CFD, sensitivity analysis and optimisation to promote the formation of dunes

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Co-reader: Stelios Vitalis
Delegate: Yawei Chen

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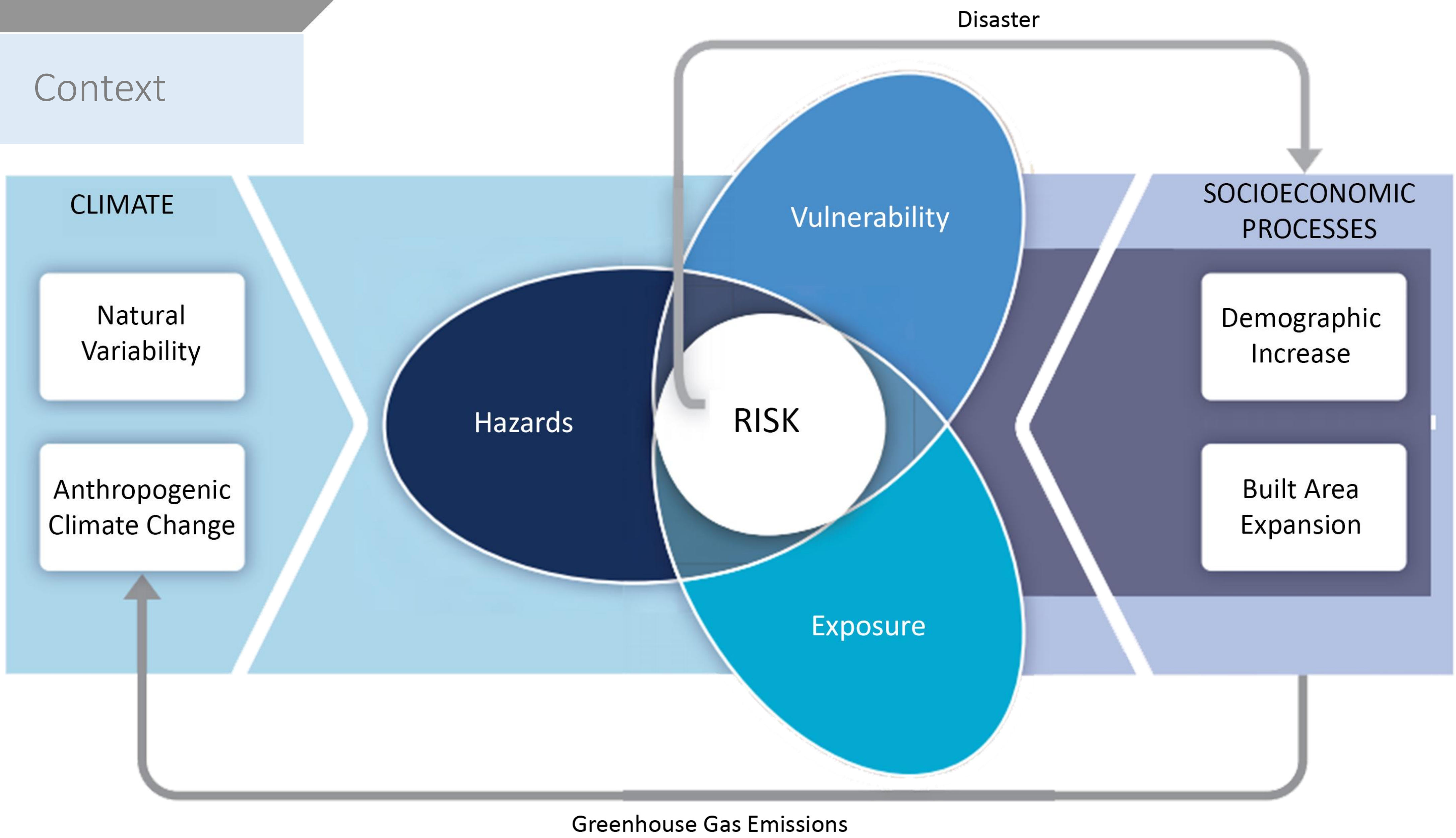
Overview

Introduction
- Context
- Research questions

Process
- Input
- CFD
- Sediment mobility
- Sensitivity Analysis
- Optimisation

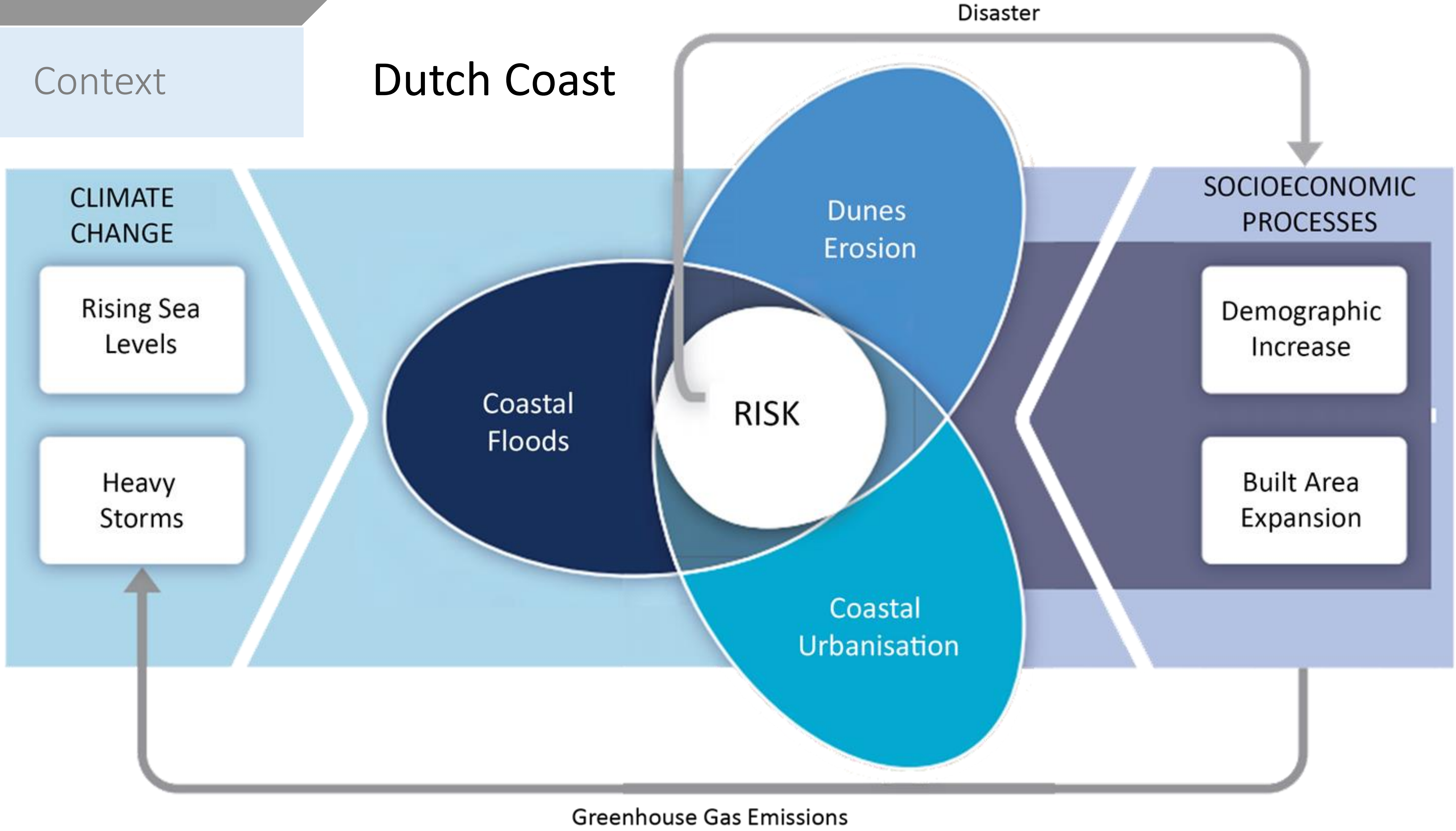
Trend results
- Discussion
- Design criteria conclusion

Conclusion
- Summary
- Limitations
- Recommendations



Source: adapted from Lavell et al. (2012)

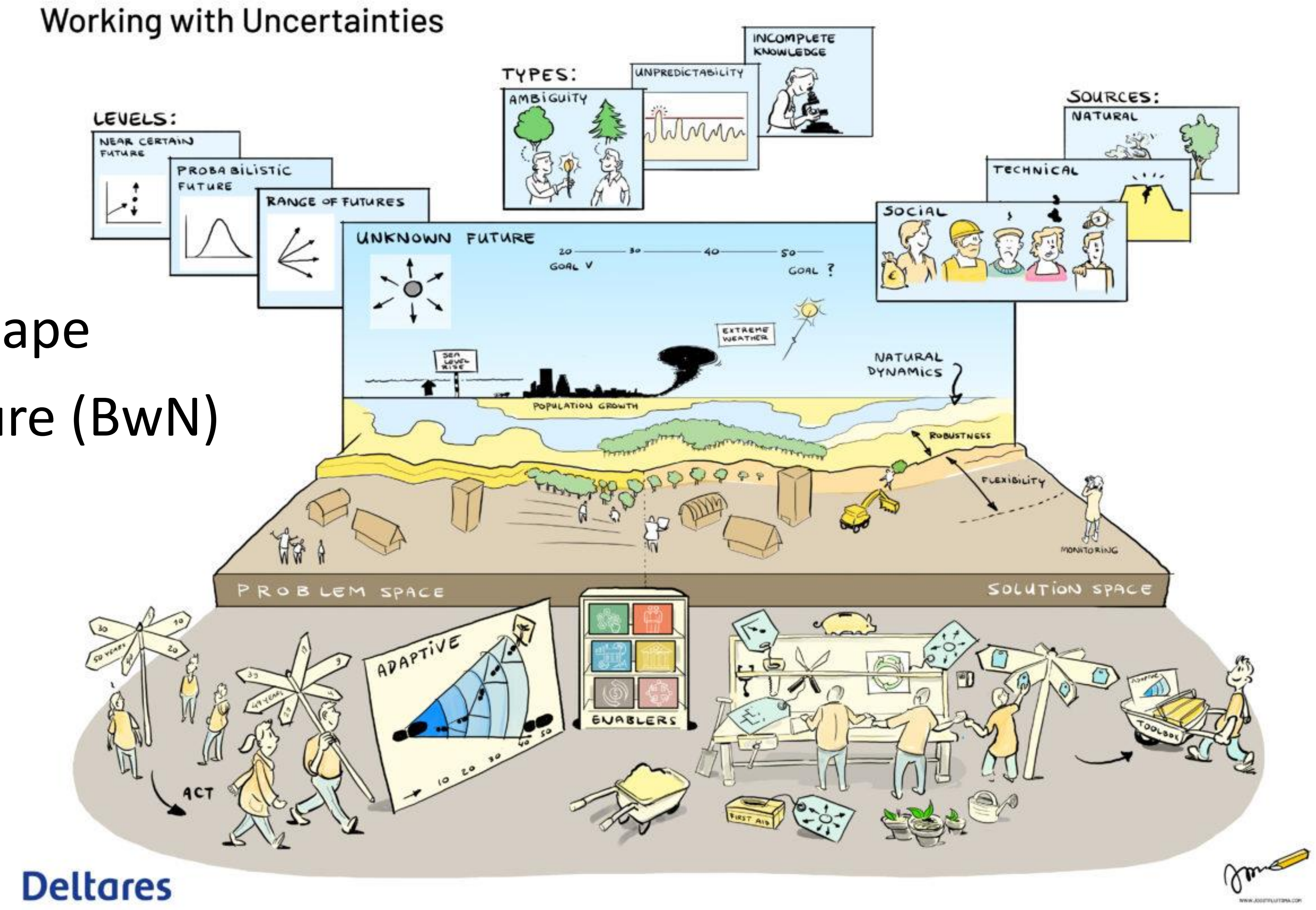
Dutch Coast



Source: adapted from Lavell et al. (2012)

Kustpact - Shorescape

Building with Nature (BwN)



Source: Building with Nature - EcoShape (2021).

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Main research question

Based on wind simulation, which beach house configuration best promotes widening of dunes?

Source: https://www.visitingthedutchcountryside.com/noord-holland/best-beaches-in-noord-holland-netherlands/

Sub-research questions

- Wind simulation:

How to set up a computational domain suitable for the scenarios to be tested?

- Housing configurations:

What are the parameters to define these house configurations?

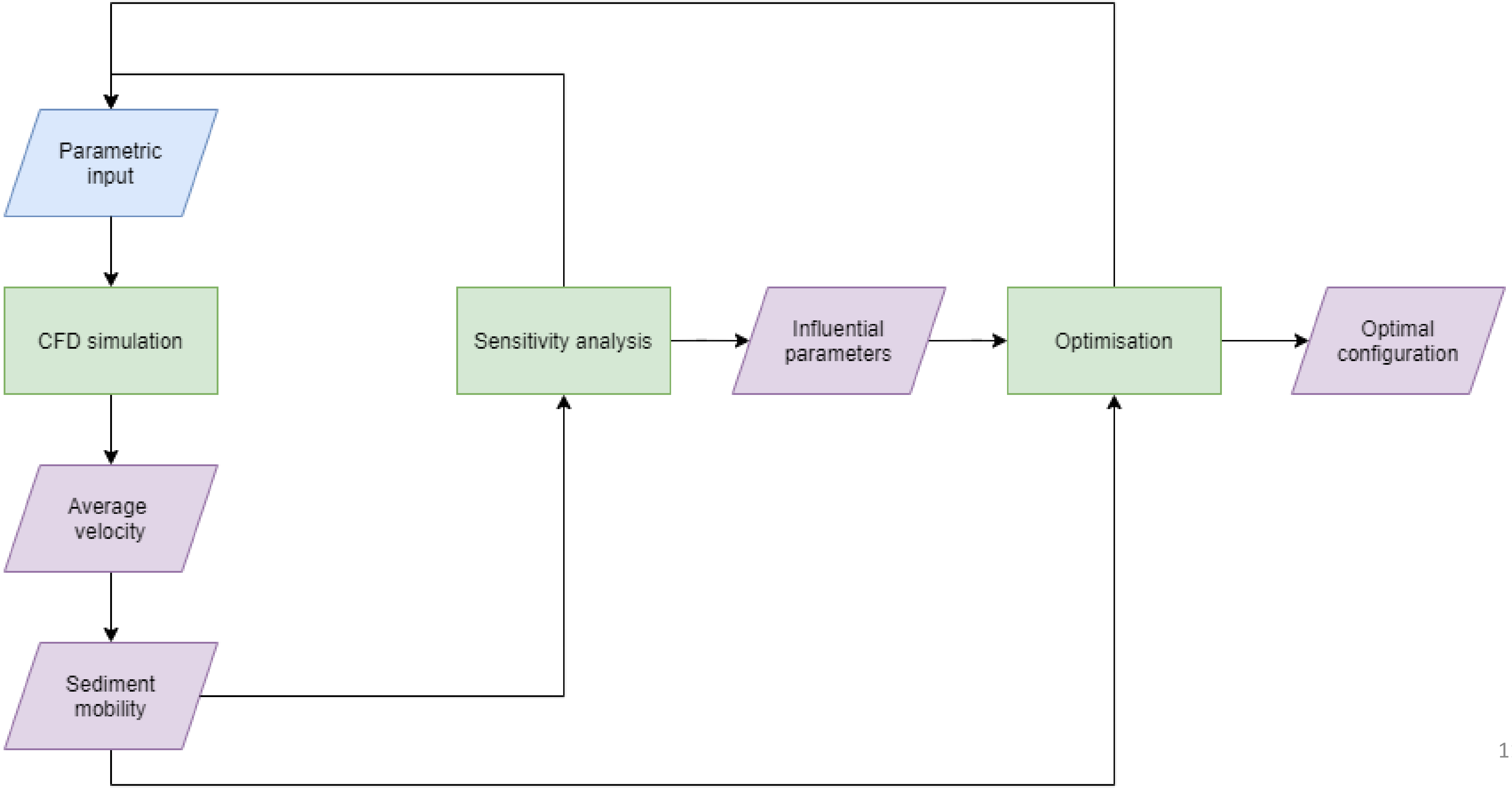
Which parameters are more influential on the formation of the dunes?

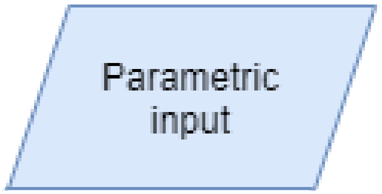
- Formation of dunes:

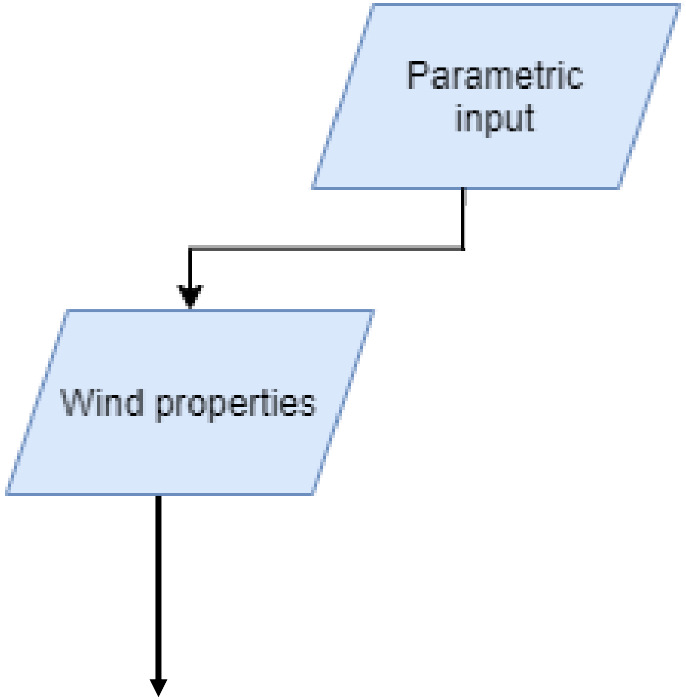
How to factor in the wind direction in the final configuration choice?

What are the indicators to evaluate the widening of the dunes?

