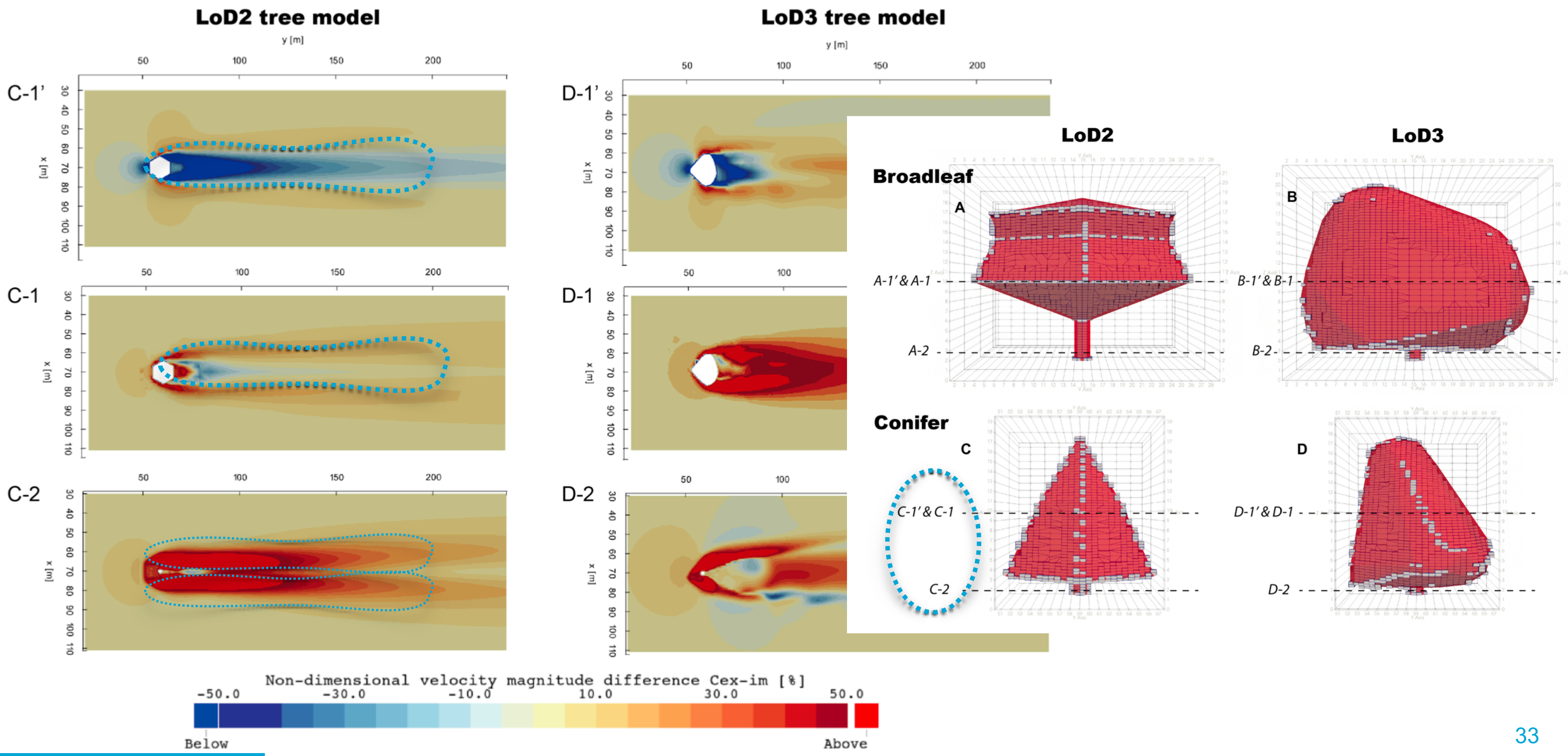
Isolated tree: EX VS IM at wake

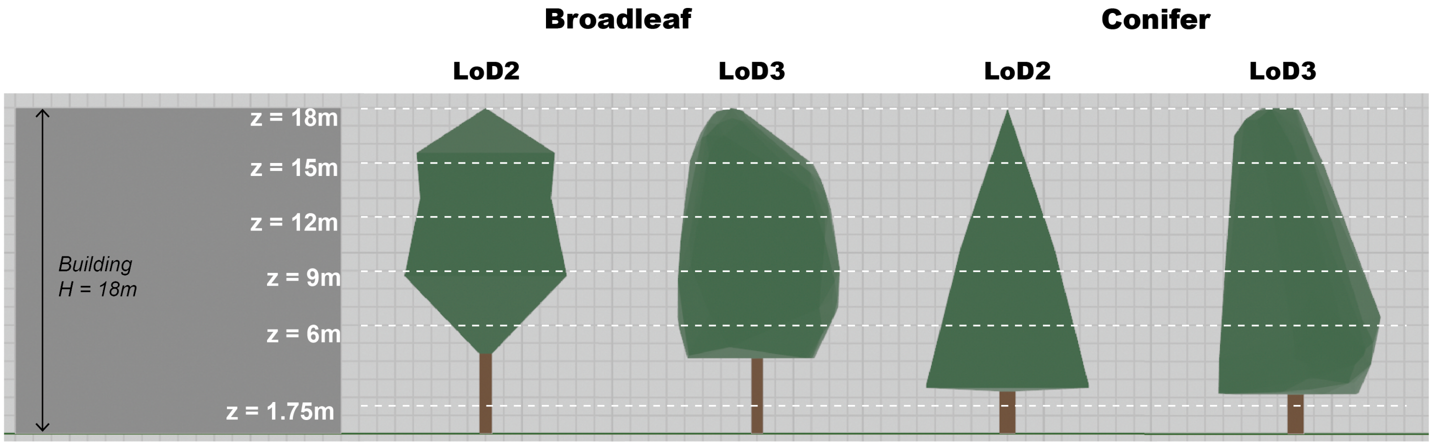
LoD2 conifer tree model		
	Measured at canopy	**Measured at trunk**
Case 7 *Explicit*		
Case 9 *Implicit LAD = 1.4*		
Case 11 *Implicit LAD = 5e10*		

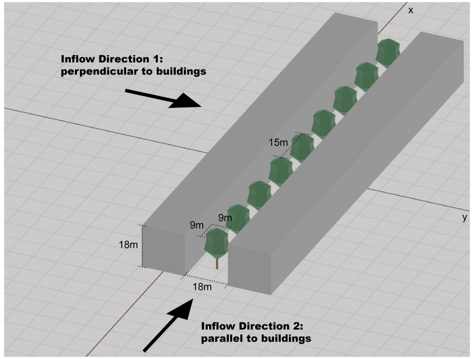
LoD3 conifer tree model		
	Measured at canopy	**Measured at trunk**
Case 8 *Explicit*		
Case 10 *Implicit LAD = 1.4*		
Case 12 *Implicit LAD = 5e10*		

Isolated tree: conifer tree



Idealized street canyon





Case ID	*Inflow direction*	*Tree shape*	*LoD of tree*	*LAD value* ($m^2\,m^{-3}$)	*Measurement Height*
13	Perpendicular to buildings	Broadleaf	2	0.2, 0.6, 1.0, 1.4, 1.8, 2.2	1.75m, 6m, 9m, 12m, 15m, 18m
14			3		
15		Conifer	2		
16			3		
17	Parallel to buildings	Broadleaf	2		
18			3		
19		Conifer	2		
20			3		

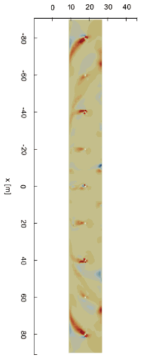
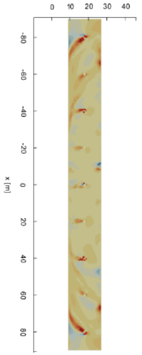
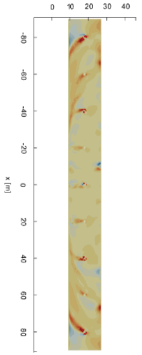
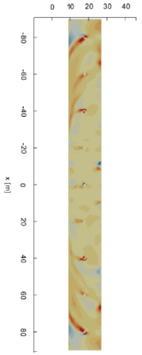
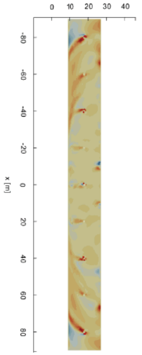
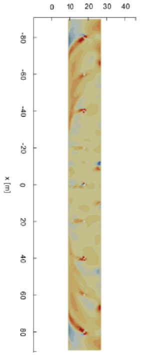
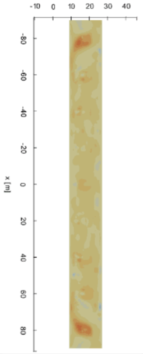
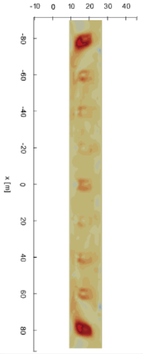
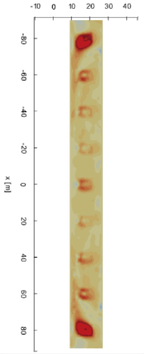
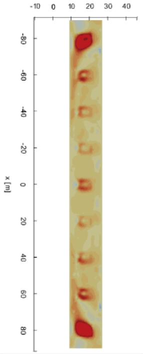
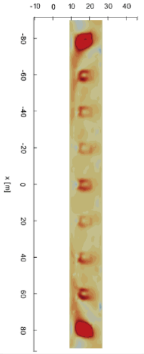
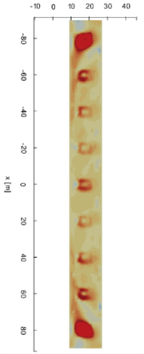
Cases need to be compared in pairs to get