Workflow


Parametric input
CFD simulation
Average velocity
Sediment mobility
Sensitivity analysis
Influential parameters
Optimisation
Optimal configuration

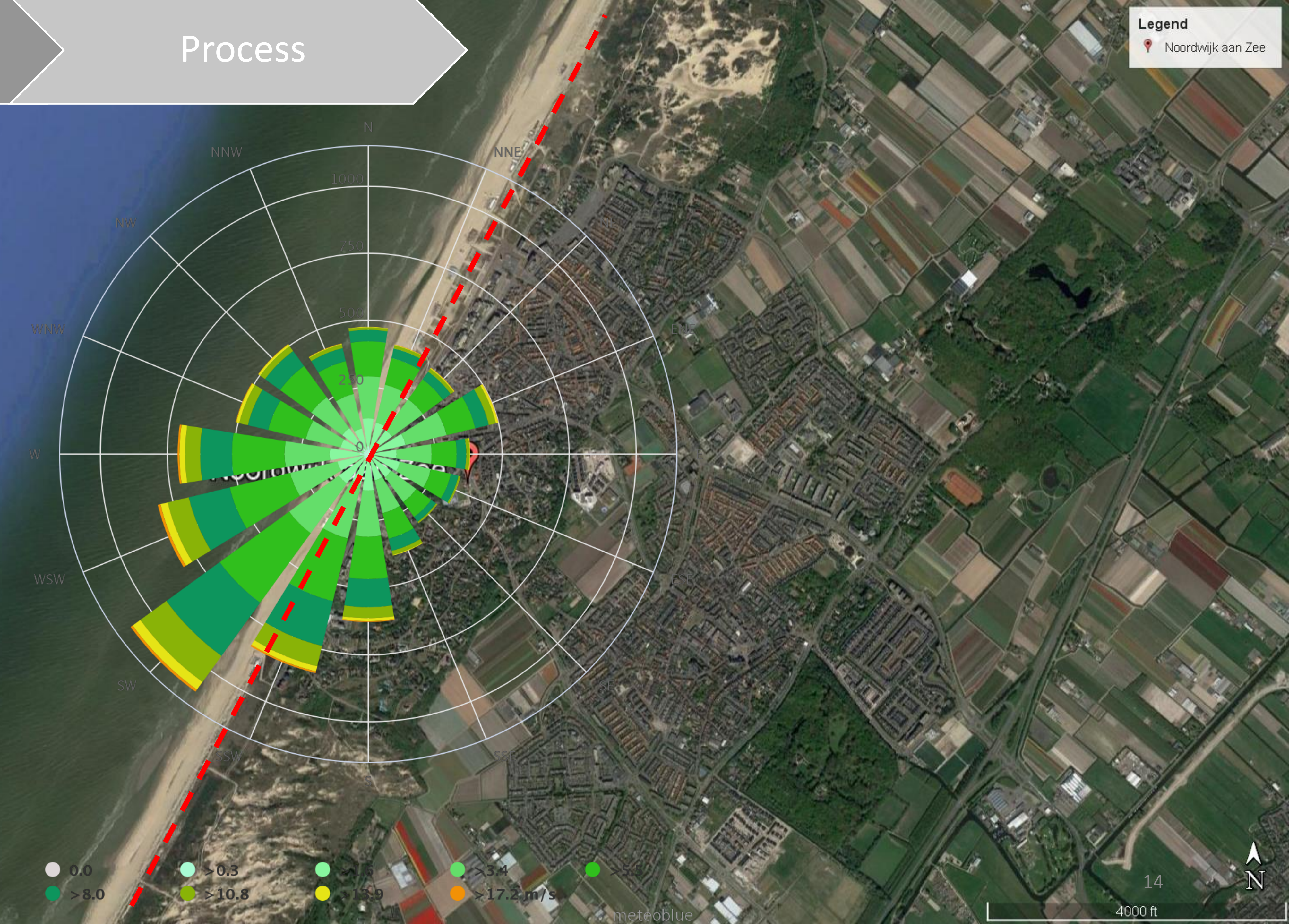

Parametric input



Depends on the case study area

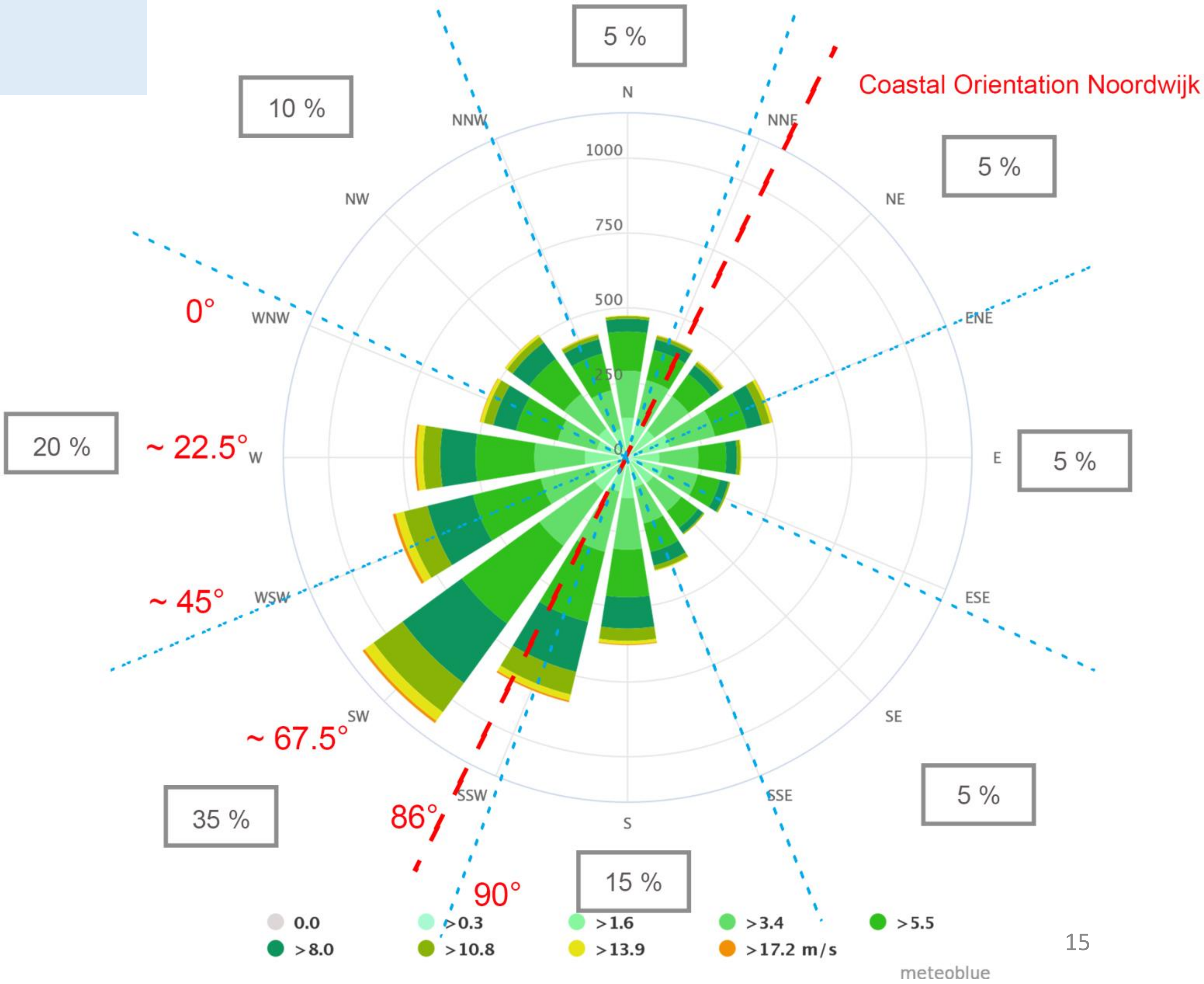
Area of study

Noordwijk



Wind properties

- Average velocity: U = 4.9 m/s
- Wind direction: w = 60°
- Wind occurrence percentage:



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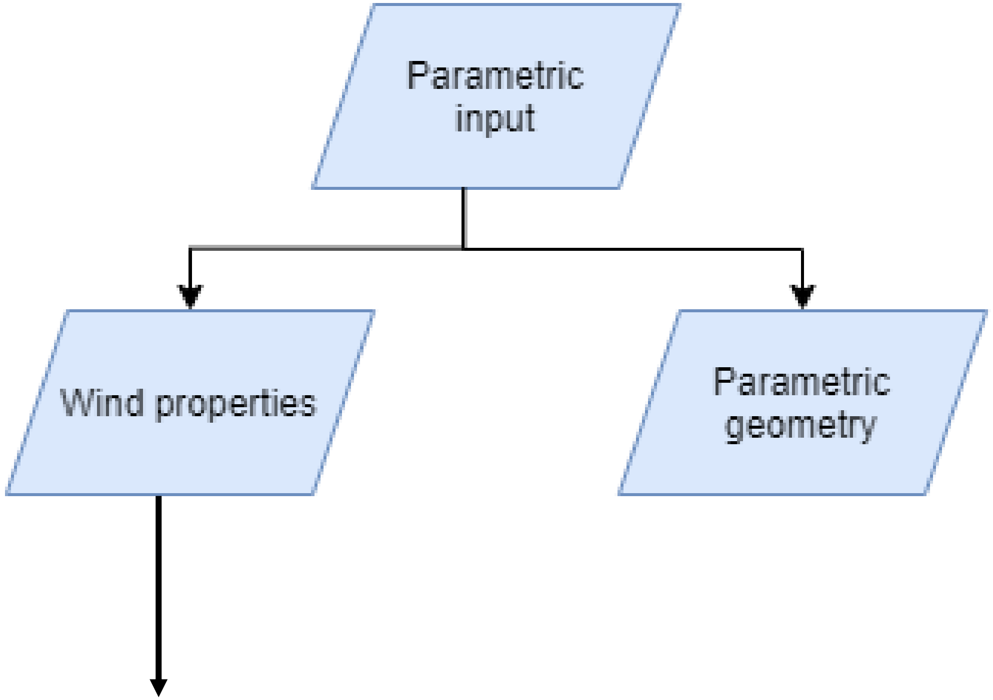

Depends on the case study area

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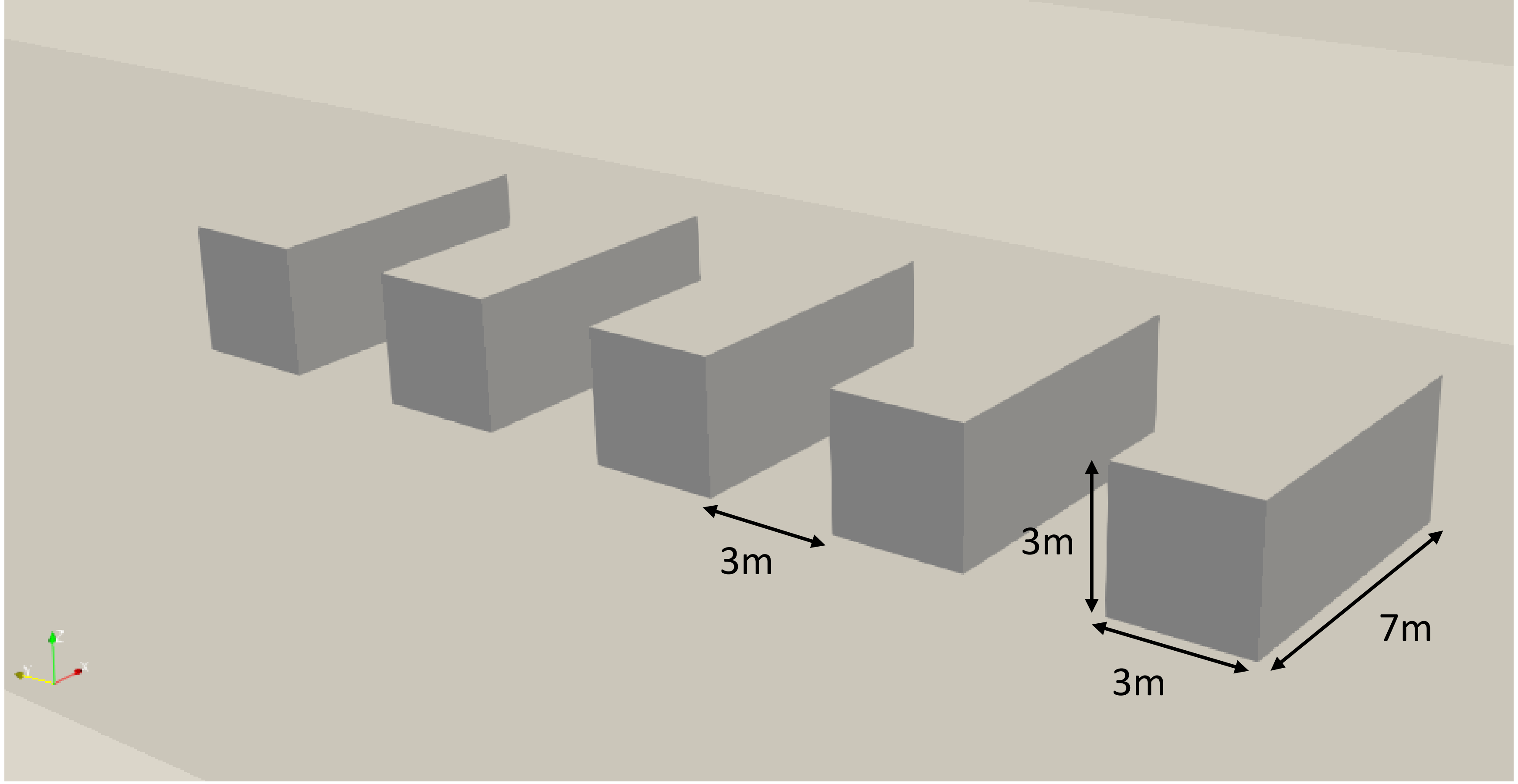
Parametric geometry

Constant parameters

- Length of house: 7 m
- Width of house: 3 m
- Height of house: 3 m
- Inter-distance between houses: 3 m

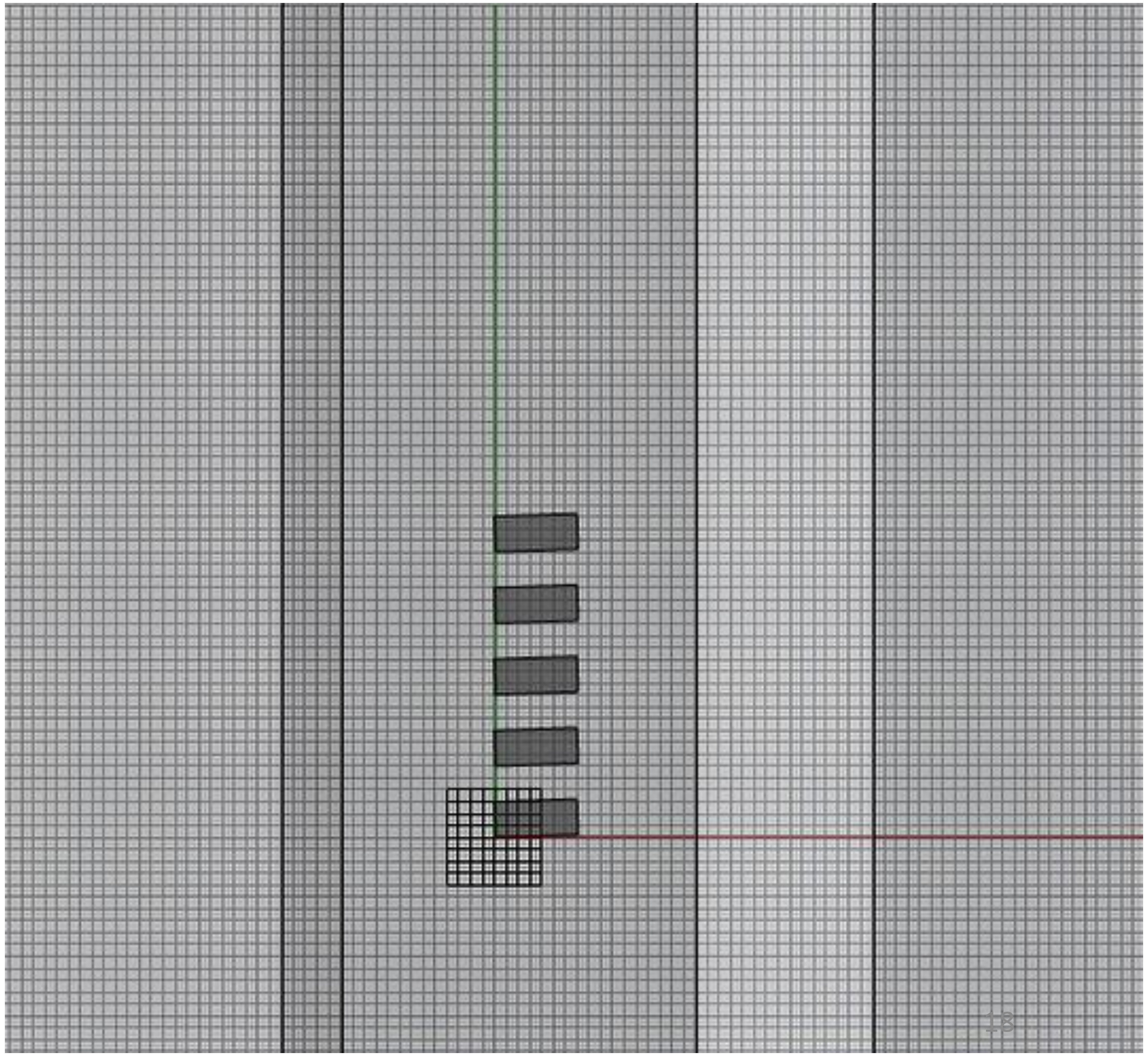


Parametric geometry

Variable parameters

- α: angle of each house relative to the shoreline

$0 \leq \alpha \leq 90$



Parametric geometry

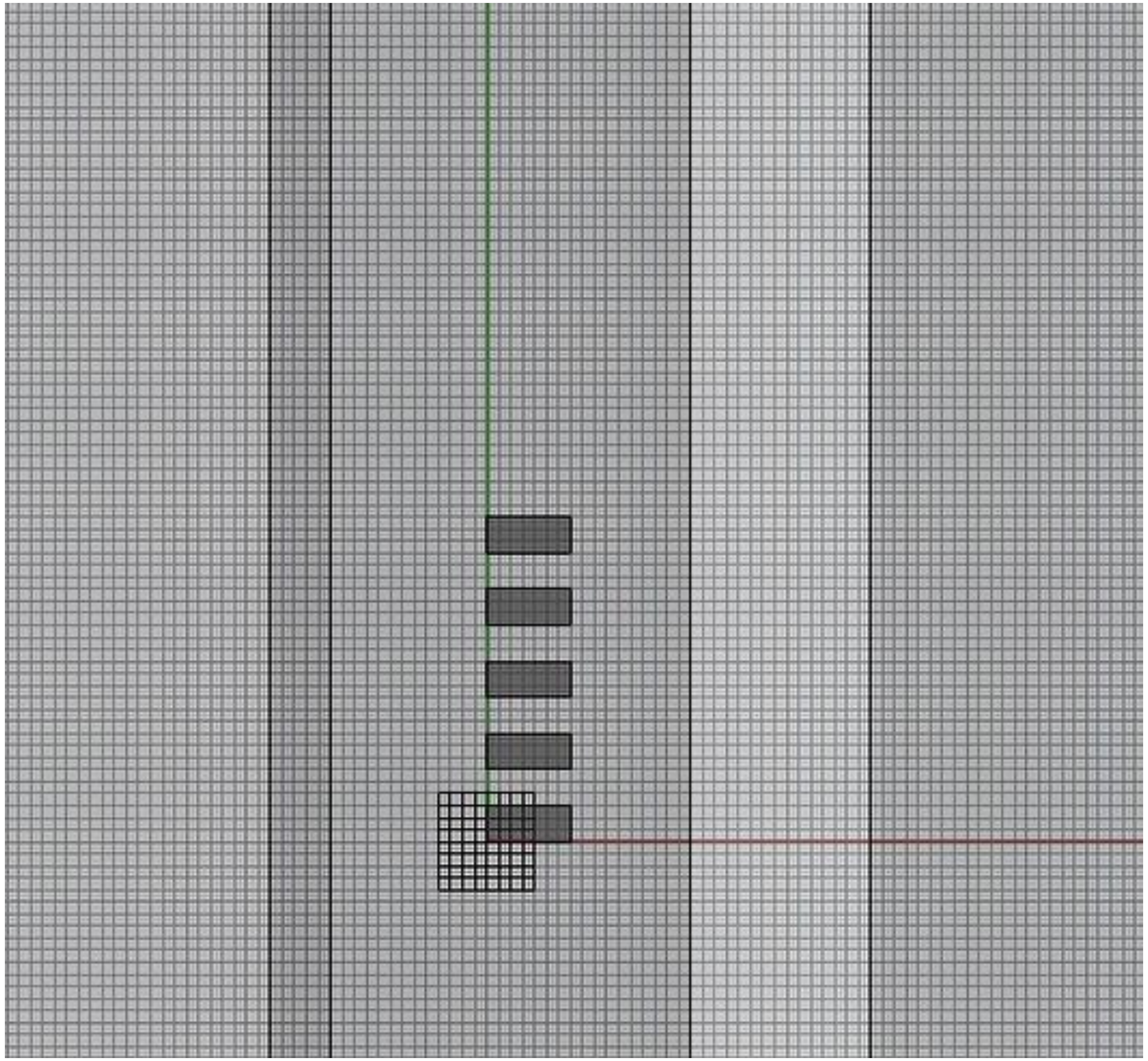
Variable parameters

- α: angle of each house relative to the shoreline

0 ≤ α ≤ 90

- ß: angle of the configuration relative to the shoreline

0 ≤ ß ≤ 90



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Parametric geometry

Variable parameters

- *α*: angle of each house relative to the shoreline

$0 \leq \alpha \leq 90$

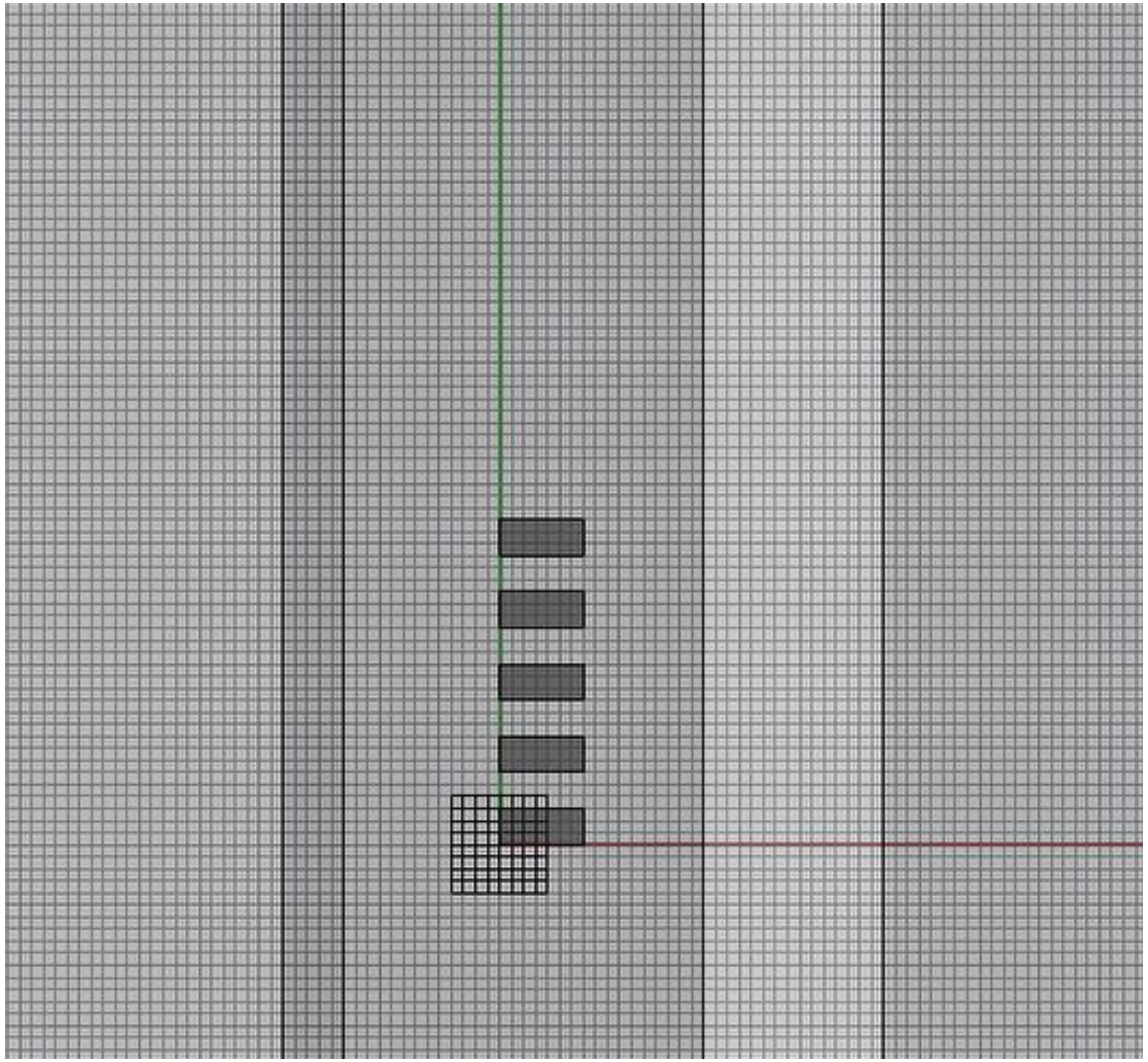
- *ß*: angle of the configuration relative to the shoreline