$$C_{l2-l3} = \frac{(U_{lod2} - U_{lod3})}{U_{ref}}$$

Idealized street canyon: Cl2-l3 Example

Inflow direction: Perpendicular to buildings
Tree shape: Broadleaf

$$\left(\frac{U_{case13} - U_{case14}}{U_{ref}}\right)$$

	LAD = 0.2	LAD = 0.6	LAD = 1.0	LAD = 1.4	LAD = 1.8	LAD = 2.2
z = 1.75m						
z = 6m						

Idealized street canyon: Cl2-l3 Example

- For most cases, the absolute values of C_{l2-l3} are below 15%, which means that the velocity magnitude differences between LoD2 and LoD3 cases are below 0.5 m/s.
- The differences between these C_{l2-l3} plots are difficult to distinguish clearly with the naked eye and need to be described in a more quantitative way.

Idealized street canyon: Inflow direction perpendicular to buildings

Motivation
Research questions
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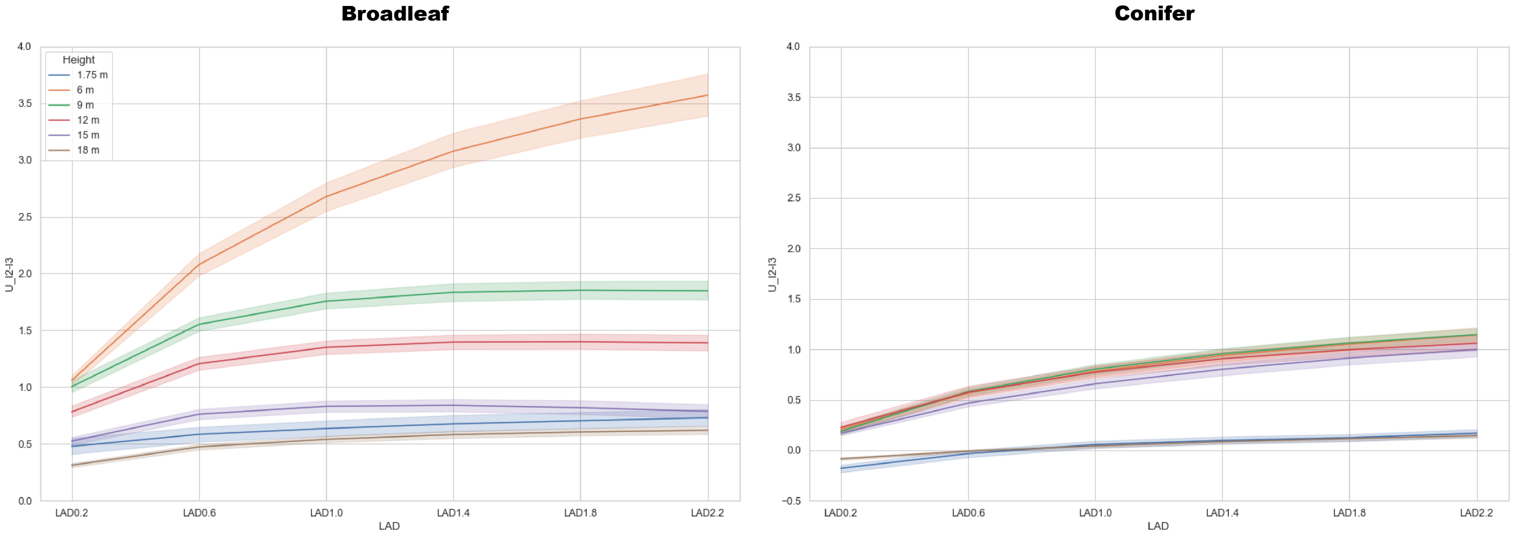
Conclusion

The mean and 95 % confidence interval of $\mathbf{C}_{l_2-l_3}$ *using the broadleaf and conifer tree models.*



- For most scenarios, average velocity magnitude of LoD2 cases ($\mathbf{U}_{lod2}$) within the street canyon is greater than that of LoD3 cases ($\mathbf{U}_{lod3}$). As most of the $C_{l2\text{-}l3}$ values are higher than 0.
- The influence of LAD can be more noticeable when its value is lower than 1.4.
- The maximum or minimum values of $C_{l2\text{-}l3}$ for broadleaf cases and conifer cases occurred at different heights.
- The difference between $\mathbf{U}_{lod2}$ and $\mathbf{U}_{lod3}$, i.e. the absolute magnitude of $C_{l2\text{-}l3}$ values, is generally lower in cases using conifer tree models than those using broadleaf tree models.

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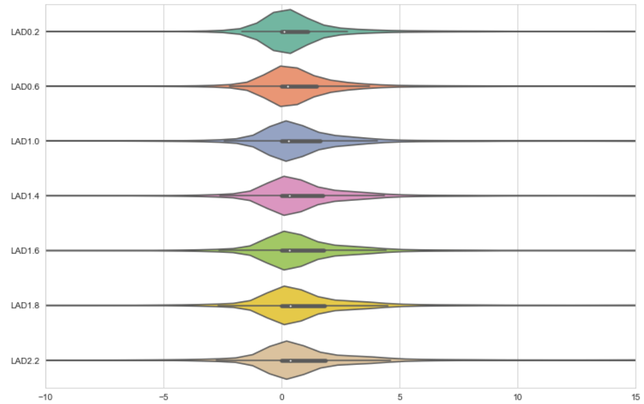
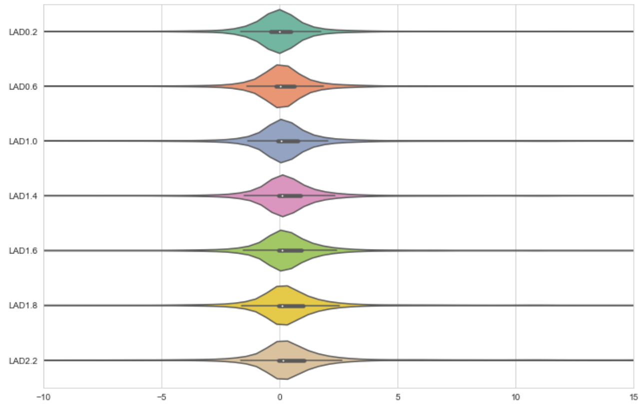
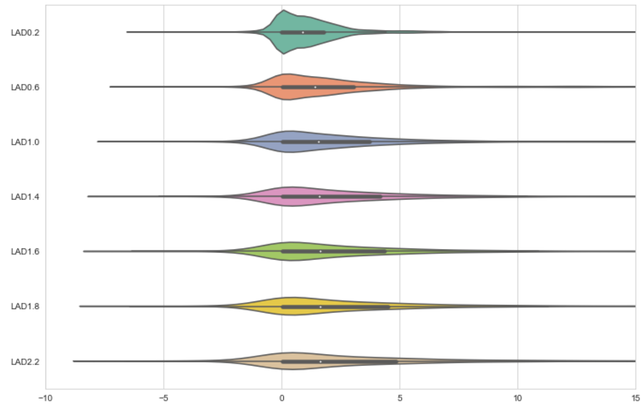
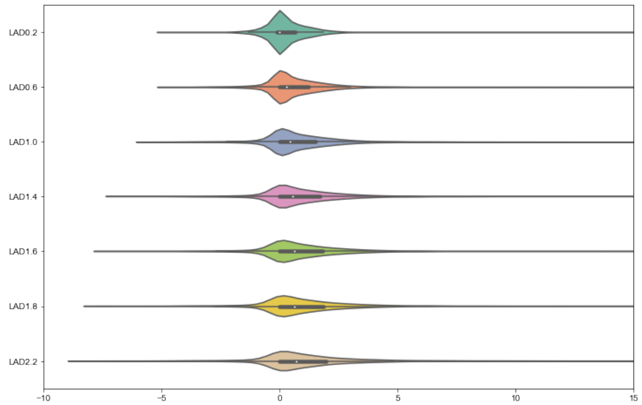
Idealized street canyon: Inflow direction perpendicular to buildings

Violin plots examples for C_{l2-l3} within the street canyon at different height

	BroadLeaf	Conifer
Z = 1.75m		
Z = 6 m		

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Idealized street canyon: Inflow direction perpendicular to buildings