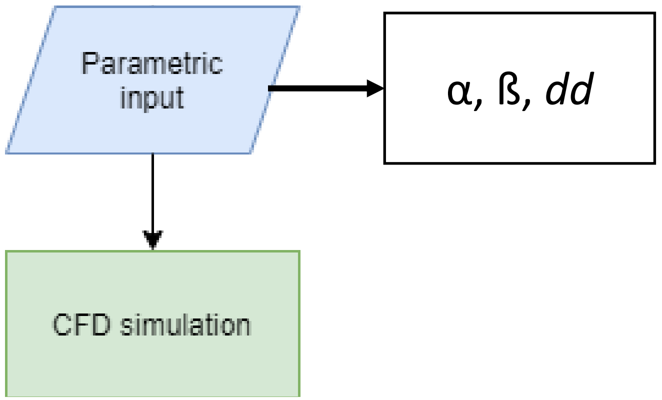
$0 \leq ß \leq 90$

- *dd*: distance to dunes

$1 \leq dd \leq 10$

→ 3D design space

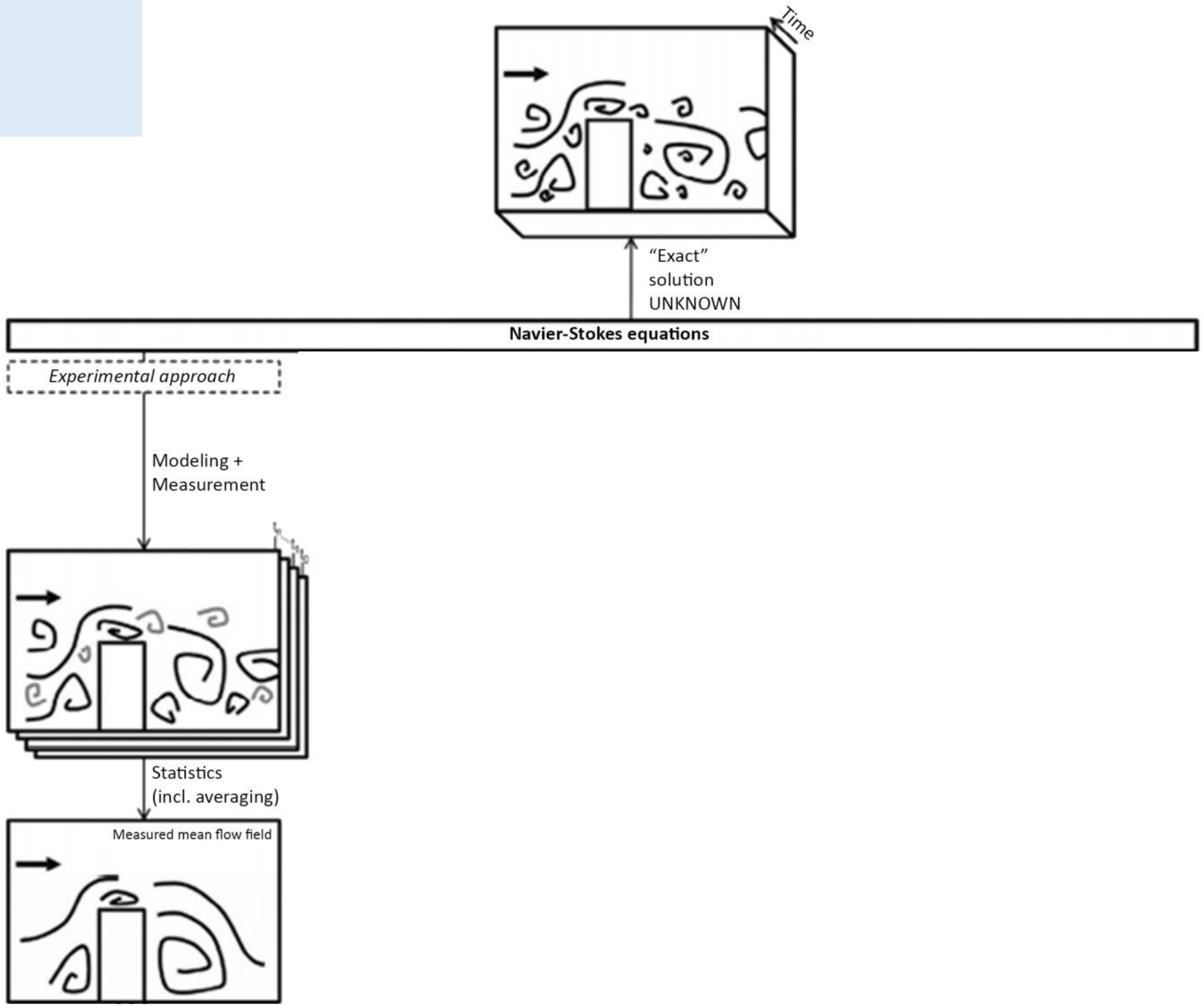



Parametric input
α, ß, dd
CFD simulation

Wind study approach

Source: Adapted from P. Gousseau’s diagram in Blocken (2018)

Wind study approach

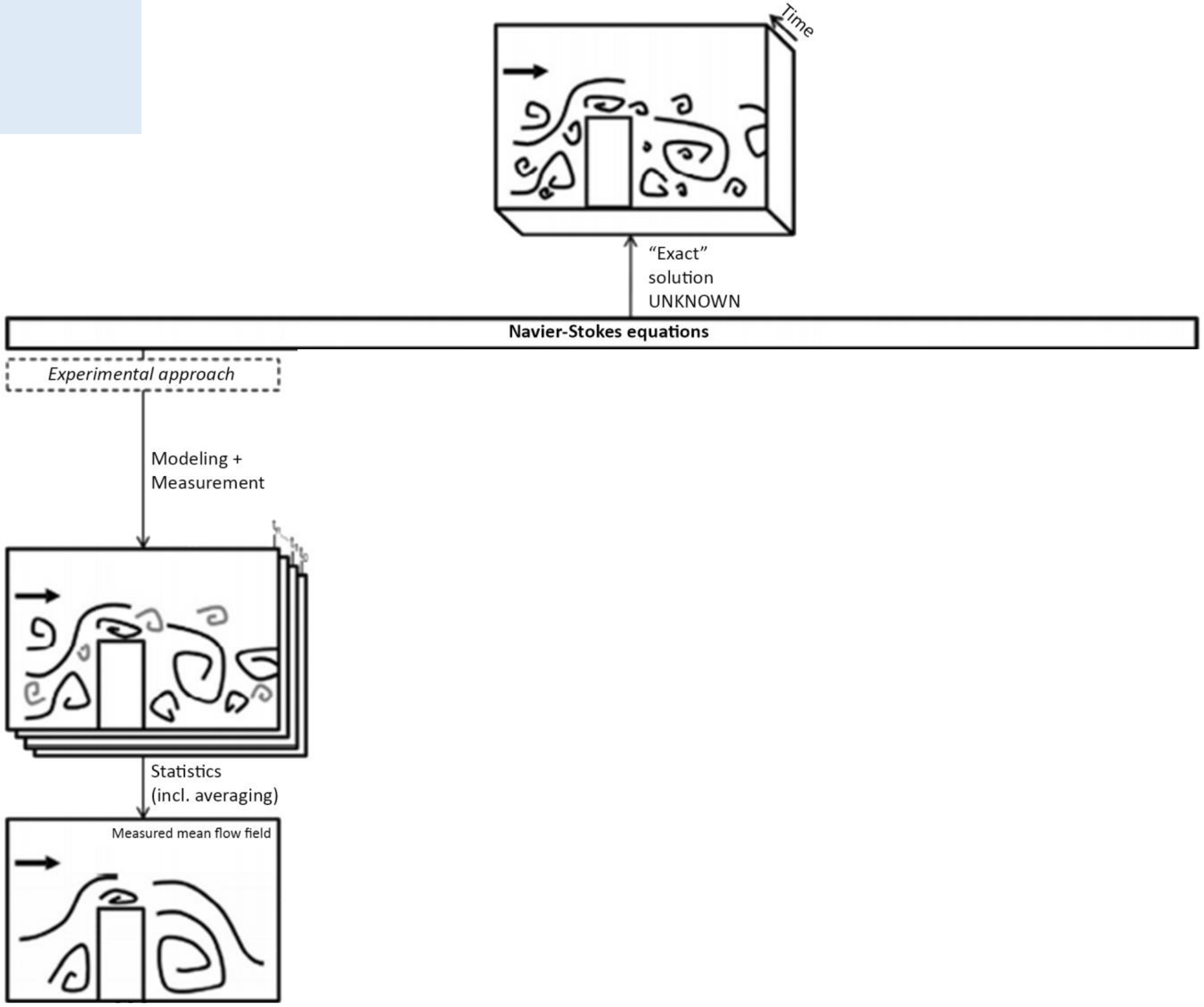


Source: Adapted from P. Gousseau's diagram in Blocken (2018)

Wind study approach

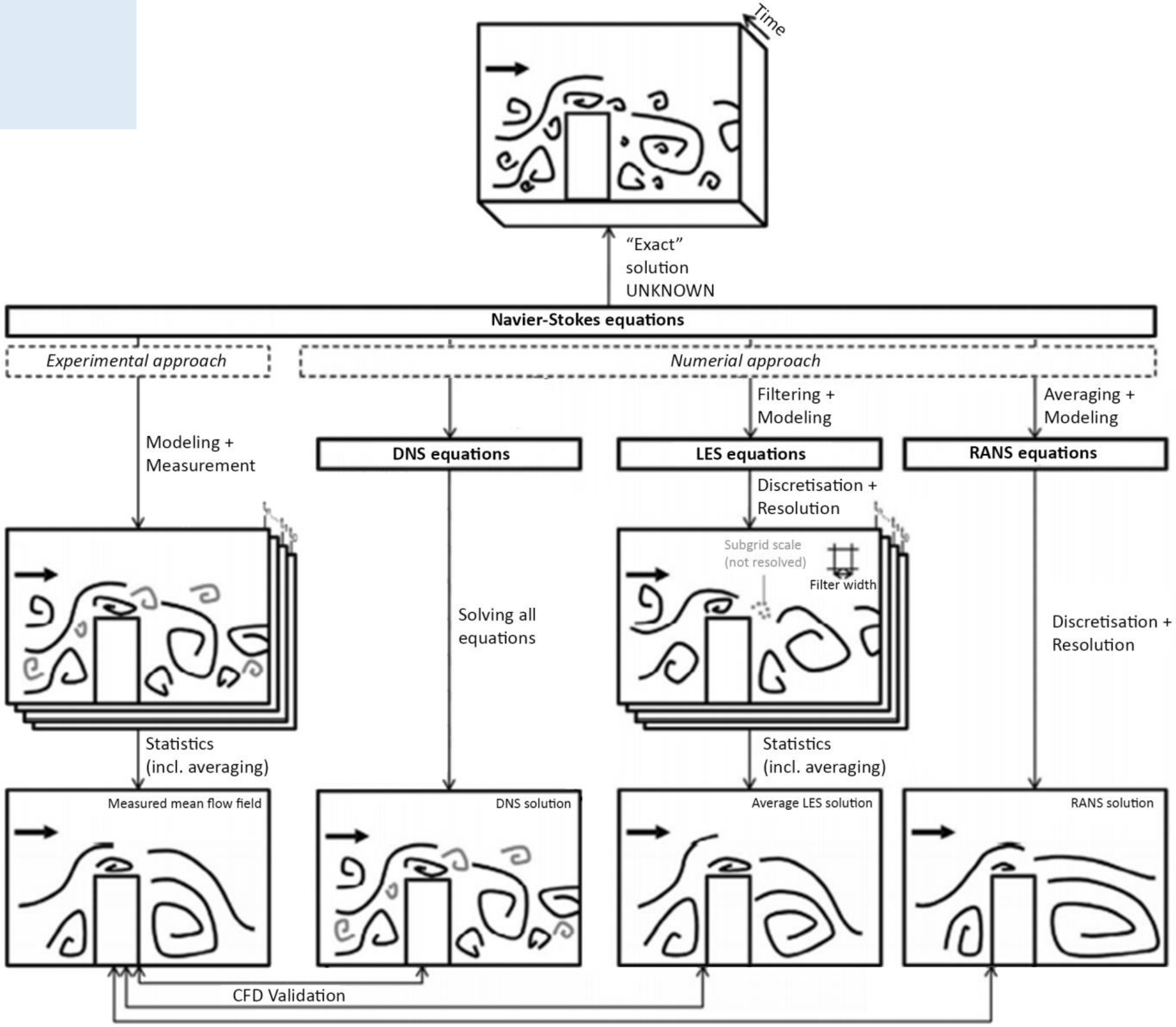
- Field measurements:
  - Not feasible to test a large number of configurations
  - No control over wind conditions

- Wind tunnel tests:
  - Takes time to test a large number of configurations
  - Difficulty to achieve dynamic similarity requirements



Source: Adapted from P. Gousseau's diagram in Blocken (2018)

Wind study approach



Source: Adapted from P. Gousseau's diagram in Blocken (2018)

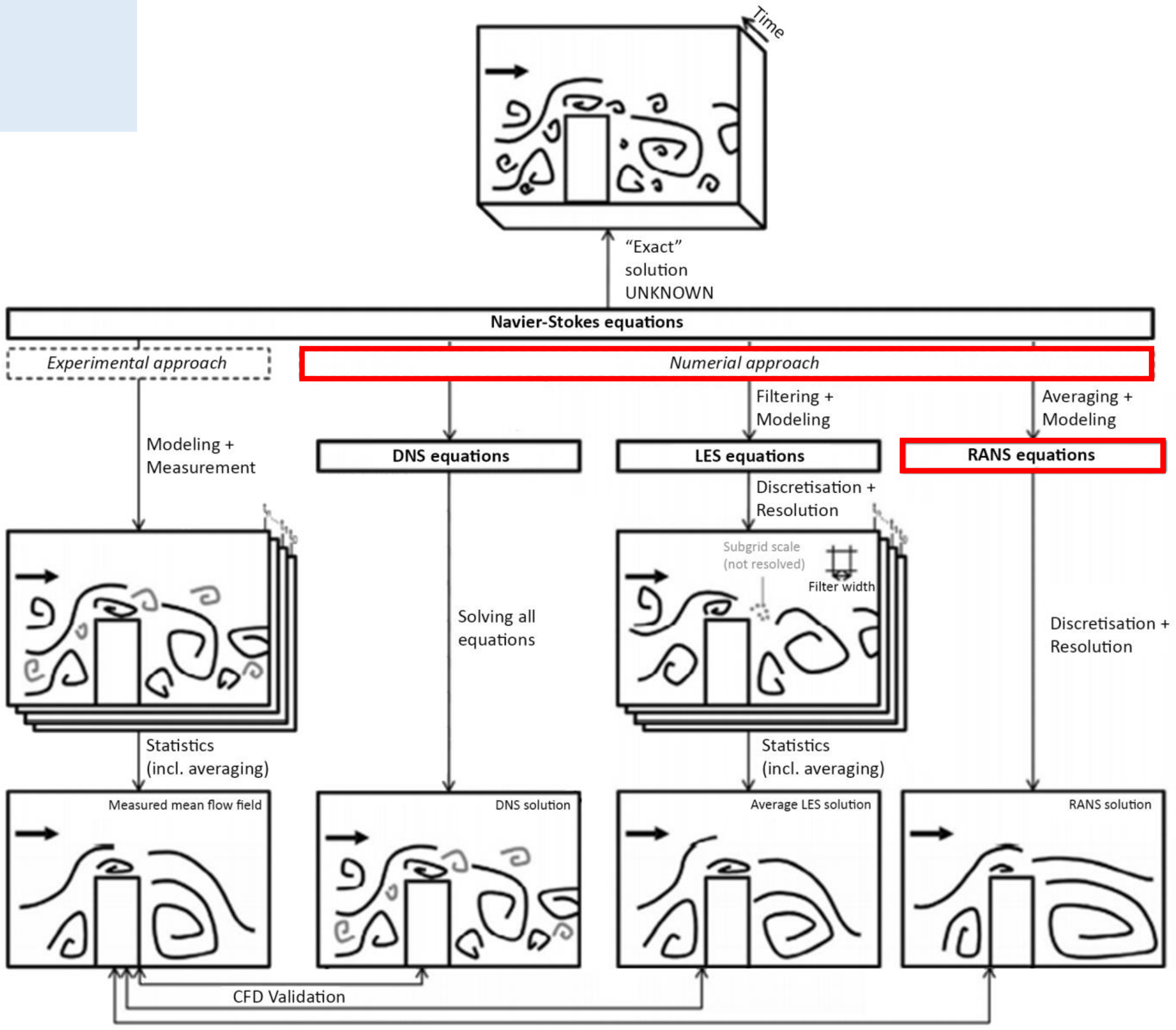
Wind study approach

↓

Reynolds-averaged Navier-Stokes (RANS)

↓

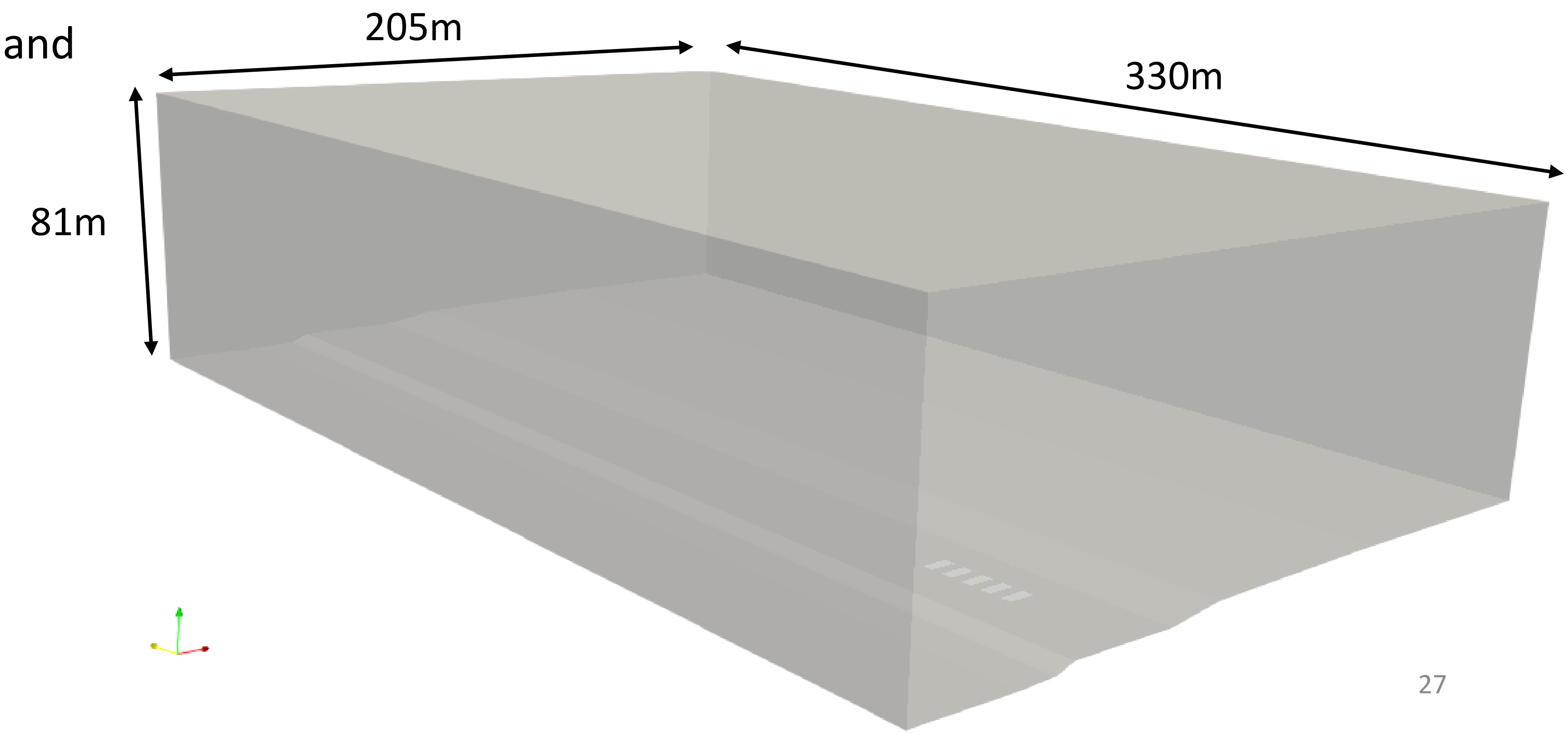
RNG k-epsilon model



Source: Adapted from P. Gousseau's diagram in Blocken (2018)

Computational domain setup

- Following blockage ratio conditions
- Respecting all configurations and South-West wind directions



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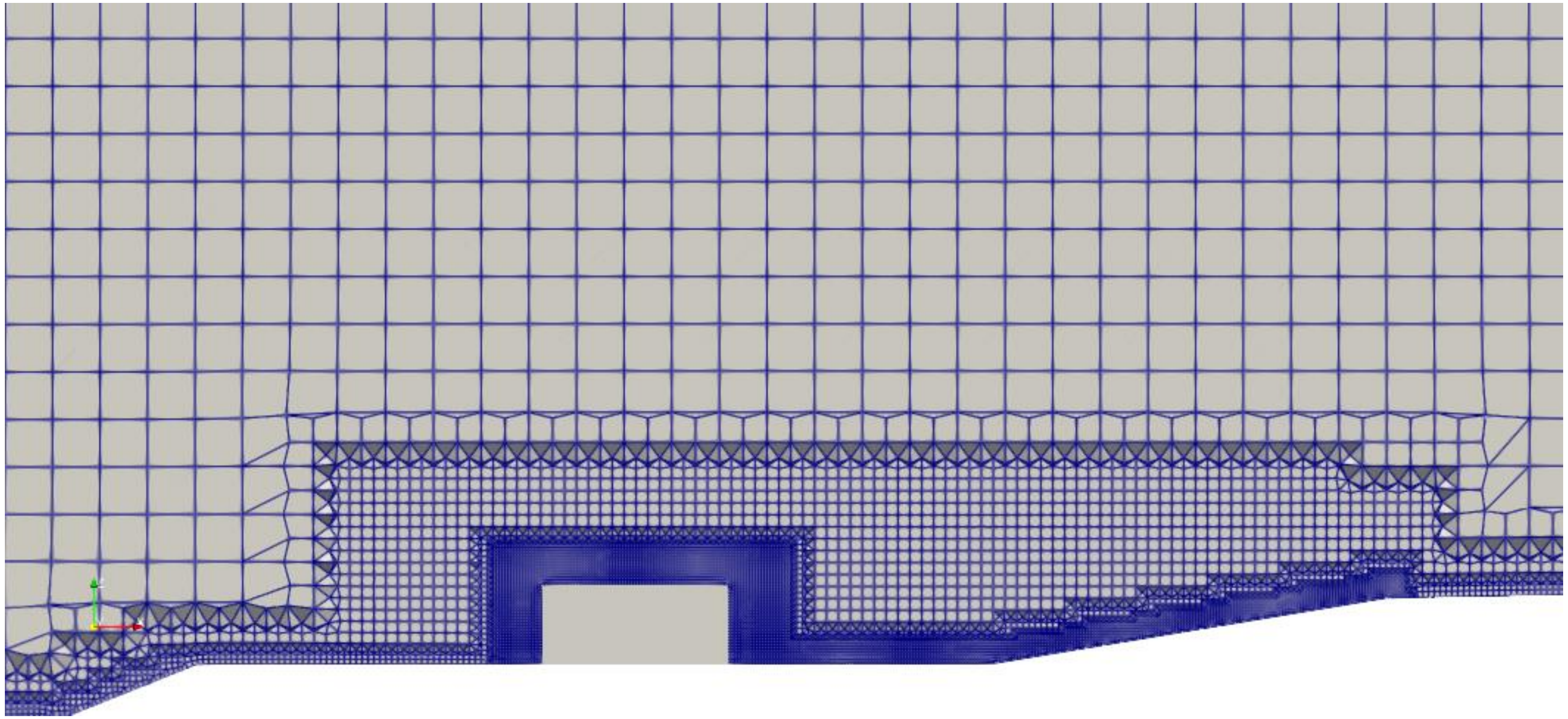
Mesh setup

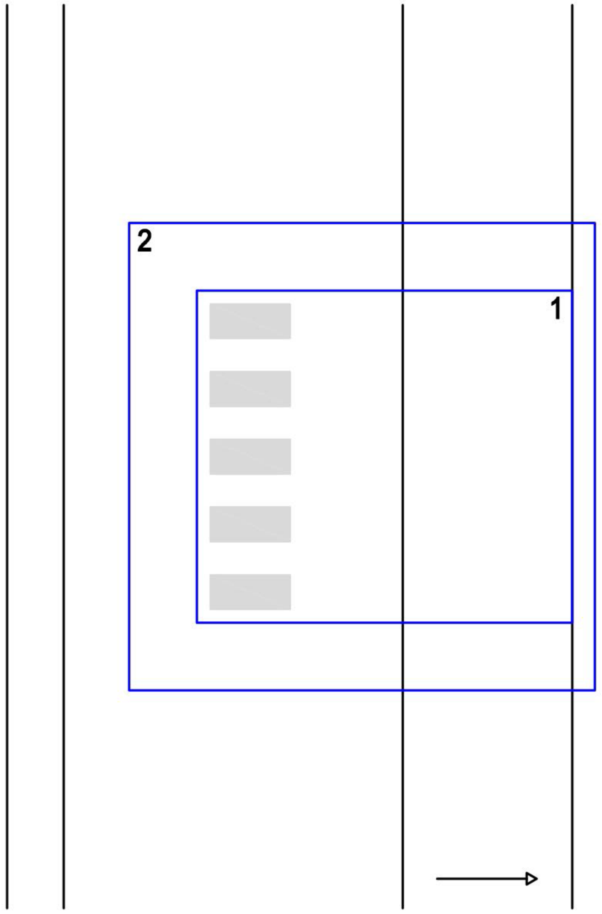
3 refinement areas:

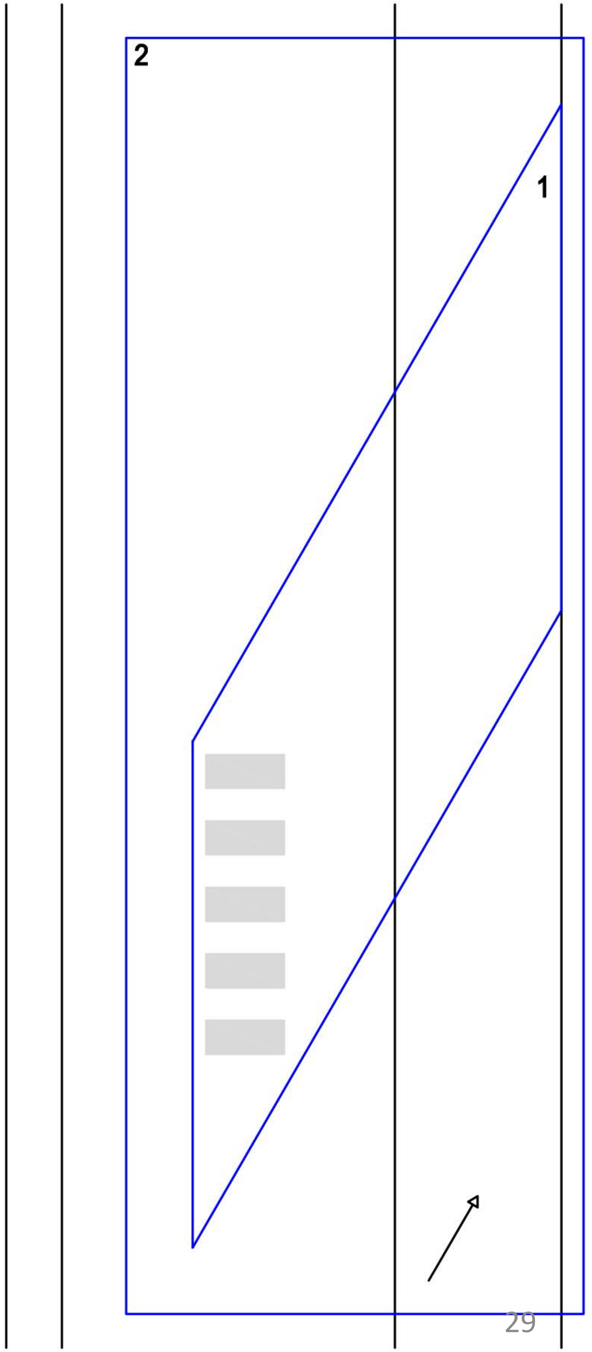
- Houses and immediate wake
- Buffer zone with the rest of the domain
- Terrain surface



Mesh setup

Refinement areas are built according to the wind direction, up until the top of the dune





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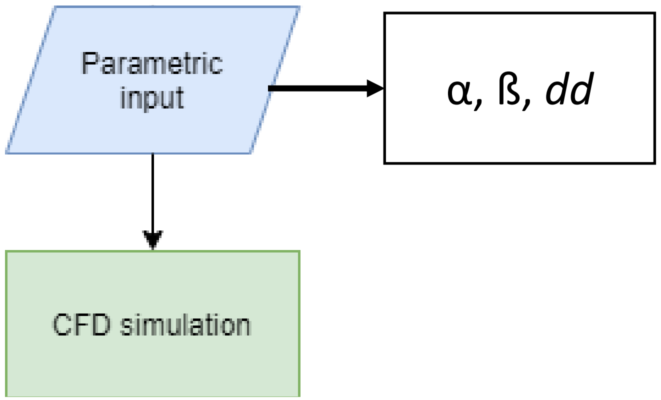
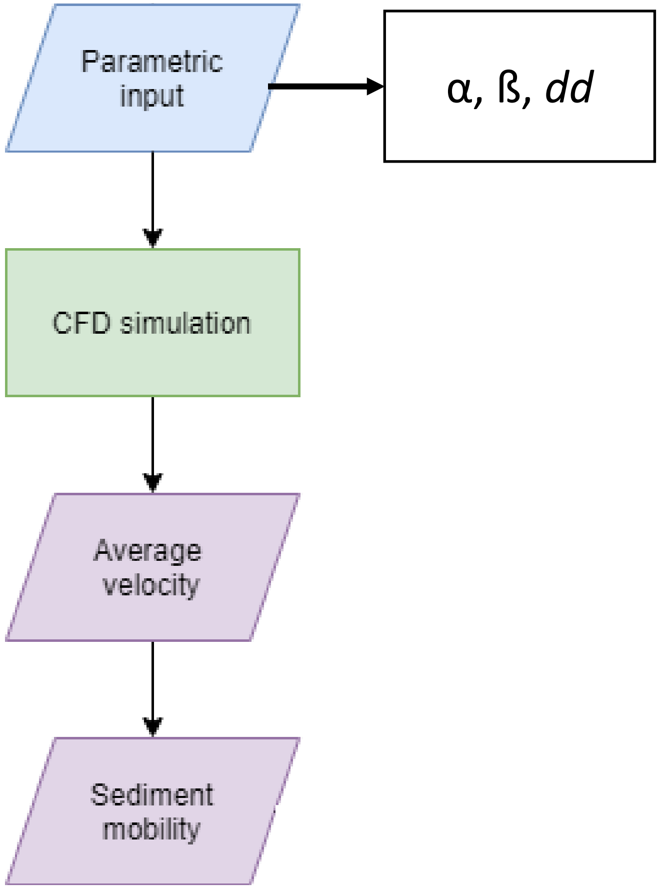
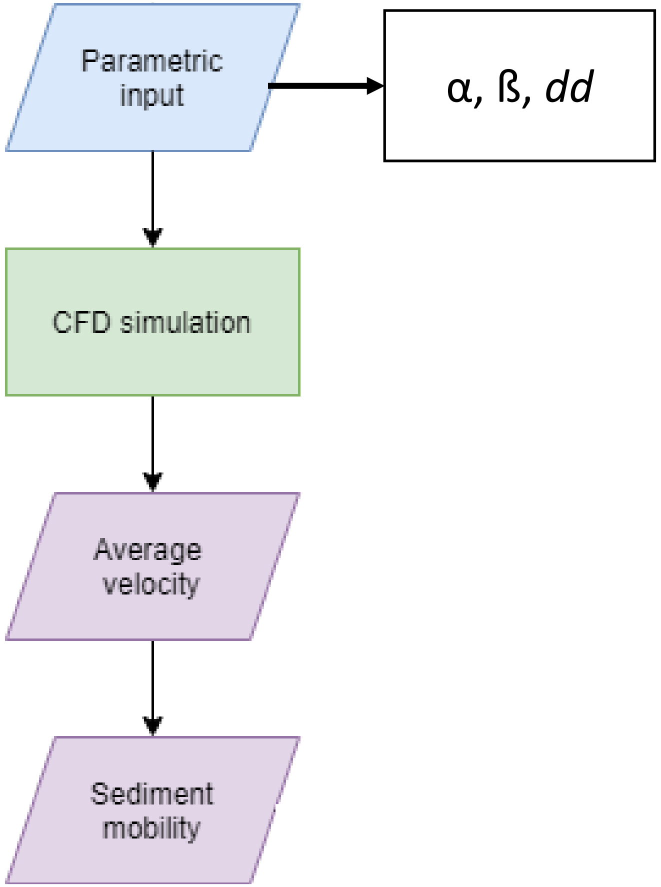
Workflow



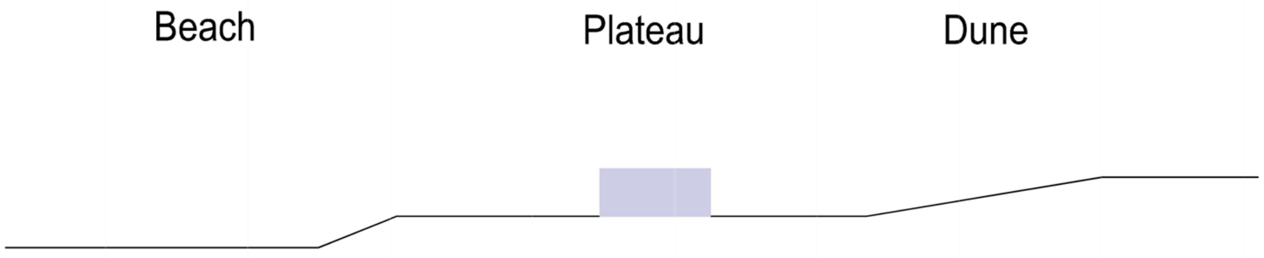
Workflow


Parametric input
α, ß, dd
CFD simulation
Average velocity
Sediment mobility

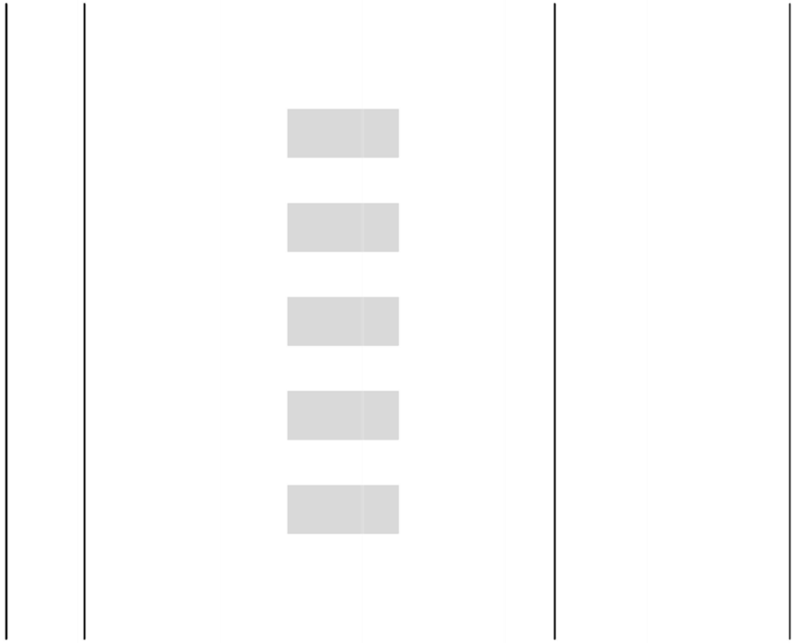


How to assess sediment mobility?