- Motivation
- Research questions
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- Conclusion

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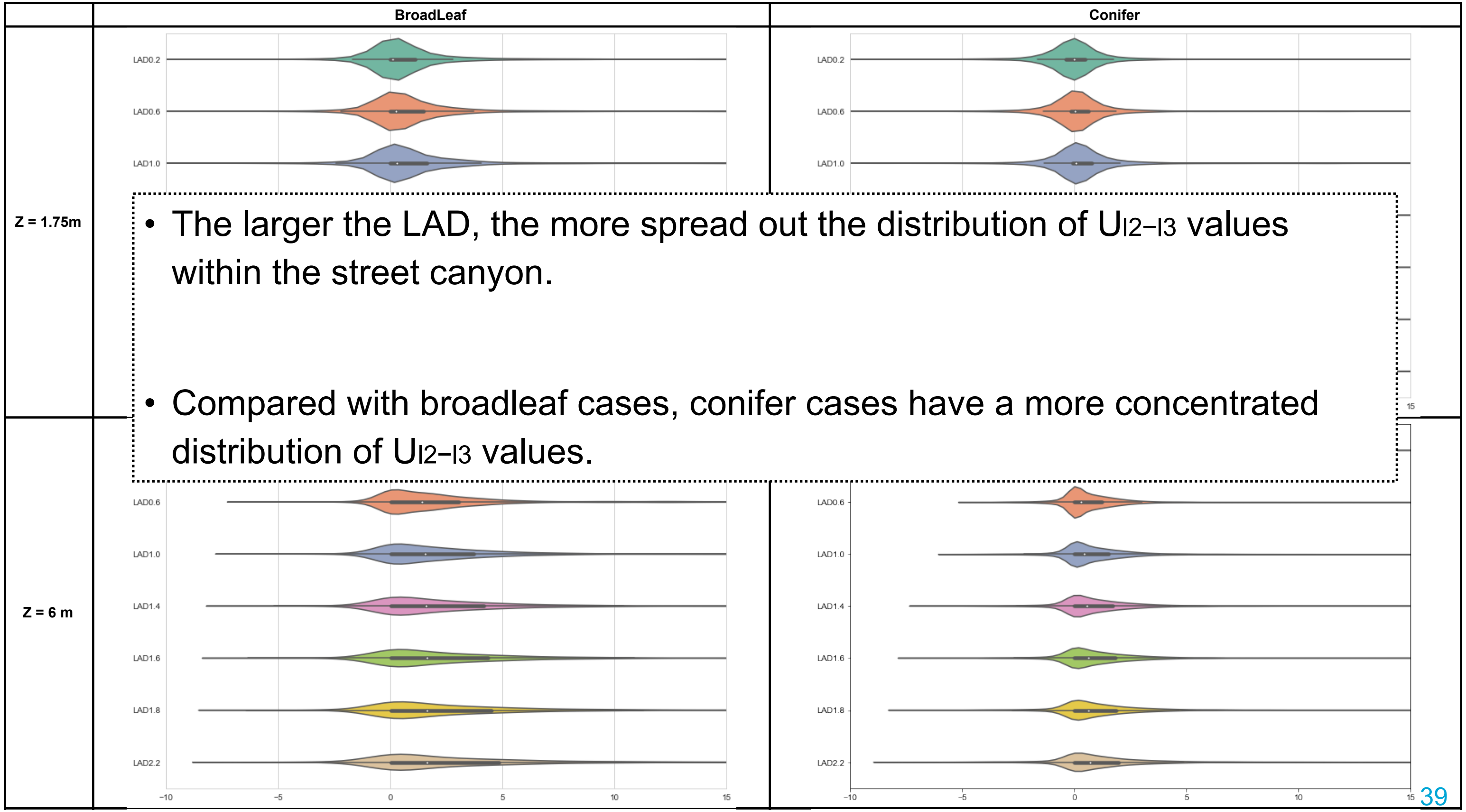
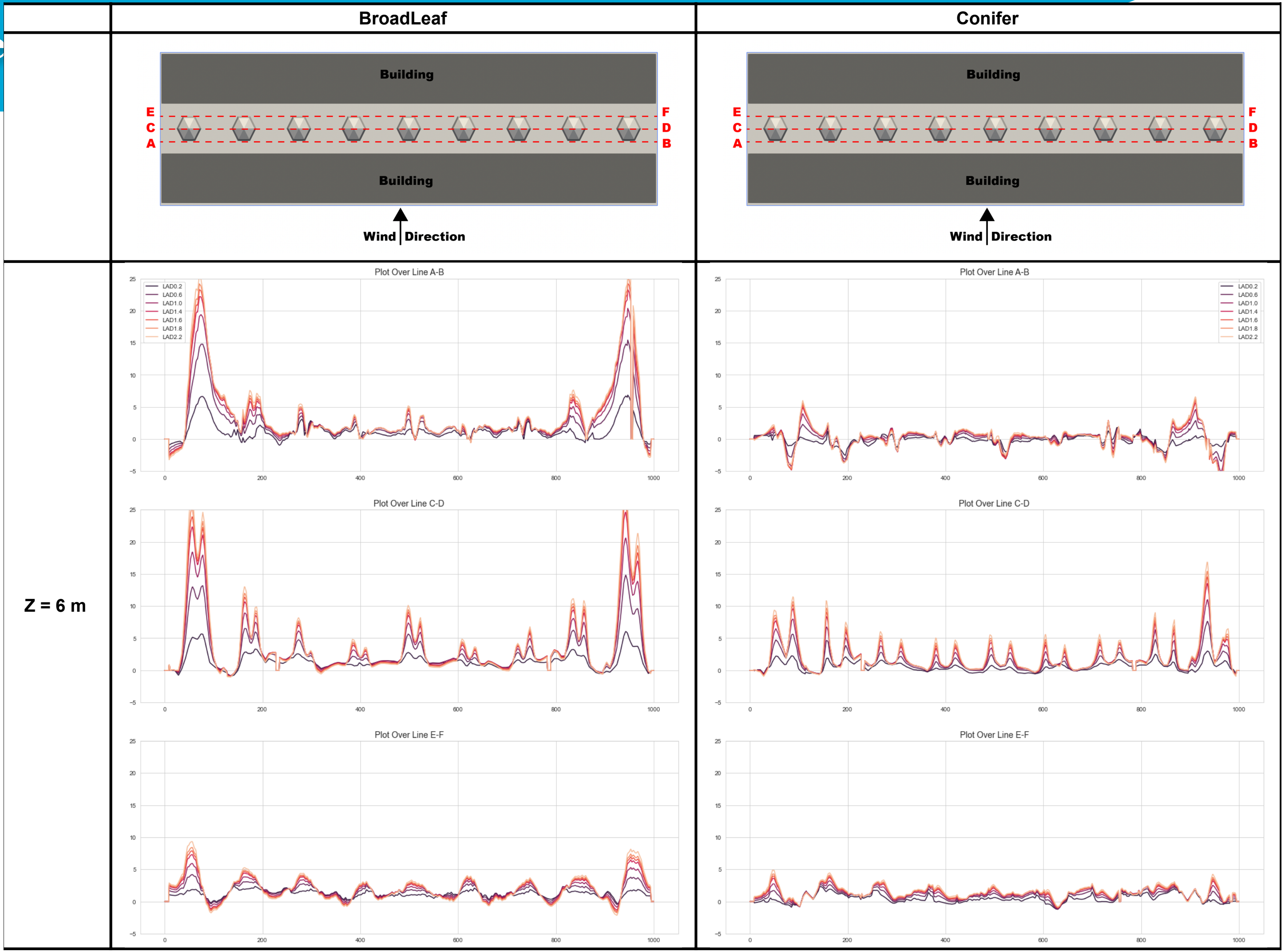
Violin plots examples for C_{l2-l3} within the street canyon at different height



- The larger the LAD, the more spread out the distribution of U_{l2-l3} values within the street canyon.
- Compared with broadleaf cases, conifer cases have a more concentrated distribution of U_{l2-l3} values.