Cross-section



Plan view



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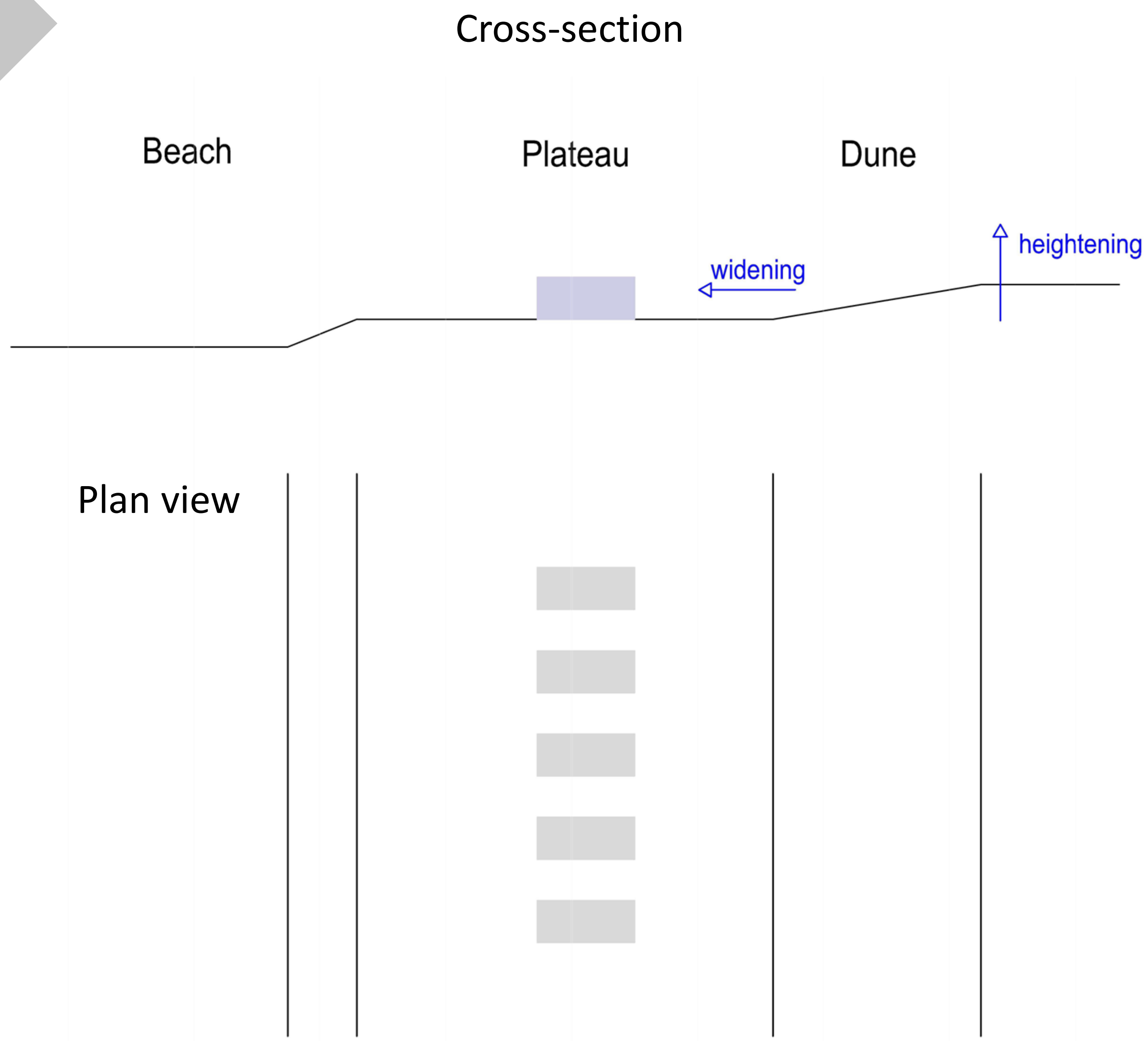
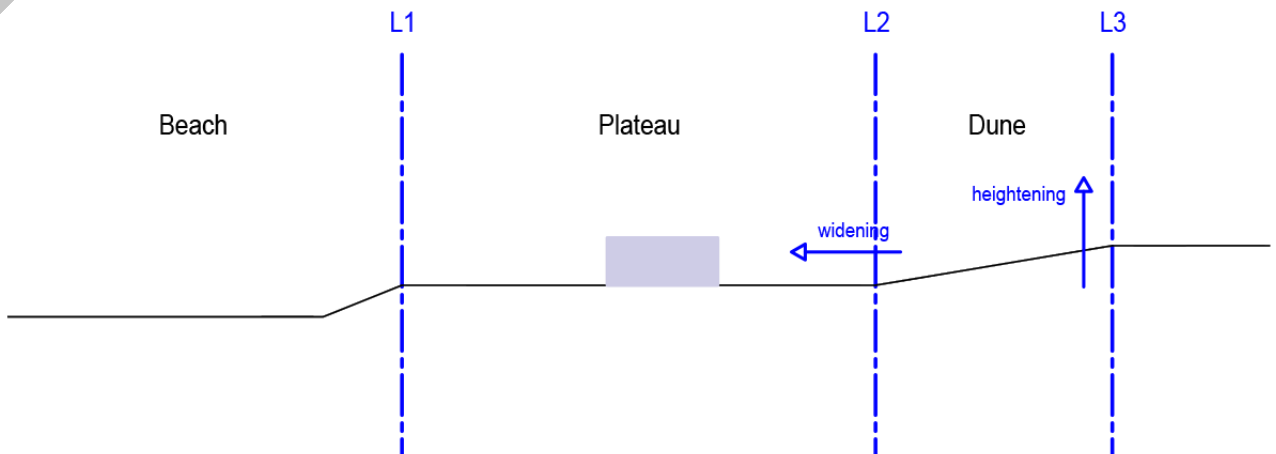
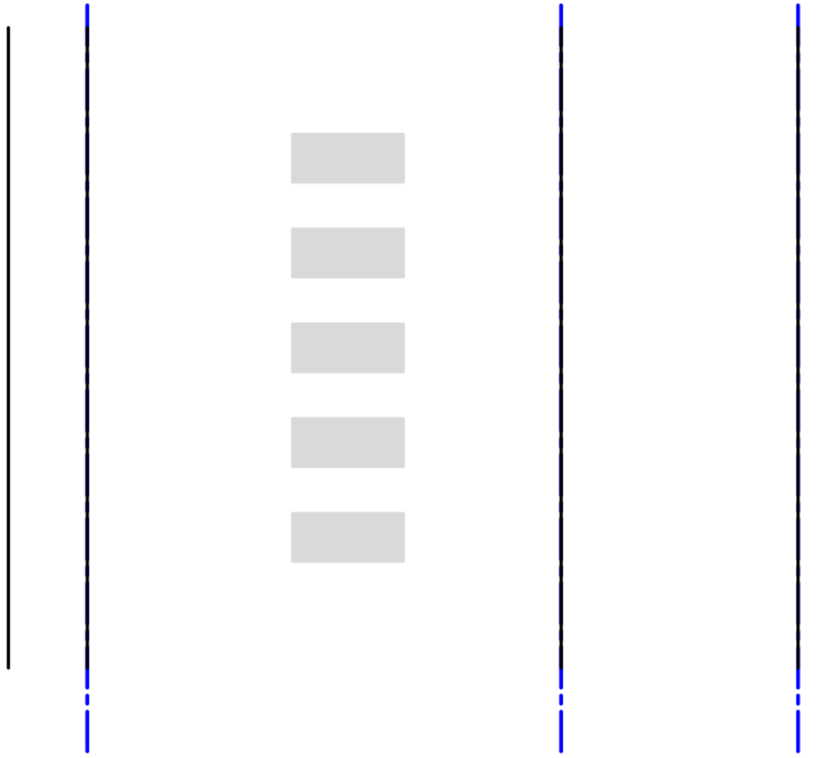

Cross-section
Beach
Plateau
Dune
widening
heightening
Plan view

Cross-section



Plan view

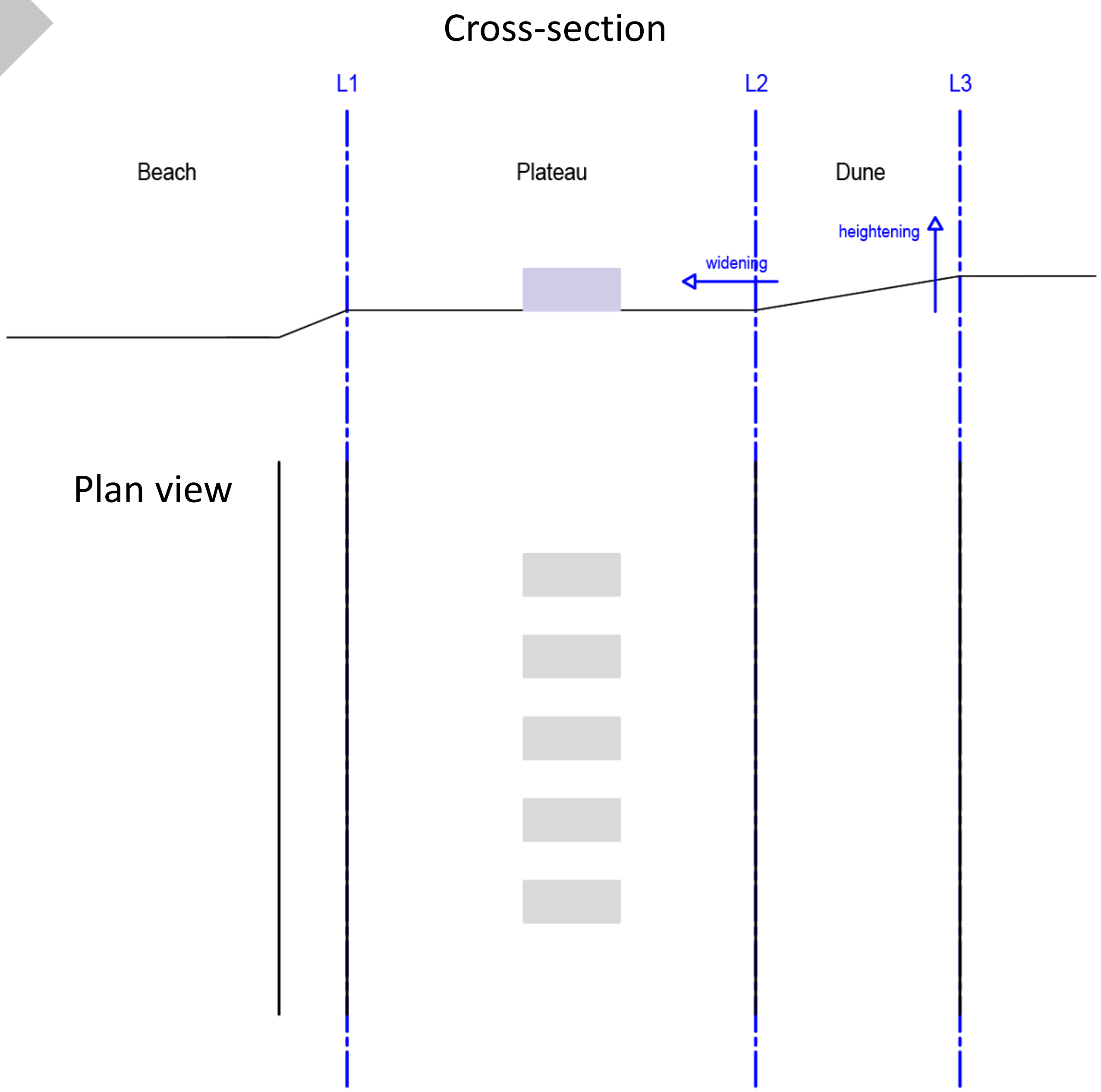


$$q_n = 1.16 \times 10^{-5} \times U^3 \times \cos\theta$$

q_n is potential transport rate in kg m^{-1} s^{-1}

U is wind speed in m s^{-1}

θ is angle of wind approach from shore perpendicular in degrees



For widening the dunes: use L1 and L2

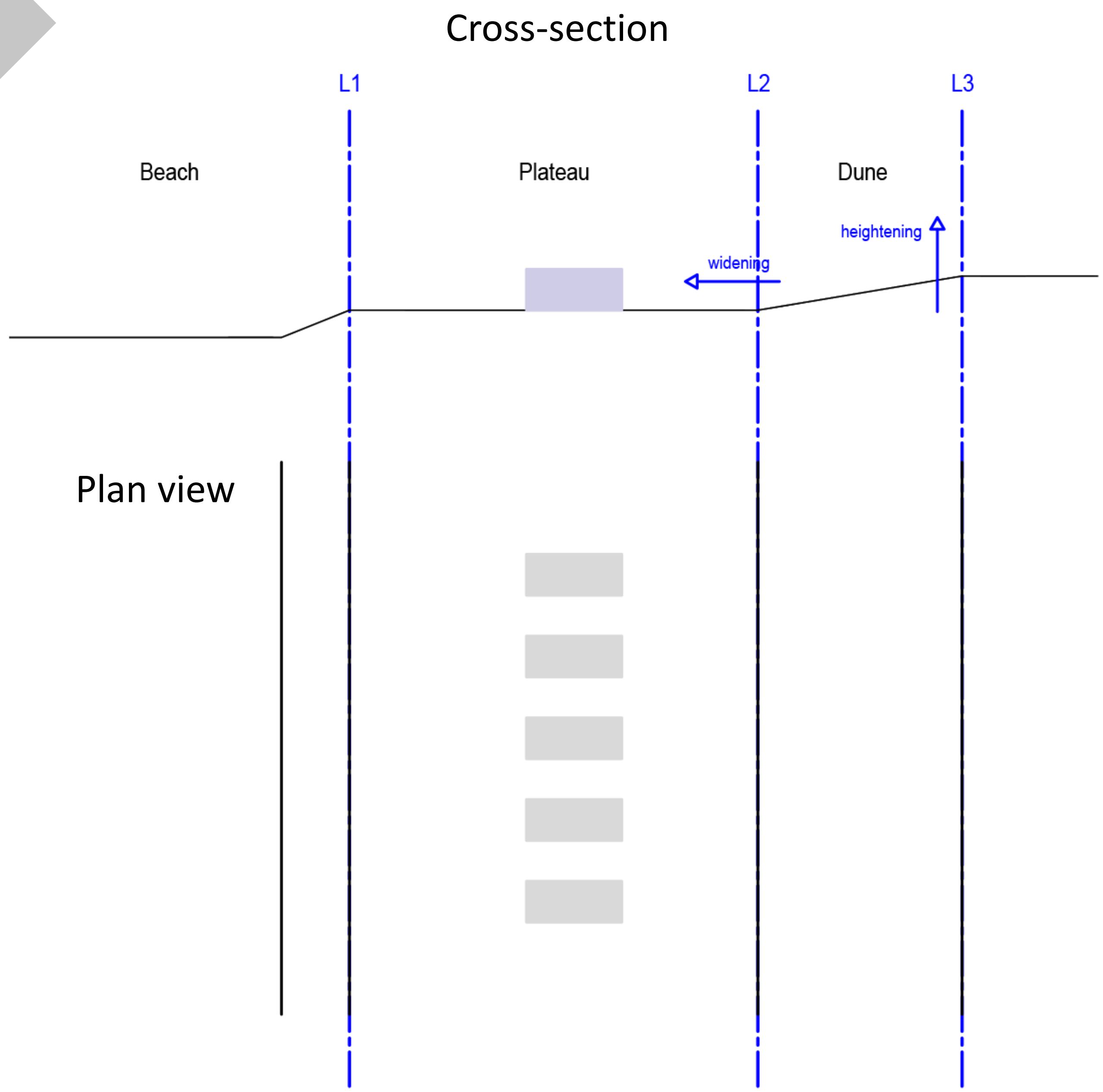
Sample velocity at 2 lines at a 30 cm height

Get transport rate at each line

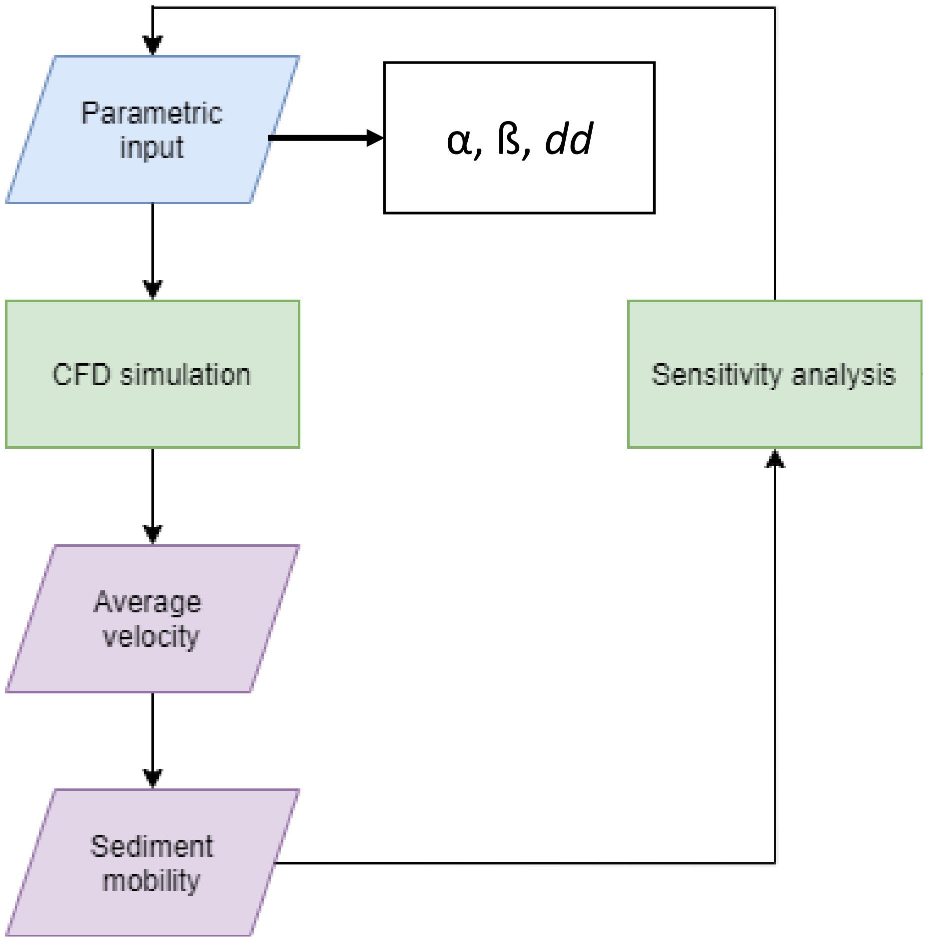
Get difference between the 2 lines (L2 – L1)

Less transport means more sedimentation

Objective: Minimise the difference (=bigger negative difference)

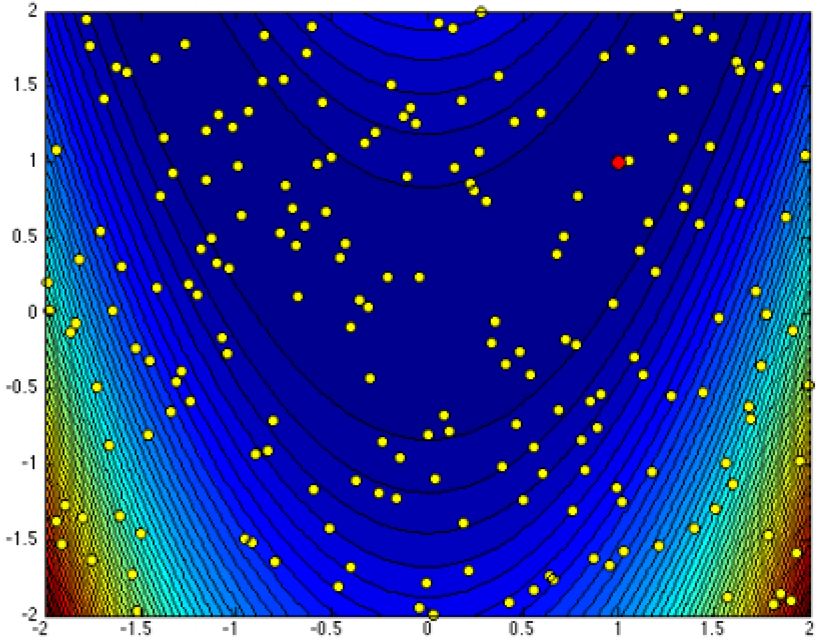


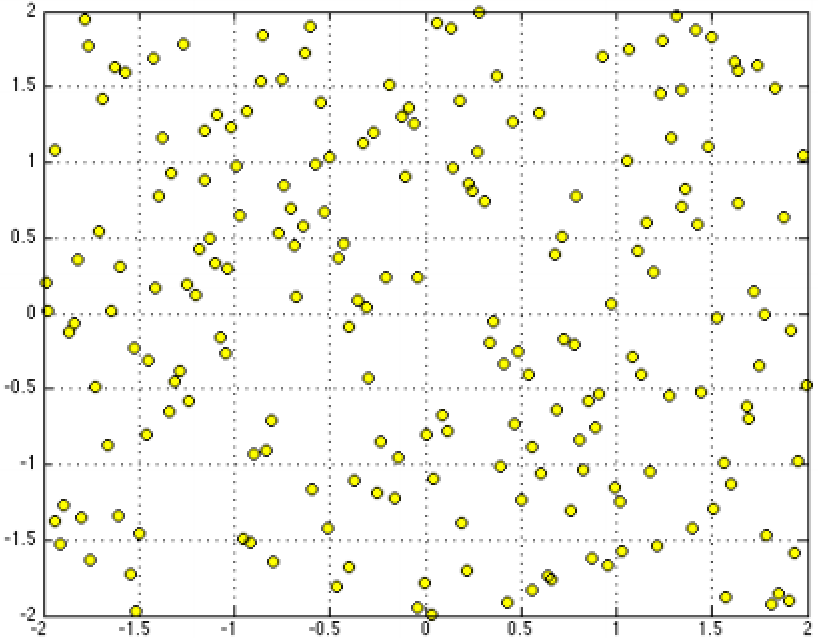
Workflow


Parametric input
α, ß, dd
CFD simulation
Average velocity
Sediment mobility
Sensitivity analysis

Sampling

Need to sample the design space with the minimum number of samples in a representative way -> Latin Hypercube Sampling (LHS) and Orthogonal Array (OA)





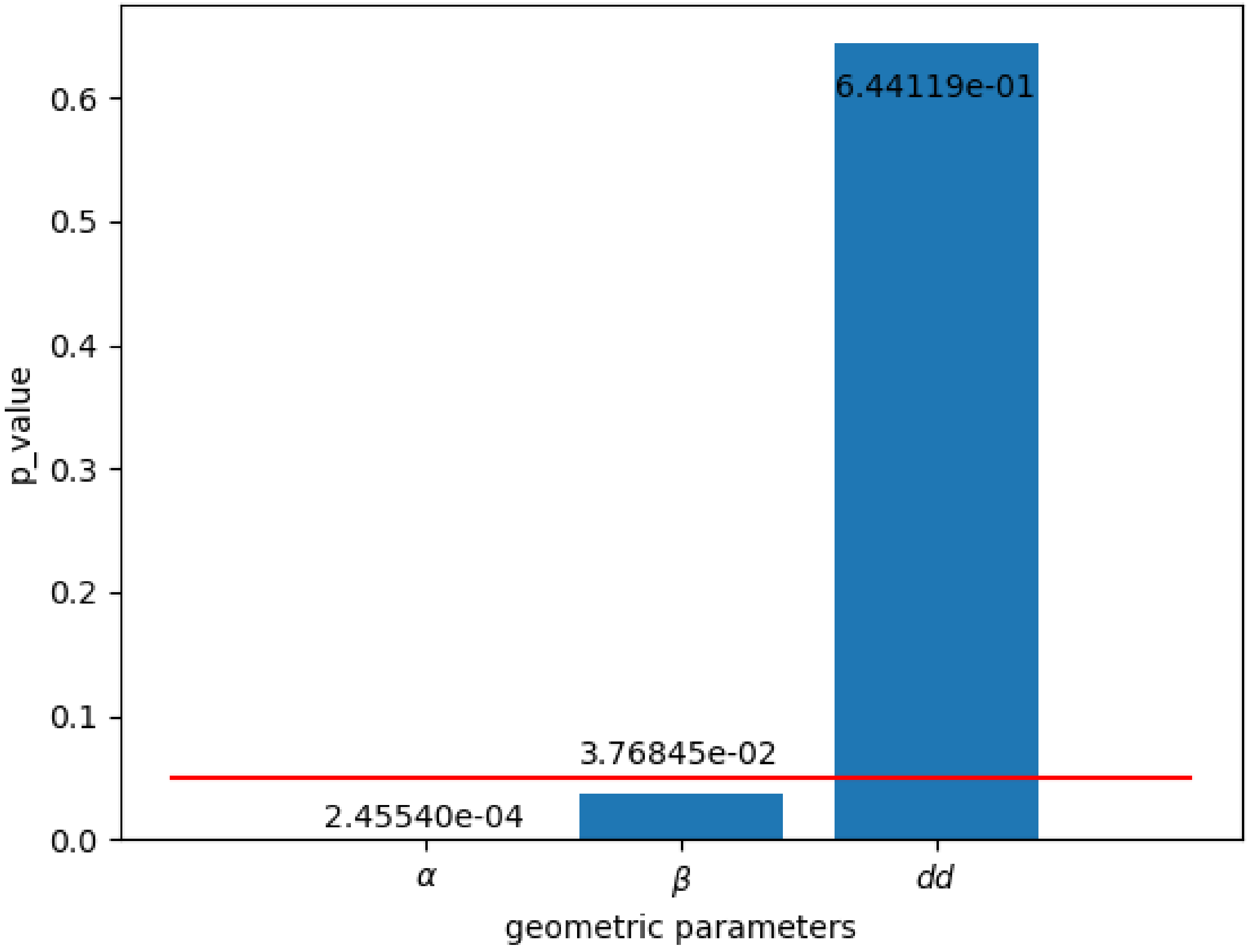
Guerrero, J. (2016). Training session on : Design of experiments , space exploration , and numerical optimization using DAKOTA and OpenFOAM. 189.

ANOVA

- Statistically identifies the effects of input variables on the output
- p-value indicates the confidence interval: a p-value of 0.05 and lower corresponds to a confidence interval of 95% and higher

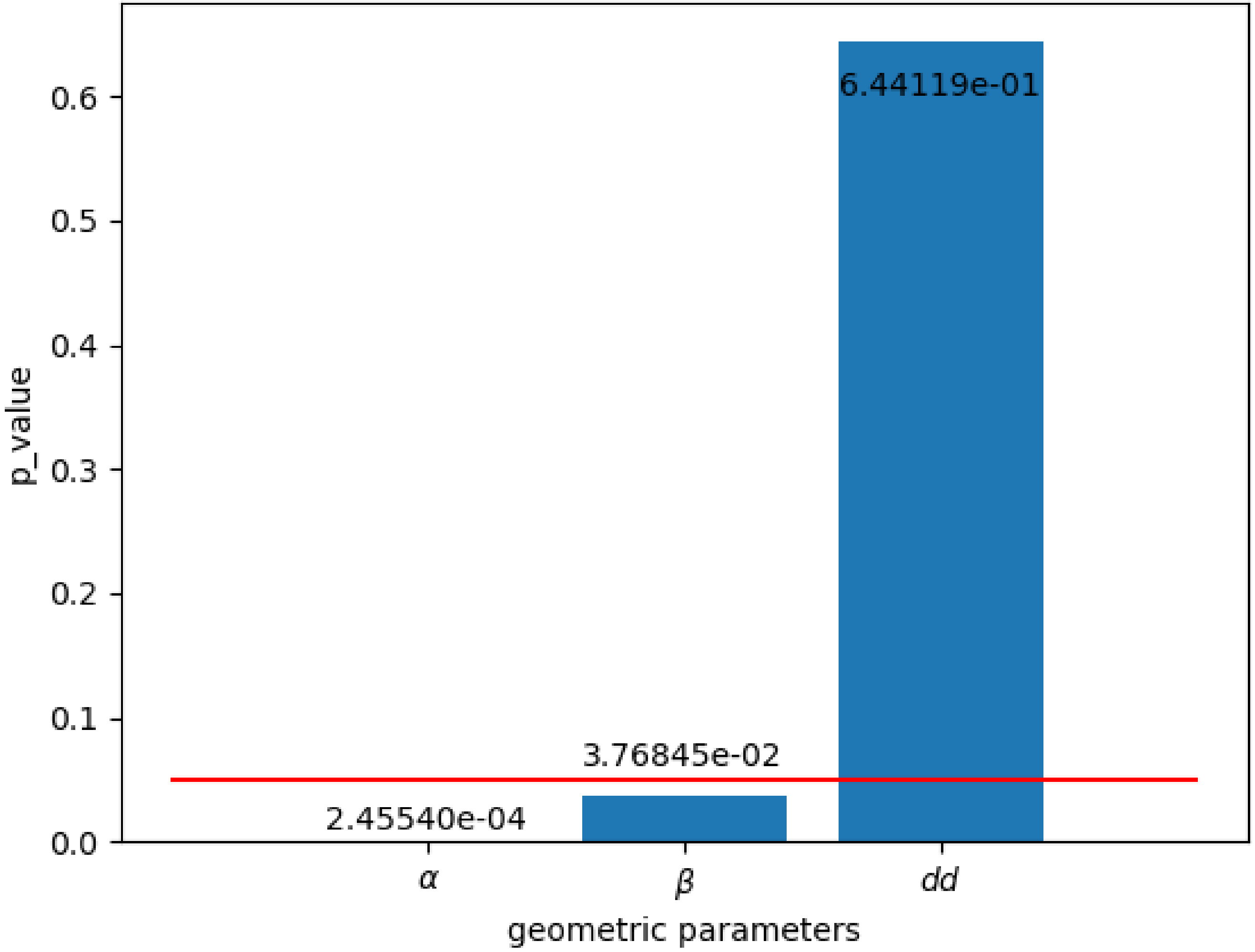
→ Following sensitivity analysis rules: 49 samples are used for the analysis

ANOVA results

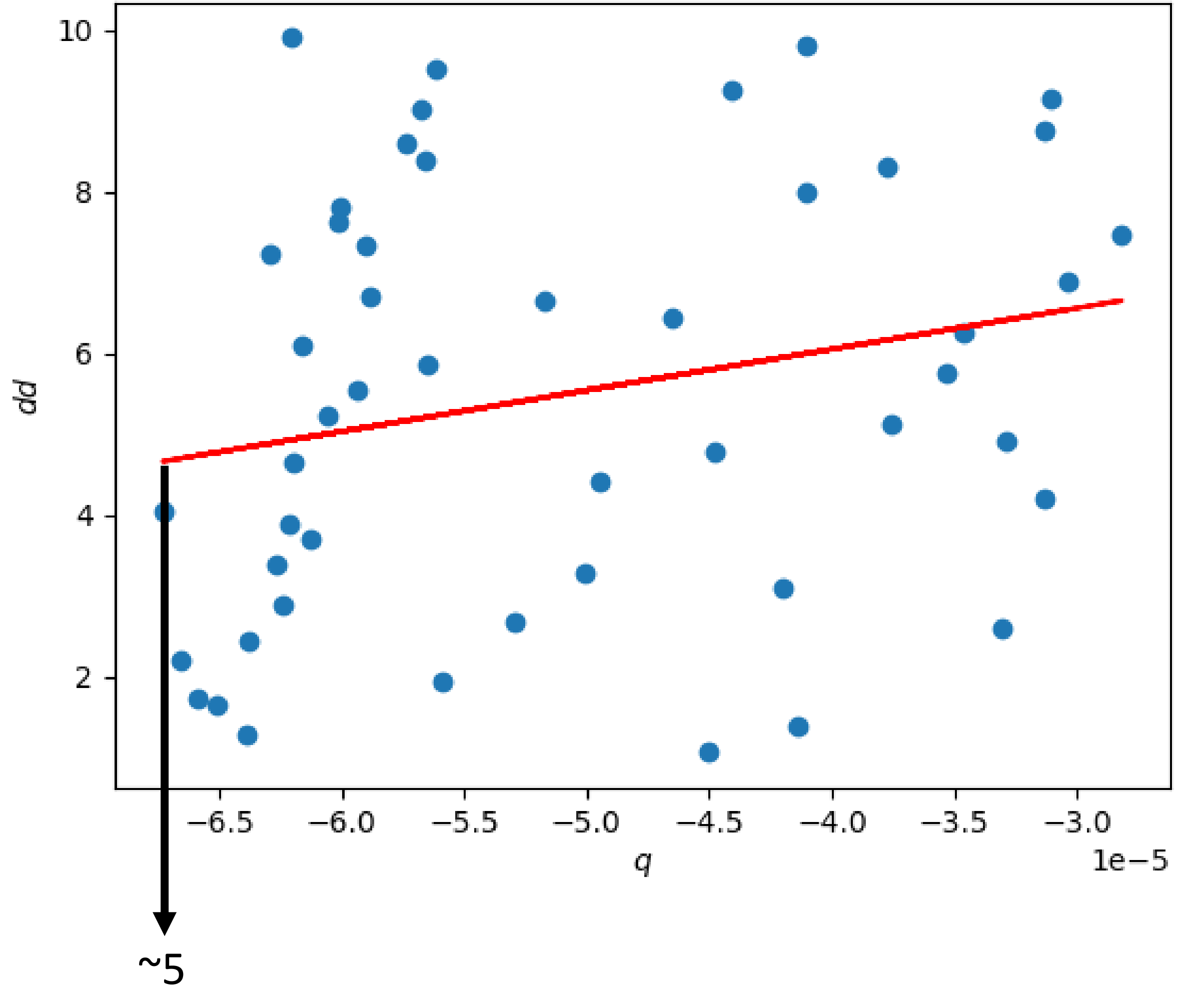


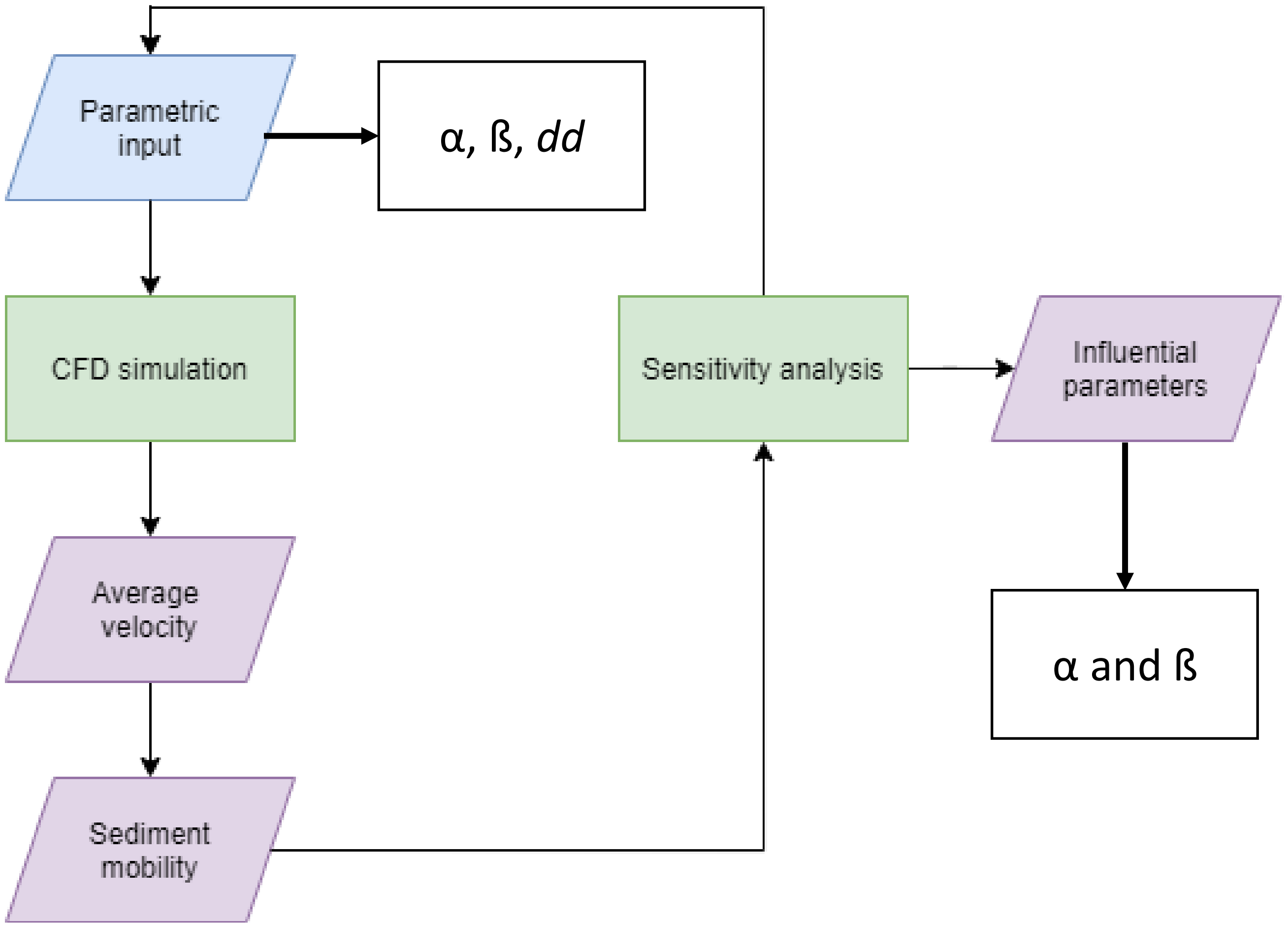
ANOVA results

From a 3D design space to a 2D design space

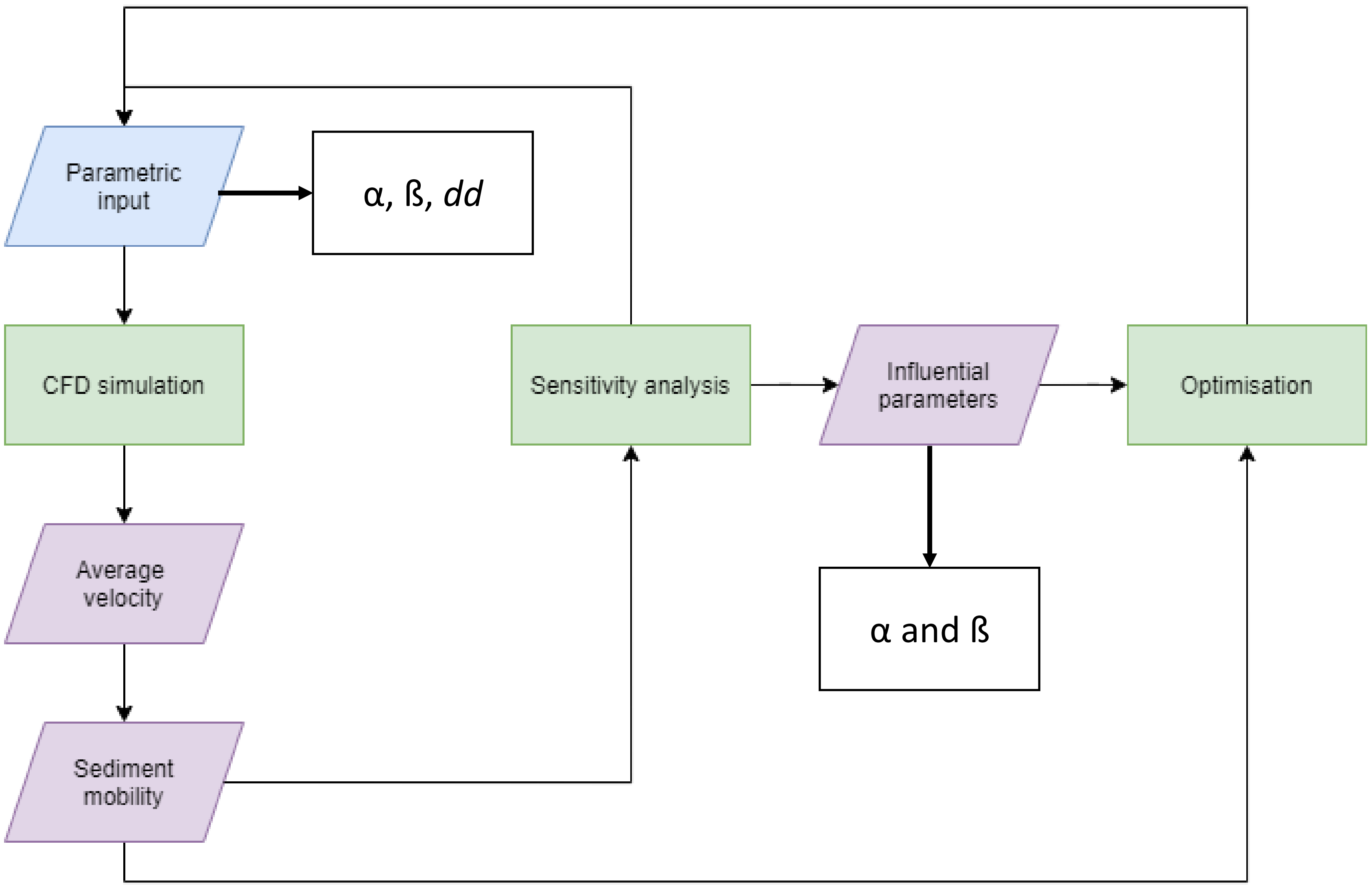


Choose a value for the new constant in the system




Parametric input
α, ß, dd
CFD simulation
Average velocity
Sediment mobility
Sensitivity analysis
Influential parameters
α and ß

Workflow


Parametric input
α, ß, dd
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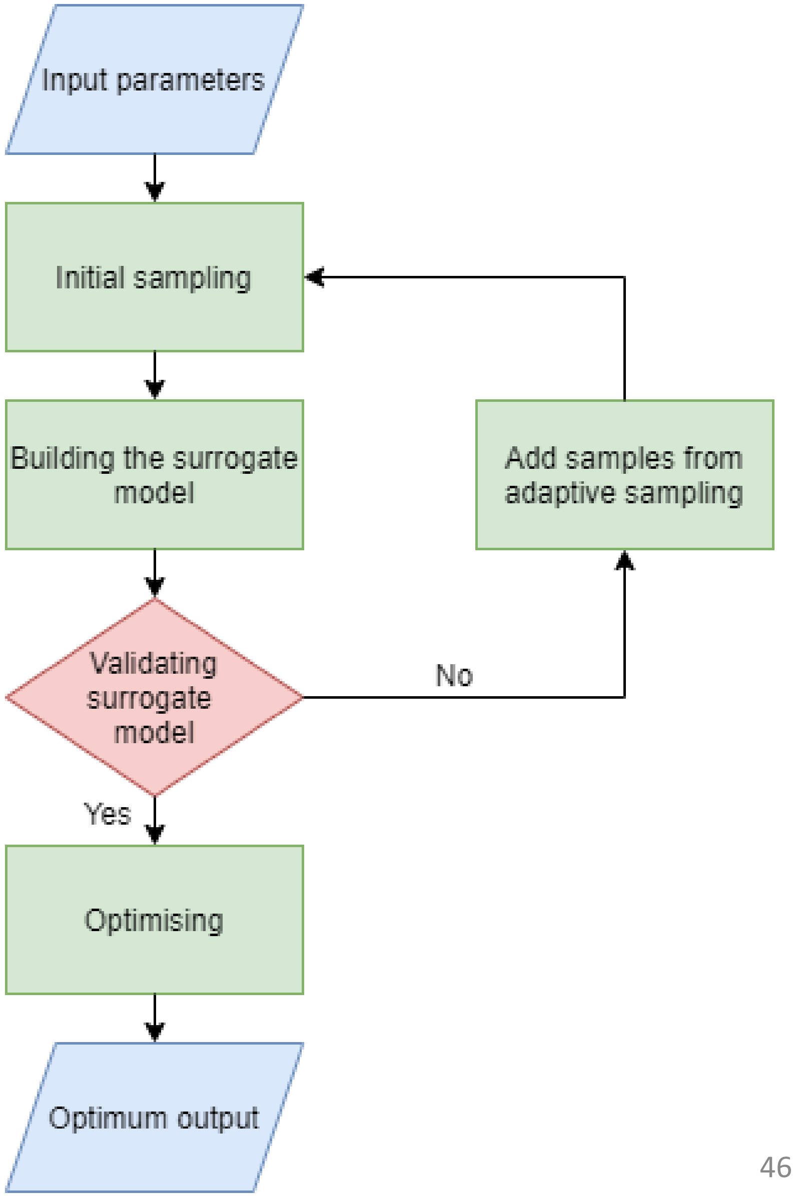
Influential parameters
α and ß
Optimisation