Idealized stre



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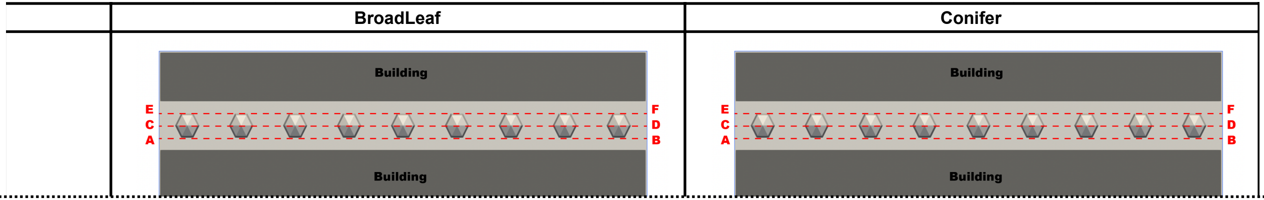
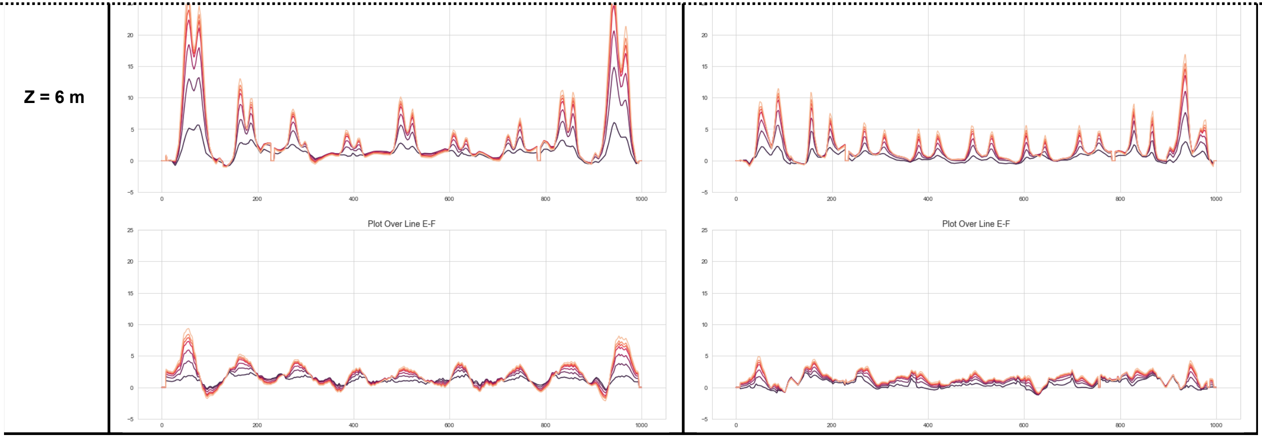
Idealized street canyon: Inflow direction perpendicular to buildings



- Differences between LAD values of 2.2 and 1.8 are smaller than the differences between LAD values of 1.2 and 0.6. This proves that the influence of LAD can be more noticeable when it has lower value.

- Value of C_{l2-l3} is higher at locations closer to tree models.



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Idealized street canyon: Inflow direction parallel to buildings

Motivation

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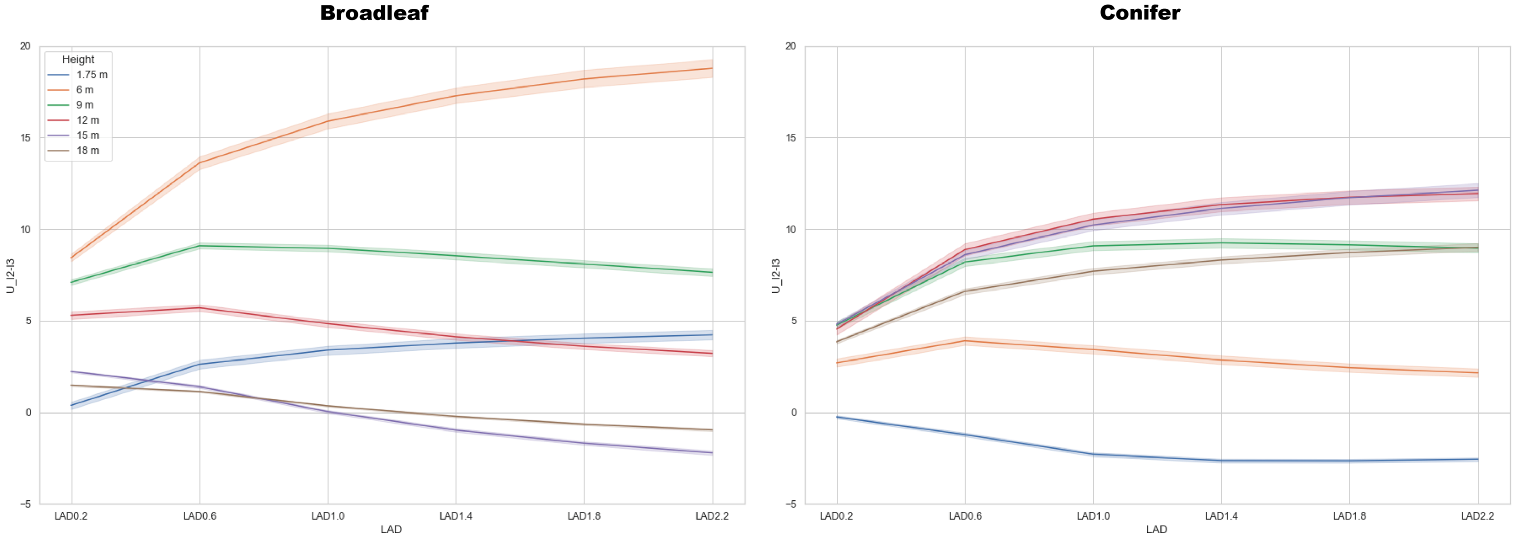
The mean and 95 % confidence interval of C_{l2-l3} using the broadleaf and conifer tree models.



- Similarly, the changing of slope of each line is greater when LAD value is below 1.4. $C_{l2\text{-}l3}$ values are generally lower in cases using conifer tree models than those using broadleaf tree models.
- However, some $C_{l2\text{-}l3}$ values are lower than 0. So LoD2 cases have lower velocity magnitude than LoD3 cases.
- When the inflow direction is parallel to the building, the difference between LoD2 cases and LoD3 cases is larger.

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Idealized street canyon: Inflow direction parallel to buildings

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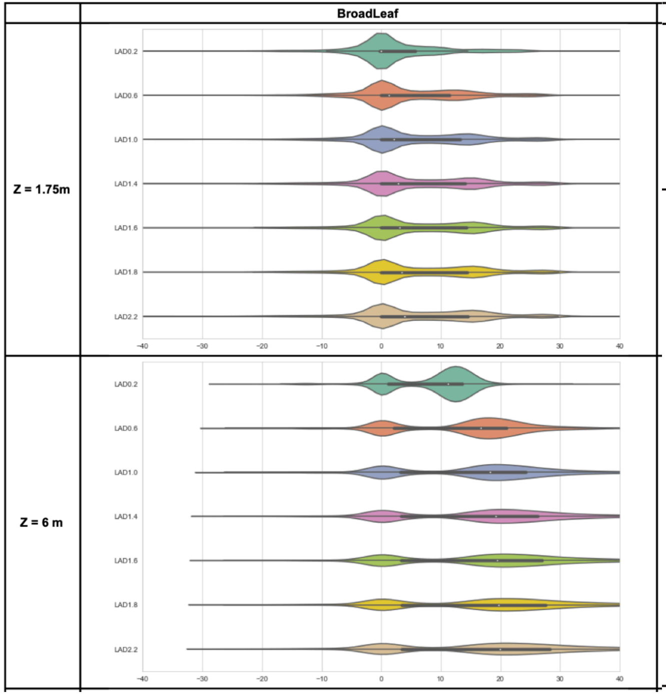
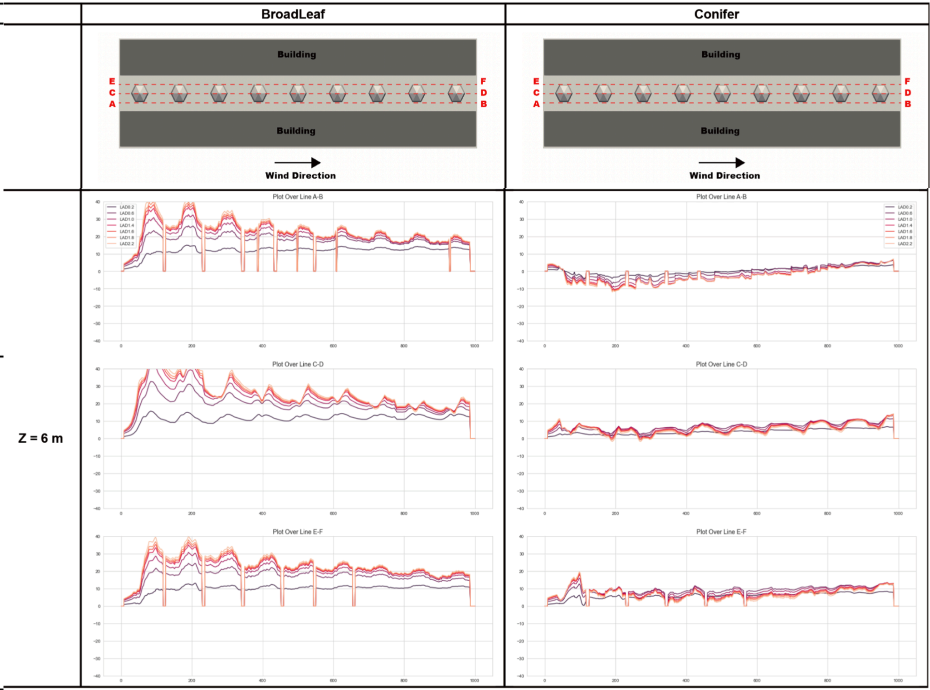
C_{l2-l3} violin plots examples



- With the inflow direction parallel to buildings, the distribution of Cl2−l3 values is more spread out.

C_{l2-l3} values on three probe lines



- With the inflow direction parallel to buildings, *Cl2−l3* is higher almost everywhere in the probe lines, not only at locations closer to tree models.

Idealized street canyon: conclusions so far

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- For a given measurement height, the average velocity magnitude of the cases using LoD2 tree models is faster or slower than that of the cases using LoD3 tree models, depending not only on the tree shapes, but also on LAD values and wind direction.
- The impact of tree LoDs on wind flow within the street canyon is generally more significant in the cases where the inflow direction is parallel to the buildings than in the case where the inflow direction is perpendicular to the buildings.
- Changing the LAD values does make difference to the impact of tree LoDs, and the influence of LAD can be more noticeable when its value is lower than 1.4 $m^2\ m^{-3}$.
- Also, the larger the LAD, the more spread out the distribution of C_{l2-l3} values within the street canyon.
- The maximum or minimum values of $C_{l2\text{-}l3}$ appear at different heights for cases using broadleaf models and those using conifer models.
-

Realistic urban geometry: wind speed & wind direction

Motivation

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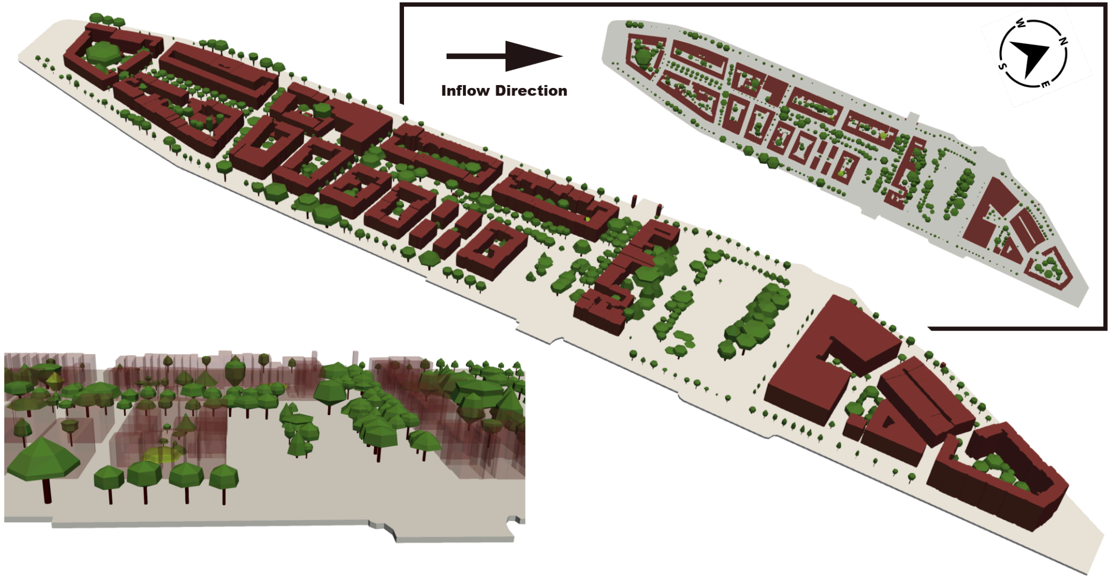
- Wind direction: all four weather stations show the average wind direction of SSW in 2021
- GEM wind speed: The maximum 5-minute average wind speed from SSW direction measured at the nearest weather station (Rijnhaven) is used to calculate the GEM wind speed, which is around 3.7 m/s at 2 m height above the terrain.

Realistic urban geometry: LoD2 tree models

ID	*Inflow wind speed at 2 m height* (m s^{-1})	*LoD of trees*	*Tree modeling approach*	*LAD values* (m^2 m^{-3})
21	3.7	without trees	Canopy: implicit; Trunk: explicit;	Broadleaf: 1.6; Conifer: 1.4;
22		LoD2		
23		LoD3		
24	7.4	LoD2		
25		LoD3		

LoD2 tree models



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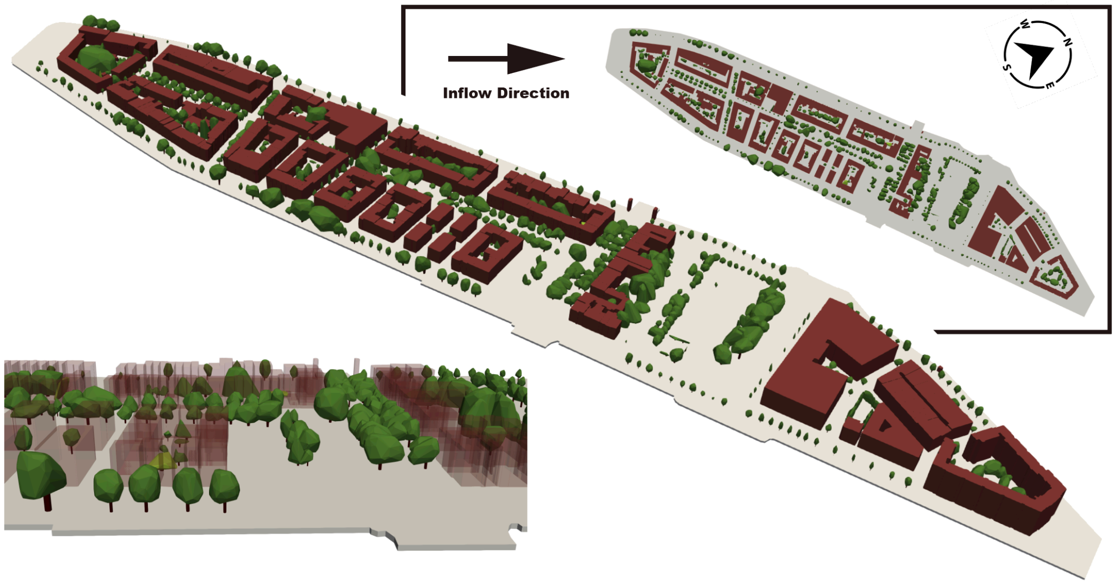
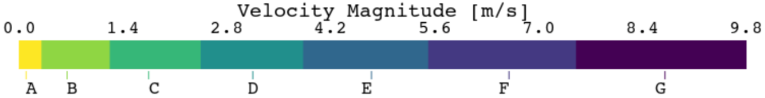
Realistic urban geometry: LoD3 tree models

ID	*Inflow wind speed at 2 m height* ($m\,s^{-1}$)	*LoD of trees*	*Tree modeling approach*	*LAD values* ($m^2\,m^{-3}$)
21	3.7	without trees	Canopy: implicit; Trunk: explicit;	Broadleaf: 1.6; Conifer: 1.4;
22		LoD2		
23		LoD3		
24	7.4	LoD2		
25		LoD3		