Surrogate-Based Optimisation



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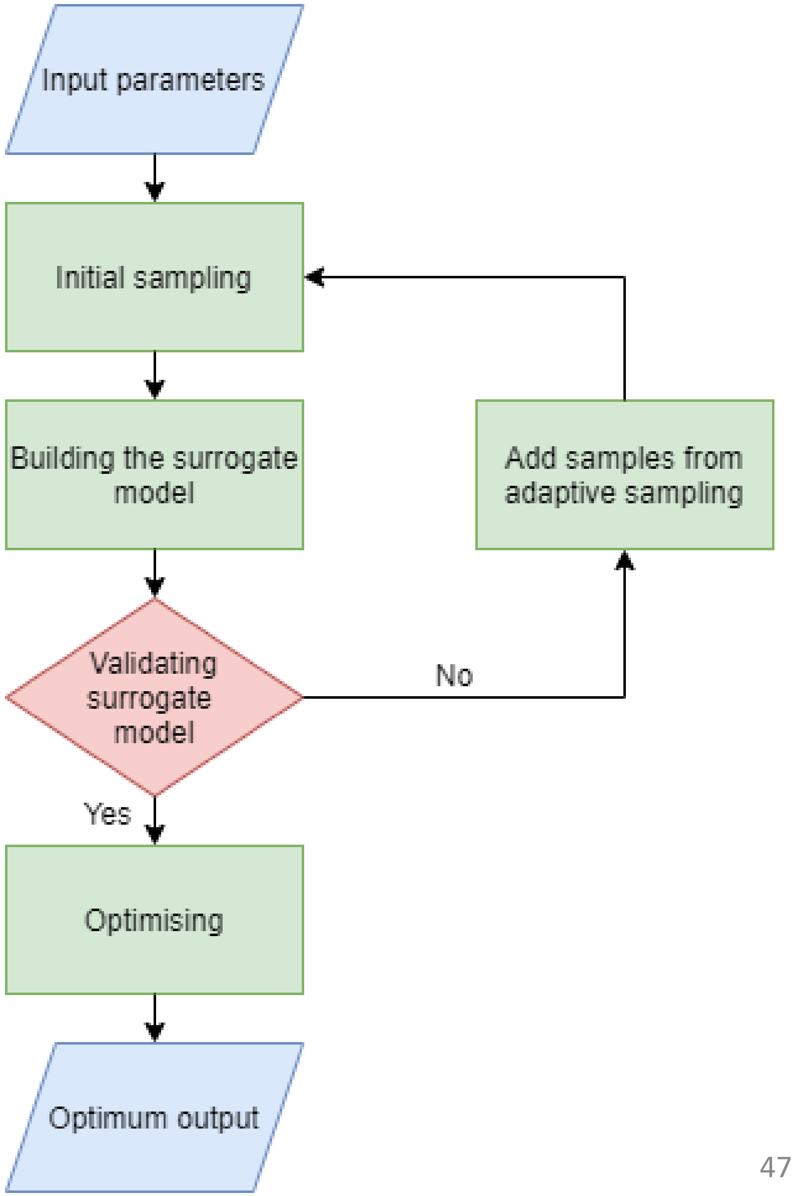
Surrogate-Based Optimisation

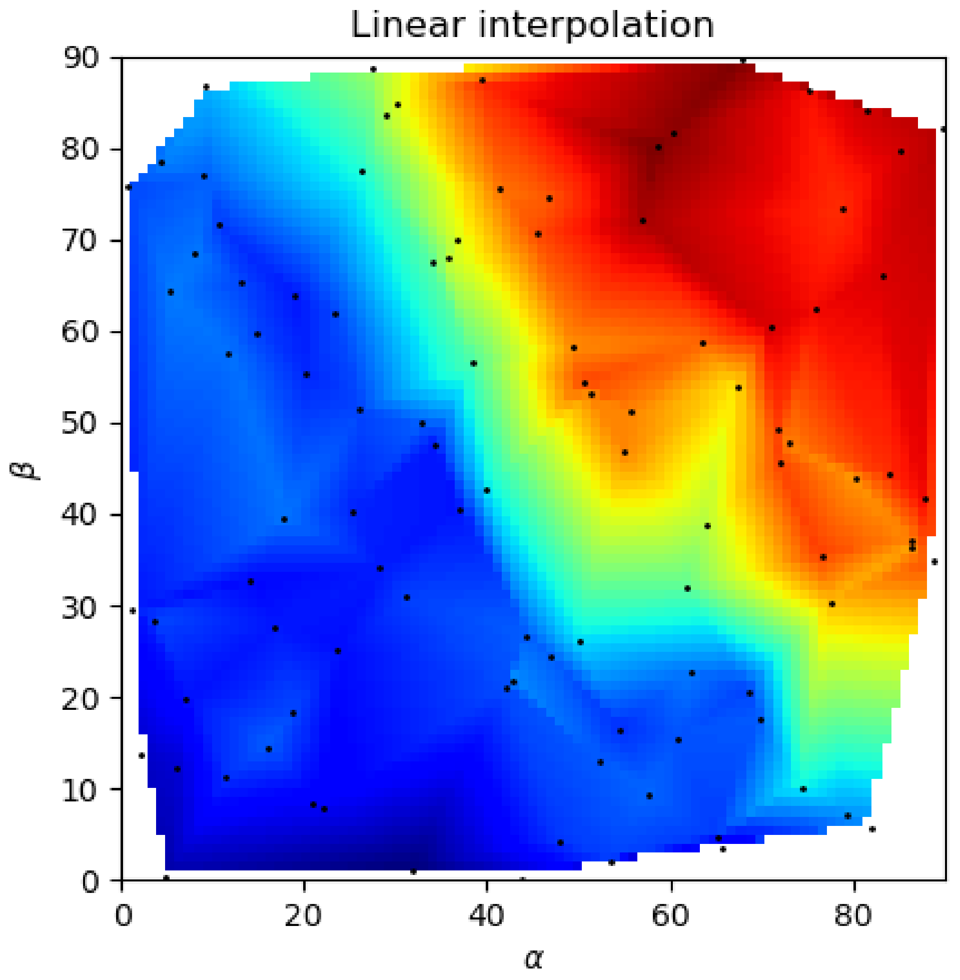
Building the surrogate

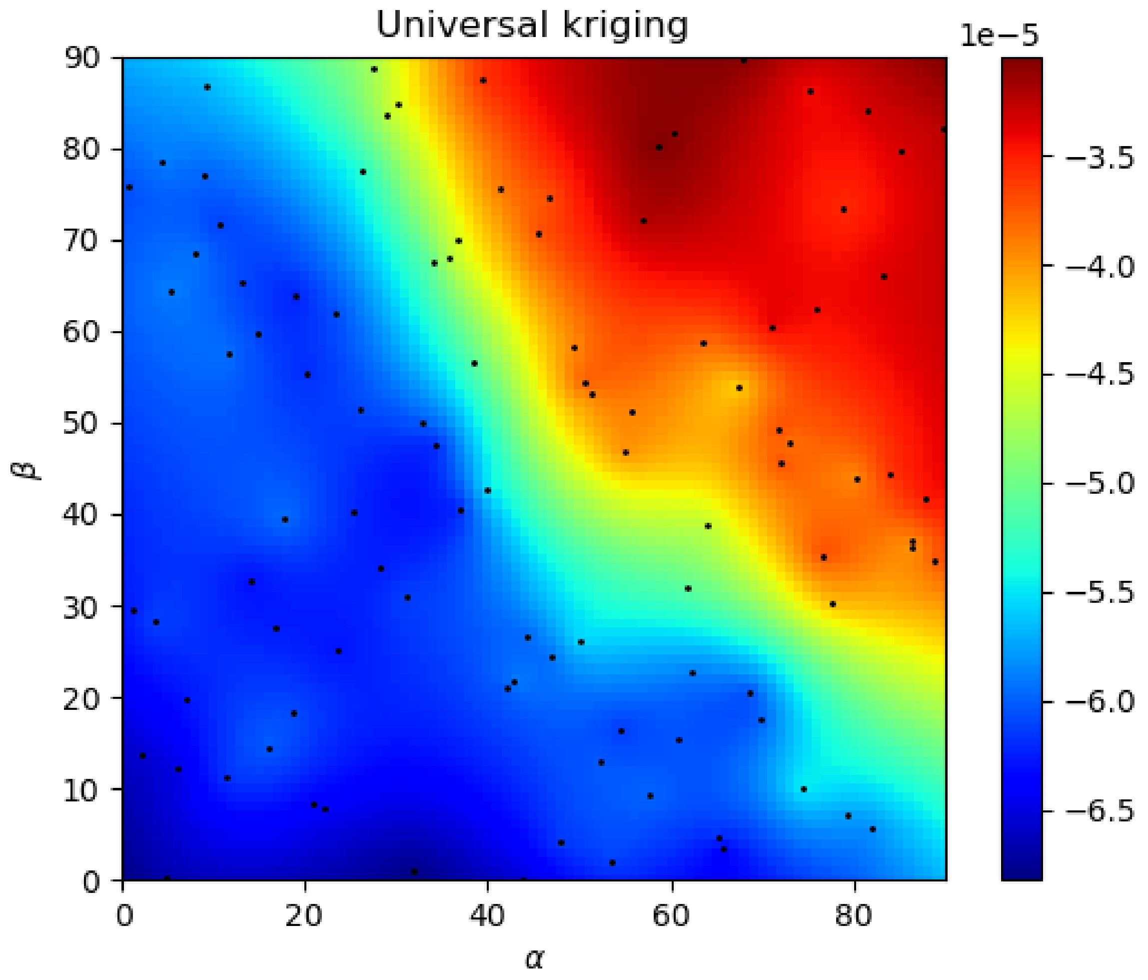
- Sampling the domain in a representative way
- 10 samples per dimension is used which leads to 100 samples
- Response surface:
    - Linear interpolation
    - Radial Basis Function
    - Kriging



Surrogate – response surface

Black dots = samples

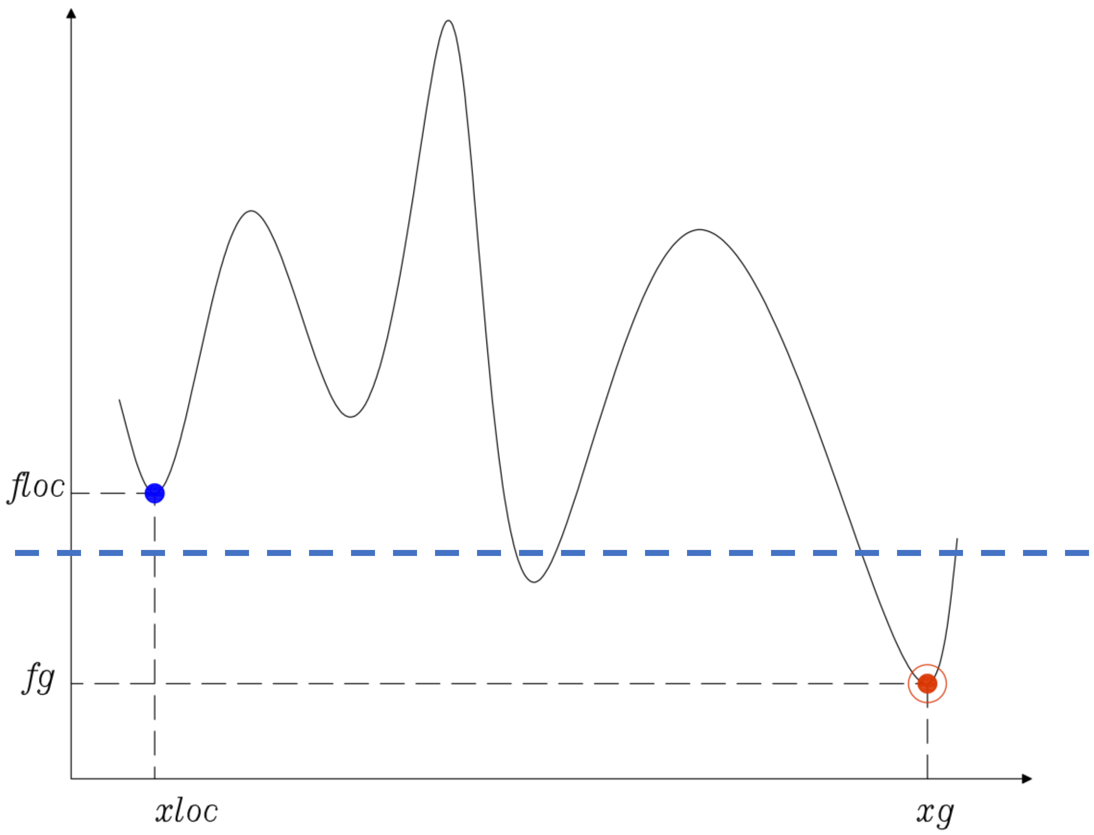


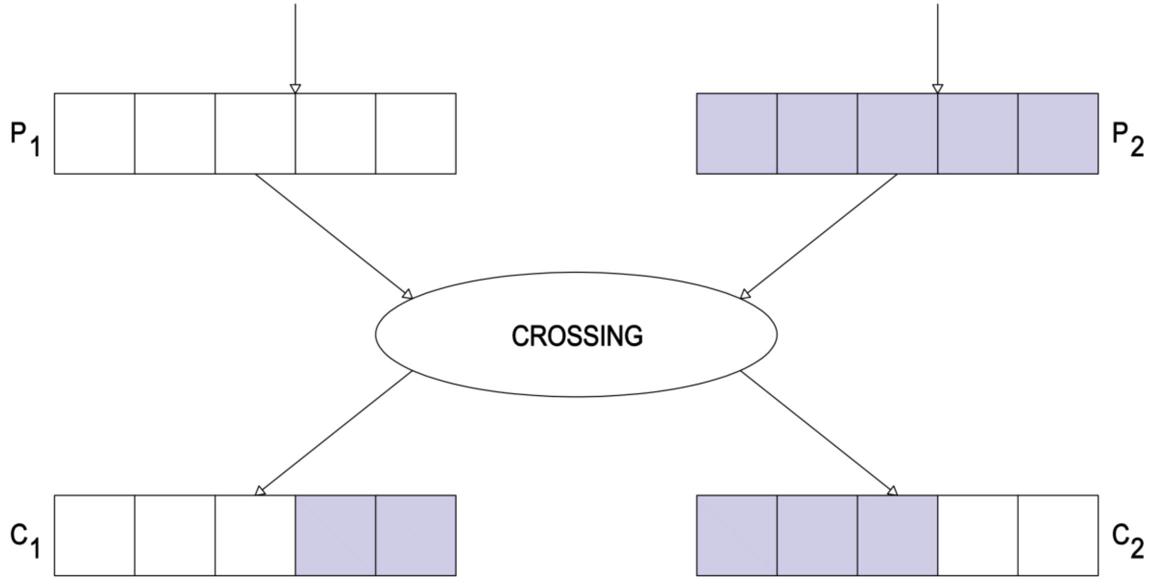


Predicted optimum from linear interpolation: α = 31° and ß = 1°

Predicted optimum from kriging: α = 0° and ß = 0°

Global optimisation – Genetic Algorithm



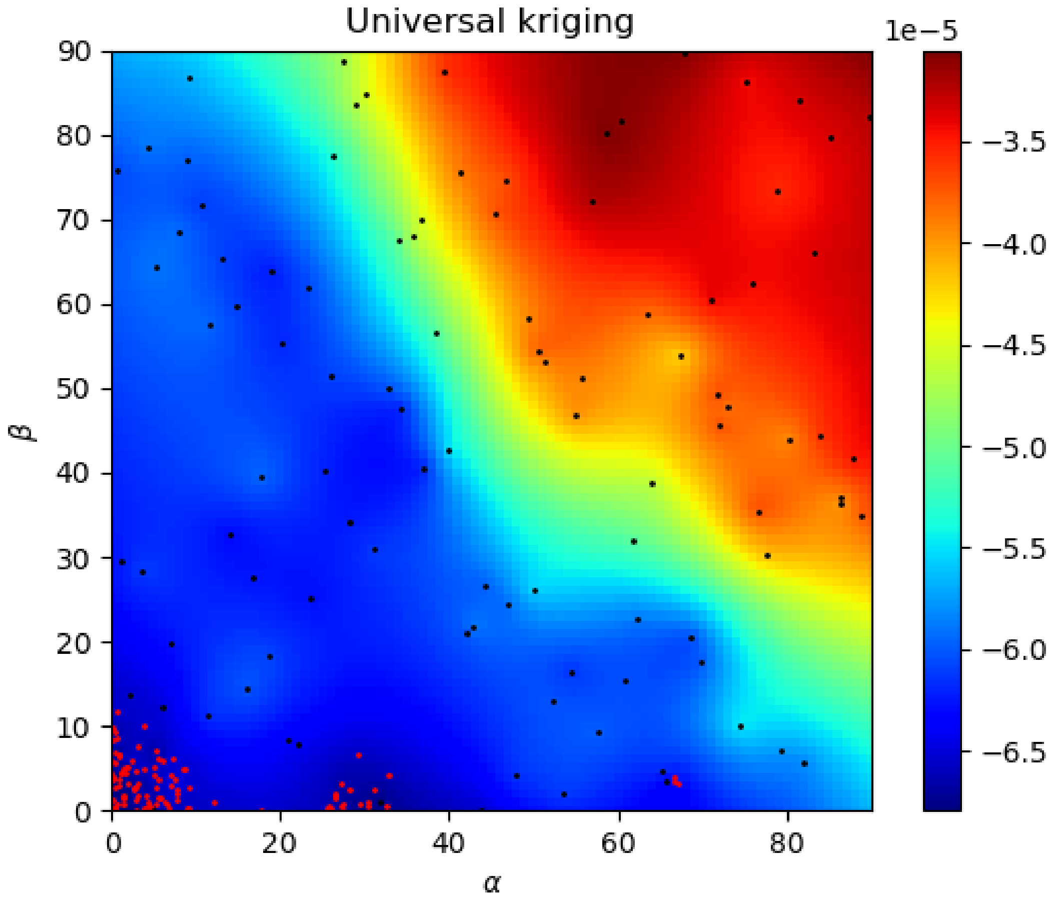


Hachimi, H. (2013). Hybridations d’algorithmes metaheuristiques en optimisation globale et leurs applications.