LoD3 tree models

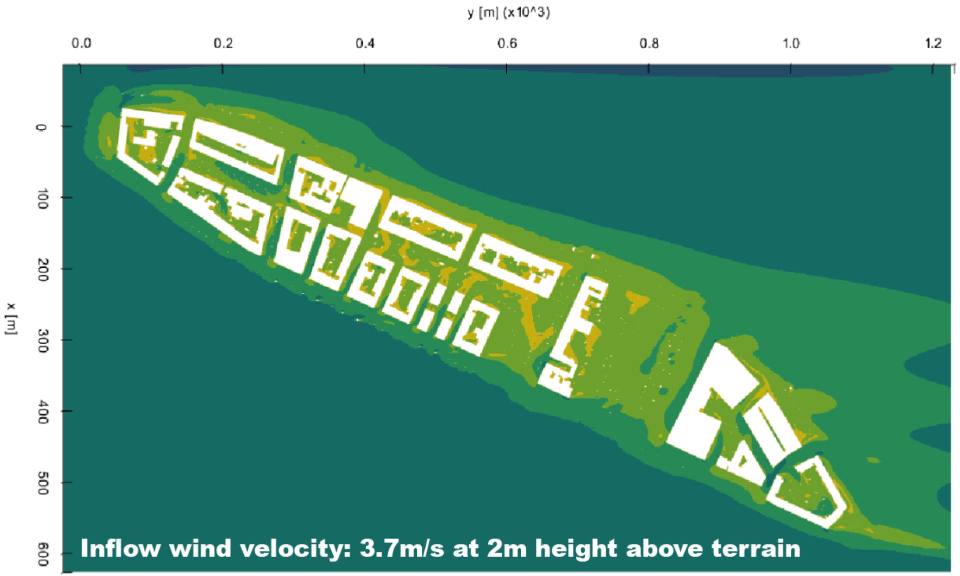


Realistic urban geometry: pedestrian wind comfort classification

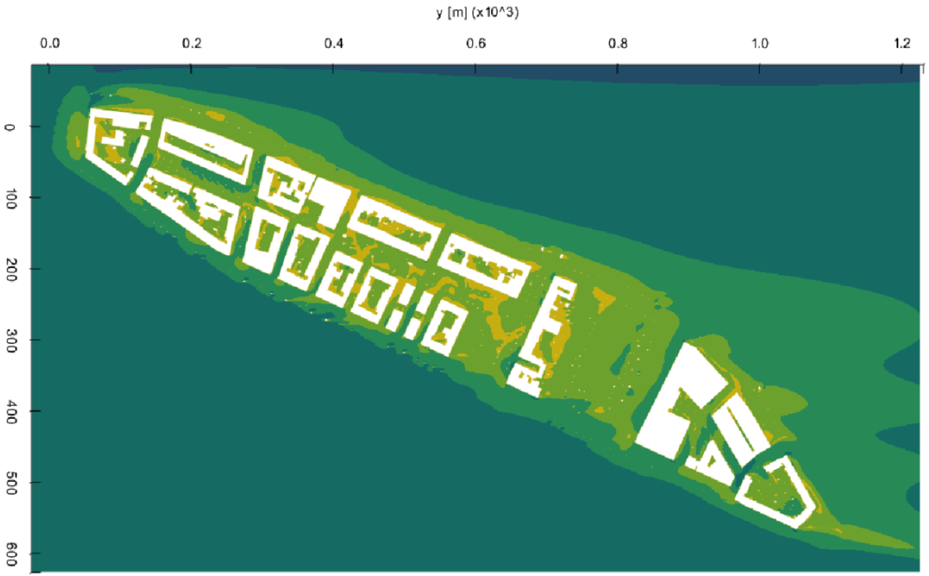


Category	*Description*	*Mean and GEM wind speed at 1.75 m height (m/s)*	*Effect*	*Acceptable activities*
A	Calm	0.0–0.1		Frequent outdoor sitting use, e.g. restaurant, café.
B	Light air	0.2–1.0	No noticeable wind	
C	Light breeze	1.1–2.3	Wind felt on face;	
D	Gentle breeze	2.4–3.8	Hair disturbed, clothing flaps, newspaper difficult to read;	Occasional outdoor seating, e.g. general public outdoor spaces, balconies and terraces intended for occasional use, etc.
E	Moderate breeze	3.9–5.5	Raises dust and loose paper, hair disarranged;	Entrances, bus stops, covered walkways or passageways beneath buildings.
F	Fresh breeze	5.6–7.5	Force of wind felt on body, danger of stumbling when entering a windy zone;	External pavements, walkways
G	Strong breeze	7.6–9.7	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forwards walking force, wind noise on ears unpleasant;	Not comfortable for regular pedestrian access

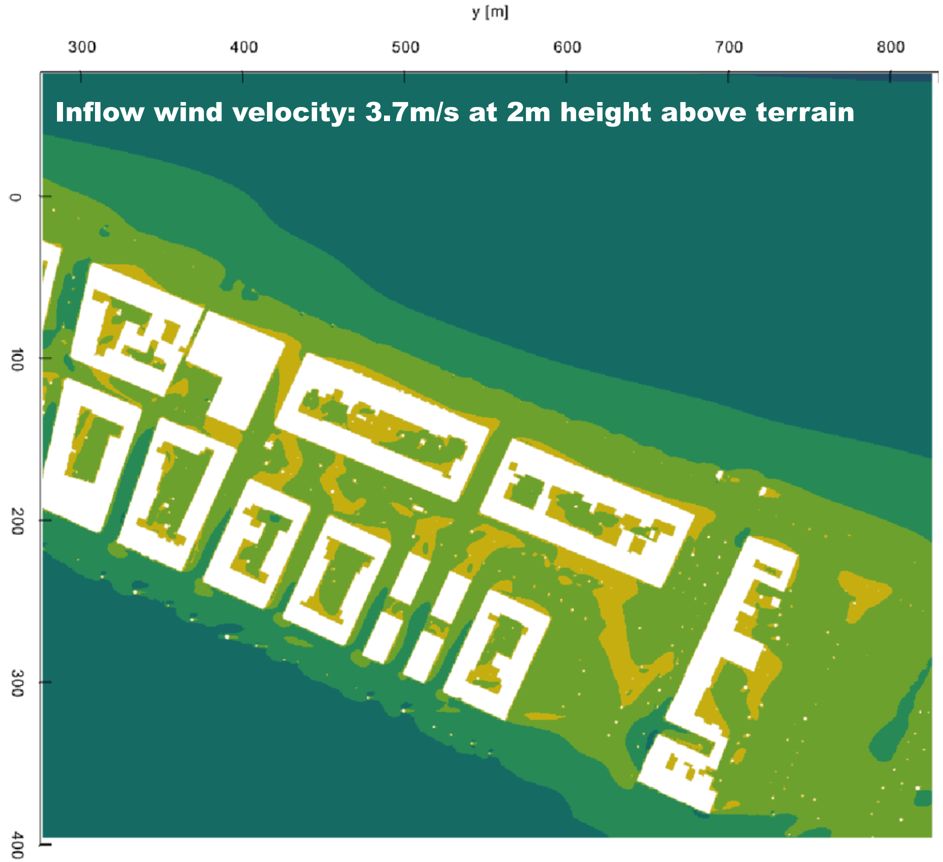
Case 22: LoD2 tree models



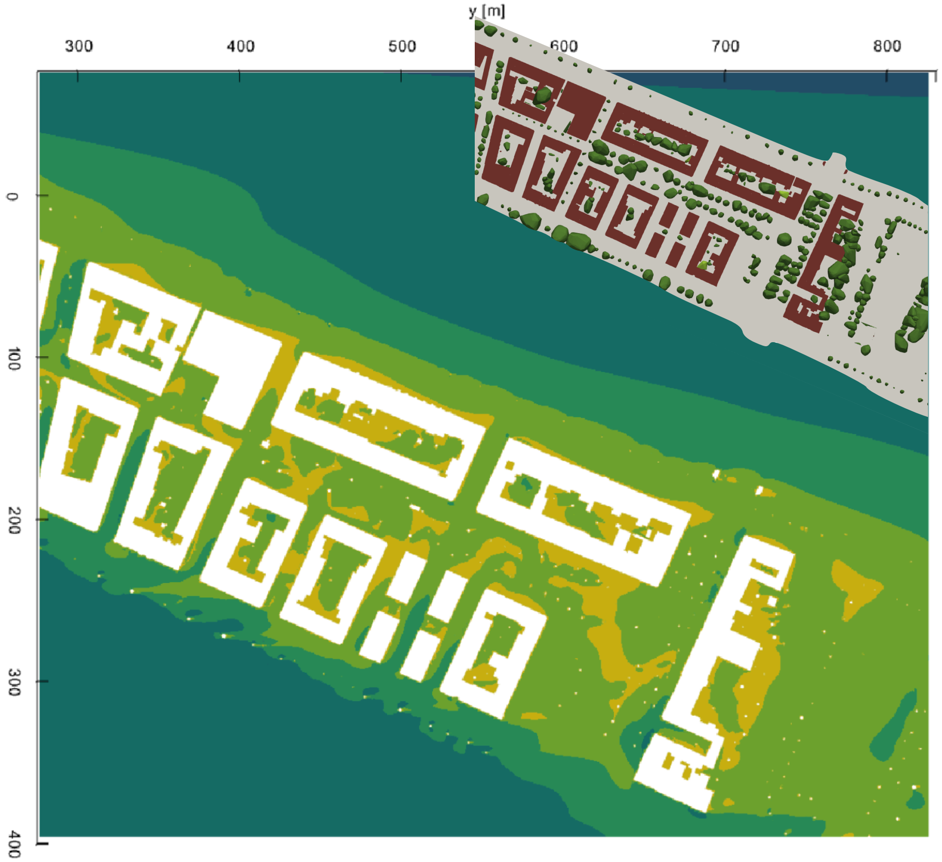
Case 23: LoD3 tree models

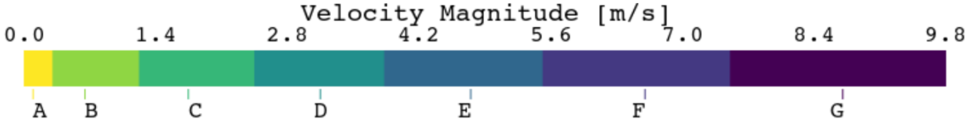


Case 22: LoD2 tree models



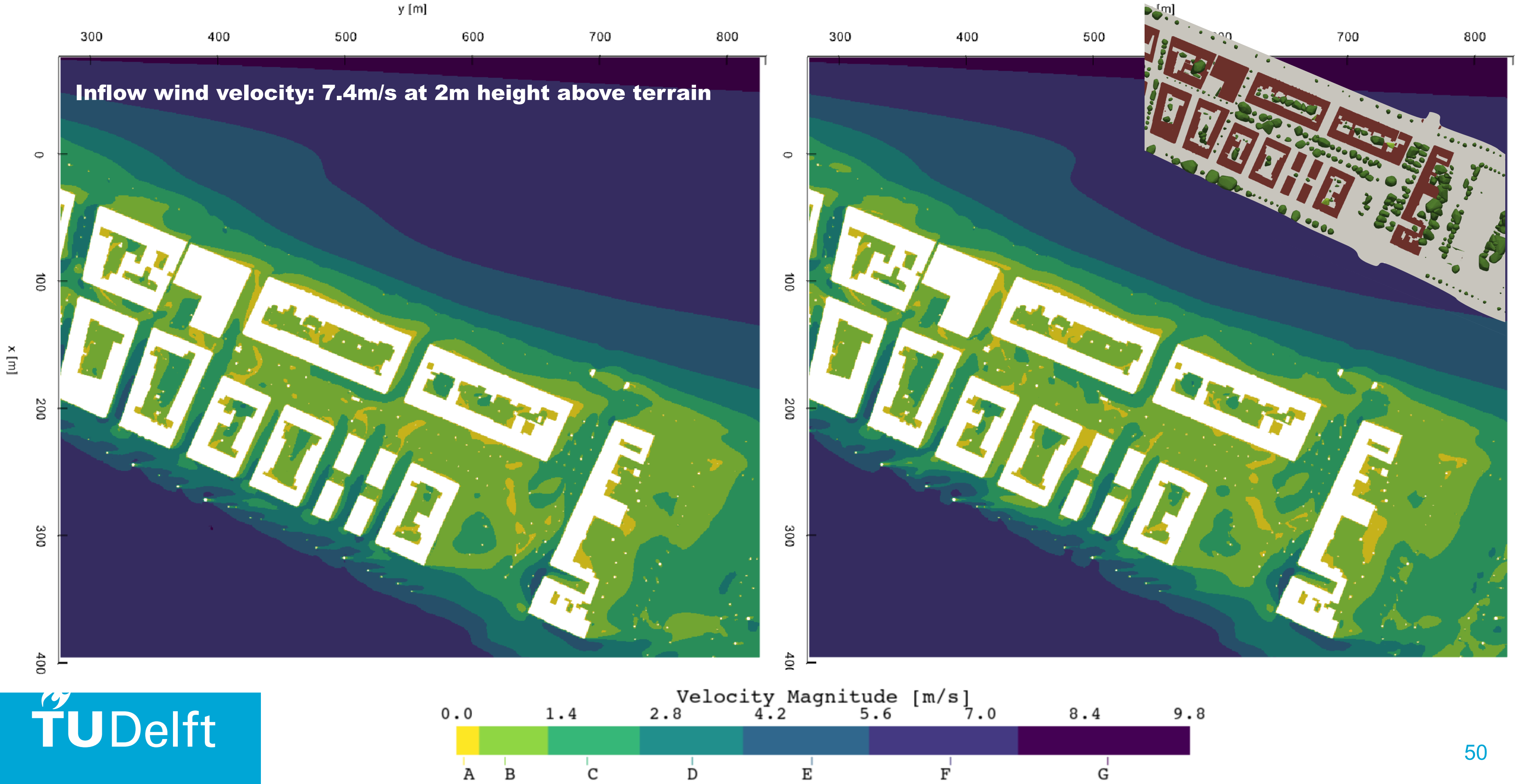
Case 23: LoD3 tree models



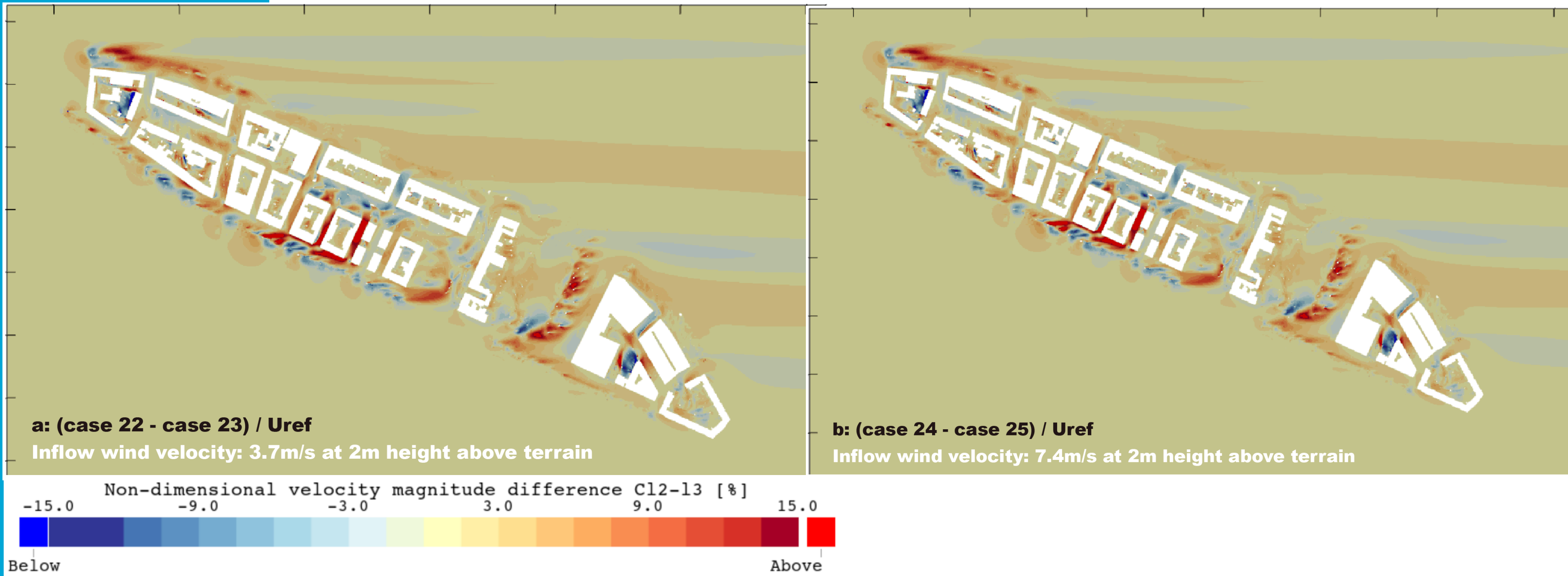


Case 24: LoD2 tree models

Case 25: LoD3 tree models



Realistic urban geometry: $C_{l2\text{-}l3}$



- Increasing the inflow velocity does not change the impact of tree LoDs on wind.
- The velocity magnitude differences between the LoD2 case and the LoD3 case is rather limited in most areas, with maximum differences in the order of 0.5 m/s. Thus, for a larger urban area like the Noordereiland, it may be good enough to have the LoD2 tree model for wind environment studies.

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Realistic urban geometry: $C_{l2\text{-}l3}$

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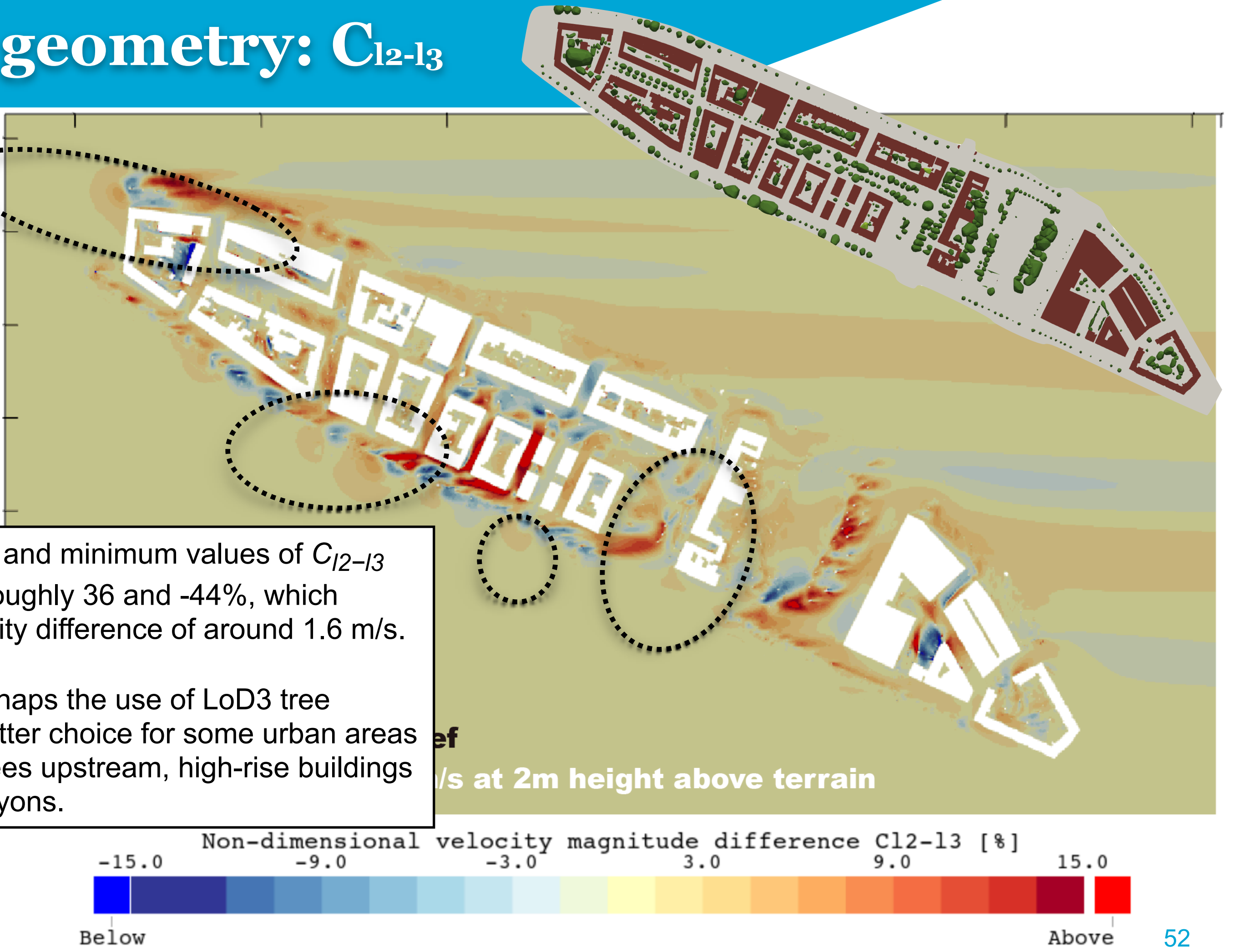

The maximum and minimum values of C_{l2-l3} can reach to roughly 36 and -44%, which means a velocity difference of around 1.6 m/s.

Therefore, perhaps the use of LoD3 tree models is a better choice for some urban areas with denser trees upstream, high-rise buildings and street canyons.

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Conclusions

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The main research question for this thesis was:

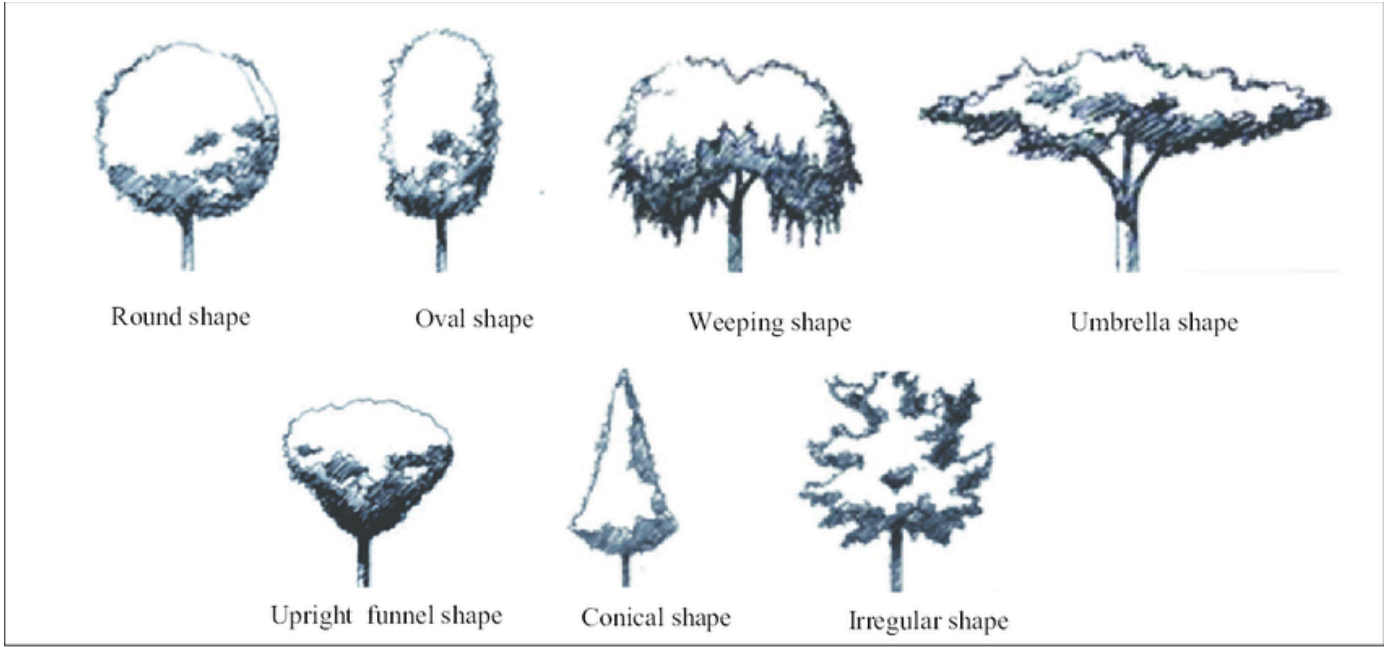
What is the impact of tree topology modelling for urban flow simulations?

1. Different tree modeling approaches and tree LoDs lead to very diverse wind patterns.
   - the implicit tree models always allow some of the wind flow into the porous cells.
   - the velocity magnitude differences between the LoD2 cases and the LoD3 cases is rather limited for the idealized street canyon and realistic urban geometry test cases simulated in this thesis.
2. Differences in tree shapes, LAD values and wind directions do change the effects of tree modeling approaches and tree LoDs.
   - for a given measurement height, the average velocity magnitude of the cases using LoD2 tree models is faster or slower than that of the cases using LoD3 tree models, depending not only on the tree shapes, but also on LAD values and wind direction.
   - It is conceivable from the data trend that the degree of changing of C_{l2-l3} values will continue to decrease as the LAD values increase, and may eventually reach stability.

Further improvements

Additional tree models with diverse shapes and heights can be tried for simulation.

we can get more knowledge about whether variations in tree features such as height, width, or canopy shape result in different characteristics of velocity, C_{ex-im}, C_{l2-l3}, pedestrian wind comfort.



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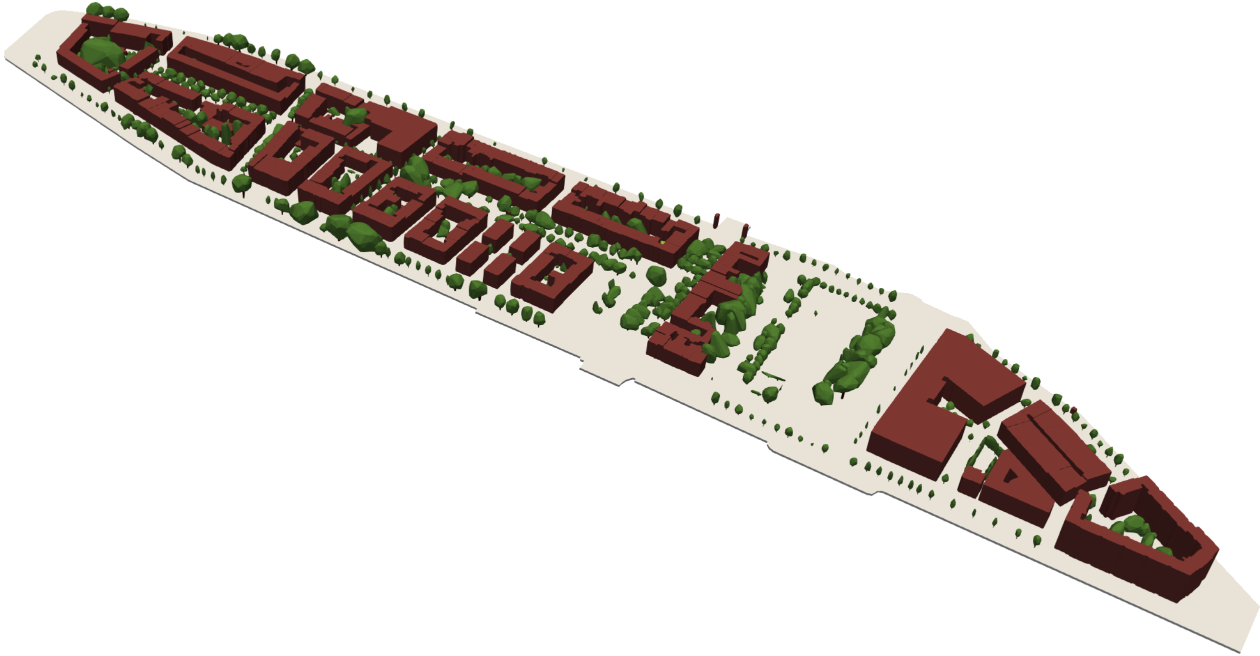
Further improvements

Improve the 3D models of the realistic urban geometry cases.

in order to save time, I simplified the 3D models of the realistic urban geometry cases. This may led to a relatively high discrepancy between the analysis results of this thesis and the real situation.



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Further improvements

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Besides wind velocity magnitude, cases can also be compared in terms of turbulent kinetic energy. This may further support some conclusions of this thesis.

Further studies can use the results of this thesis as a reference to investigate the effect of tree topology on gas/heat diffusion and numerous other concerns.

CHEERS!