Surrogate + First generation

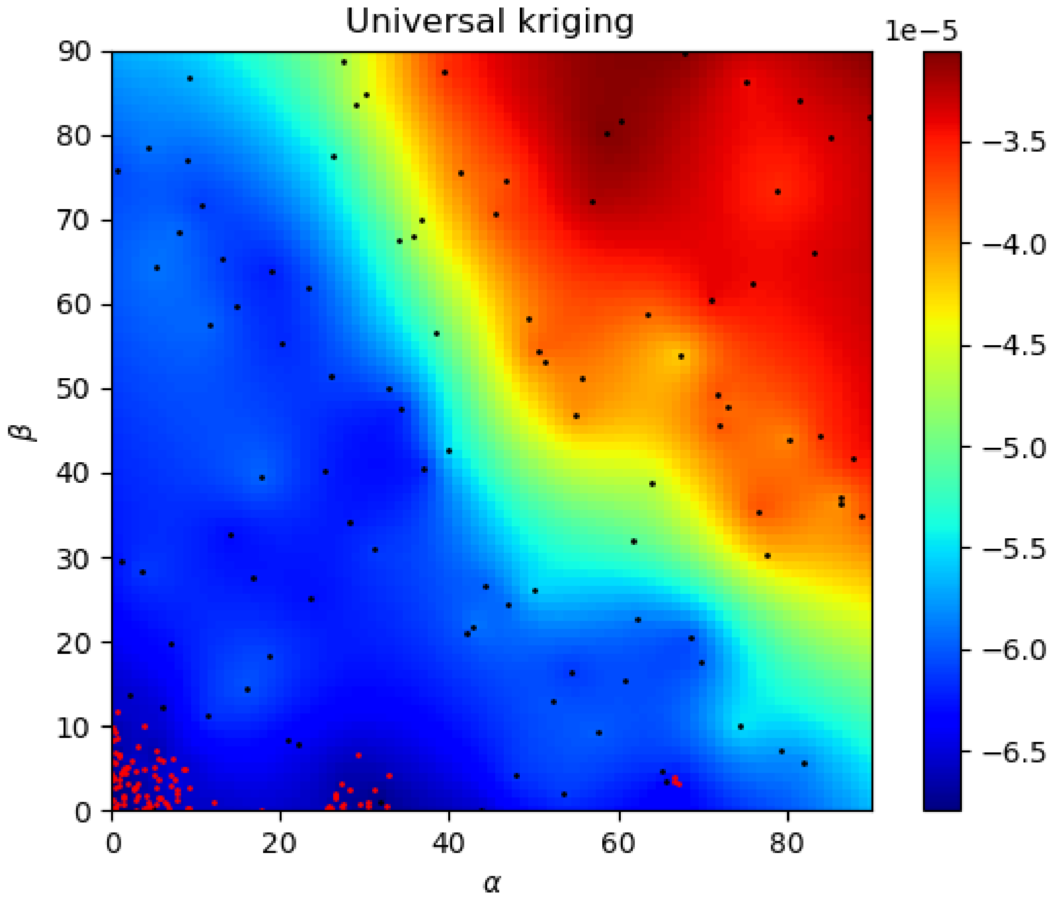
Black dots = surrogate samples

Red dots = first generation samples



Average error between surrogate and first generation: ~6%

Surrogate + First generation



Predicted optimum: α = 1° and ß = 4°

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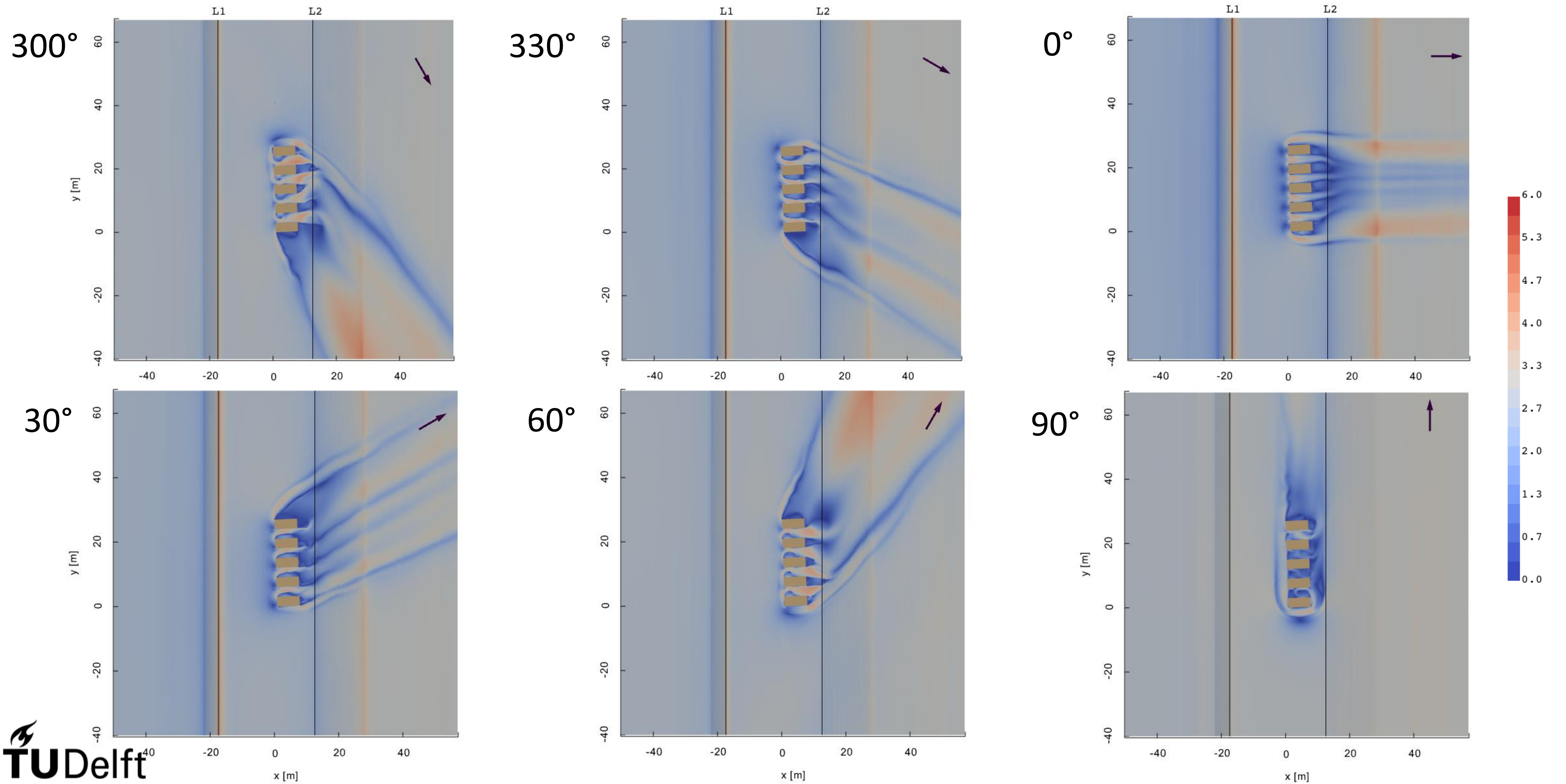
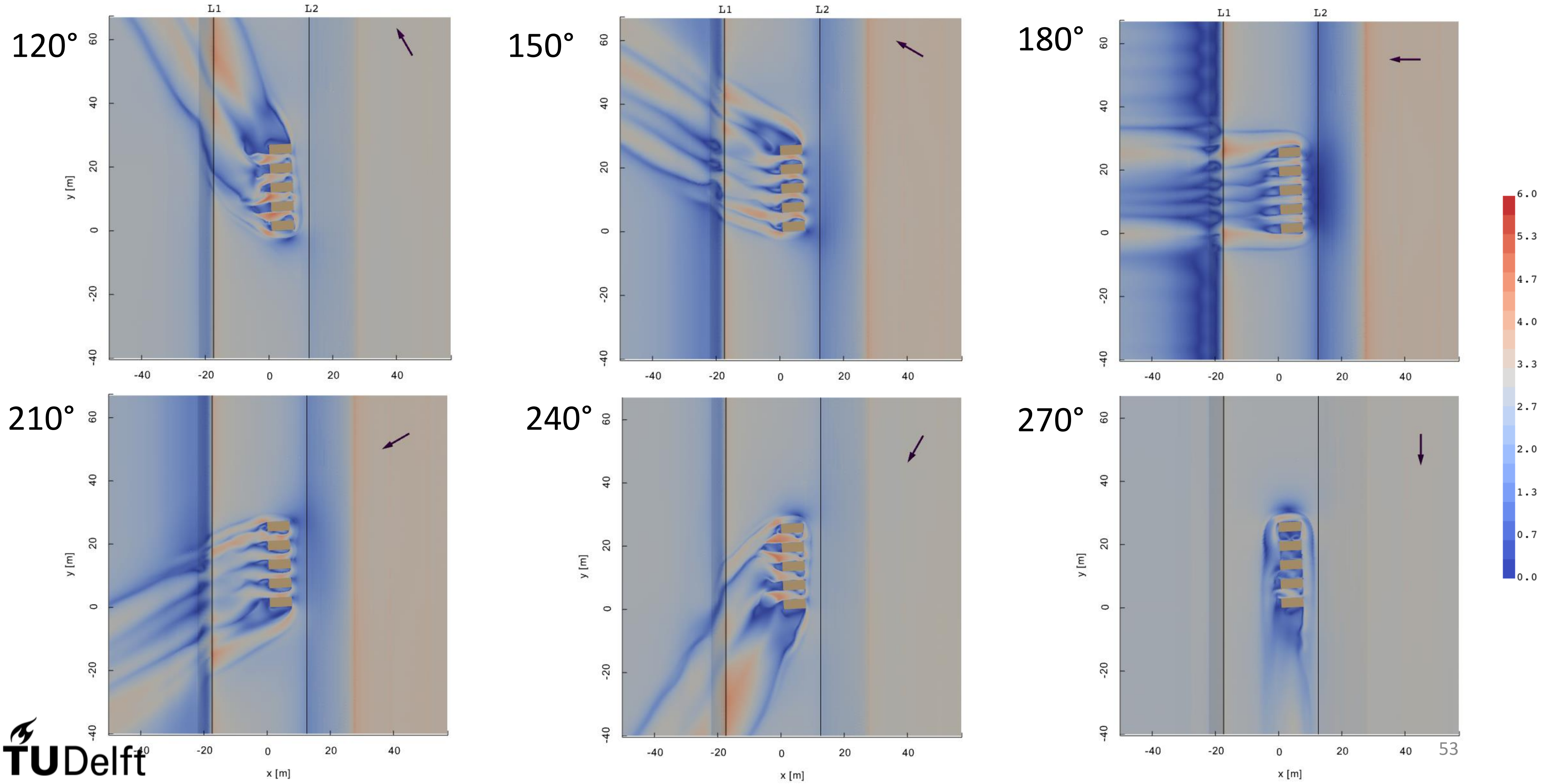
12 directions



12 directions

6.8% increase in transport



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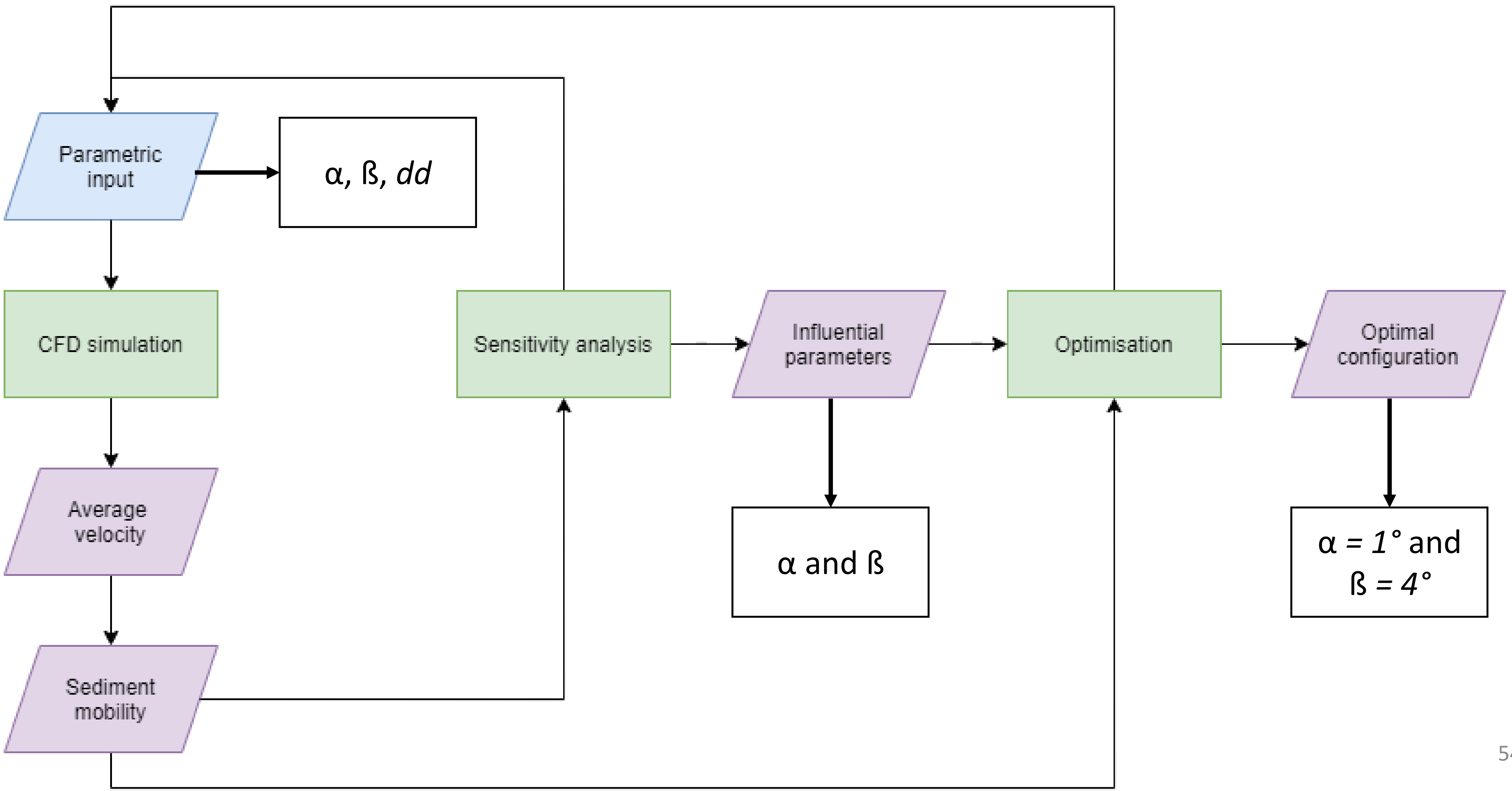
Workflow


Parametric input
α, ß, dd
CFD simulation
Average velocity
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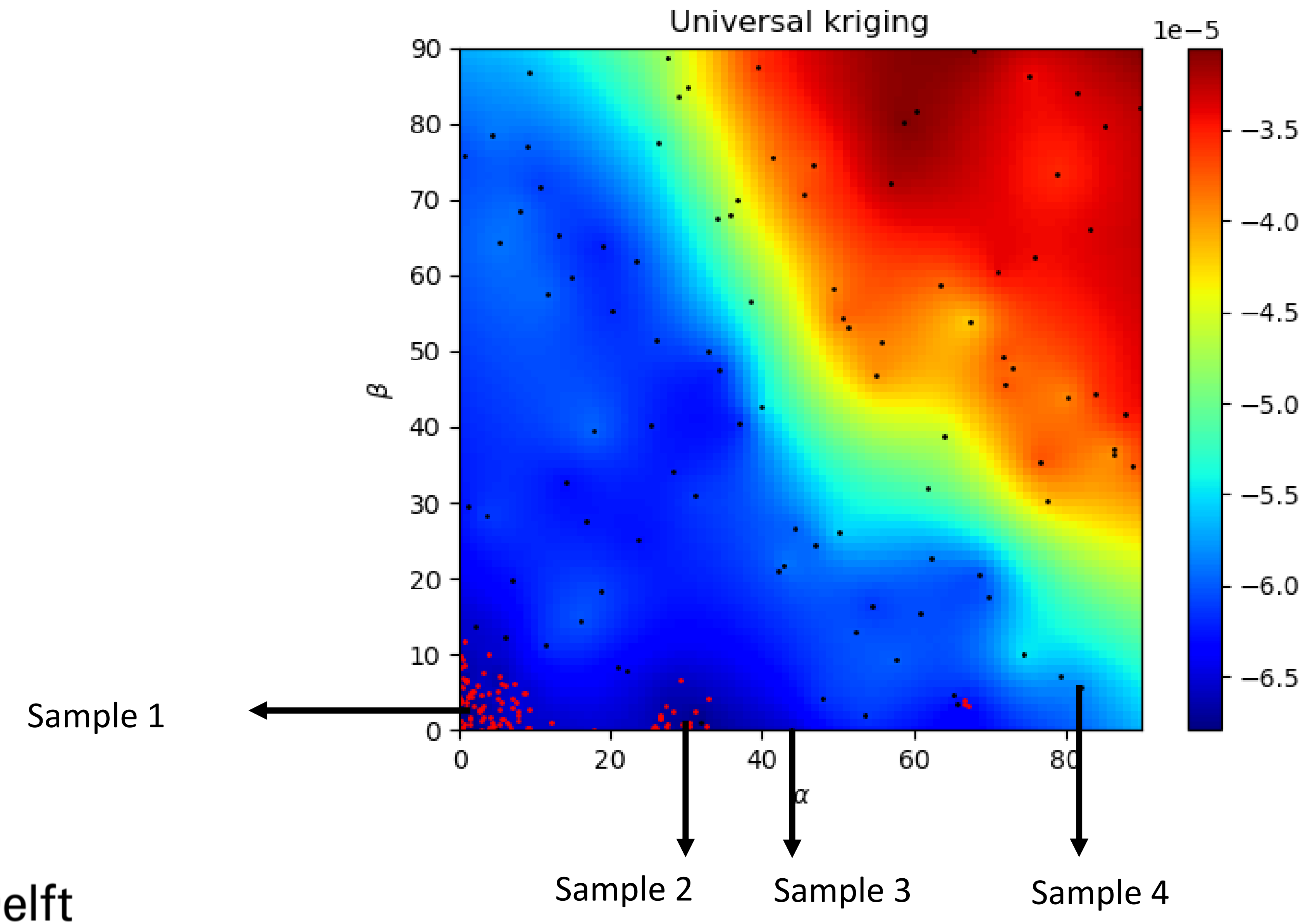
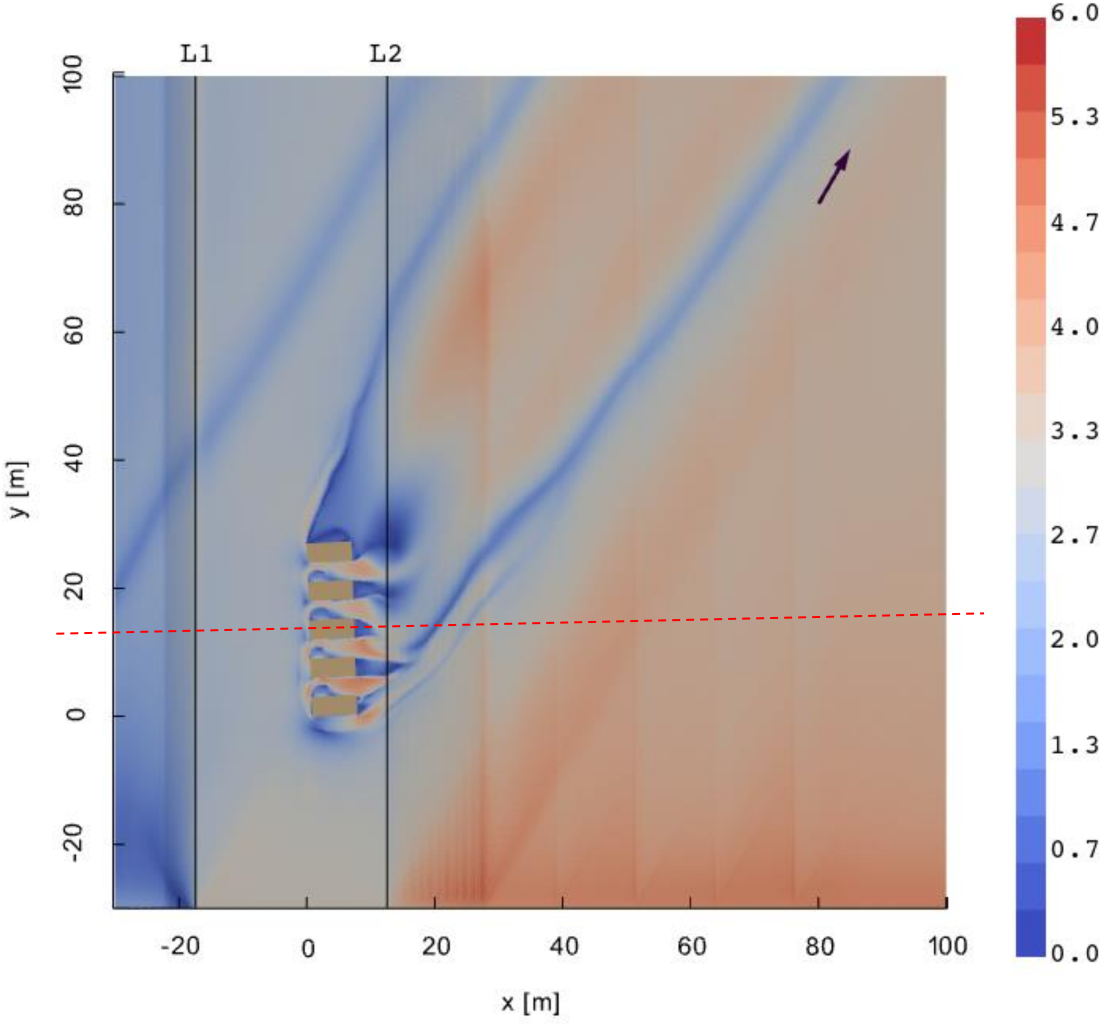
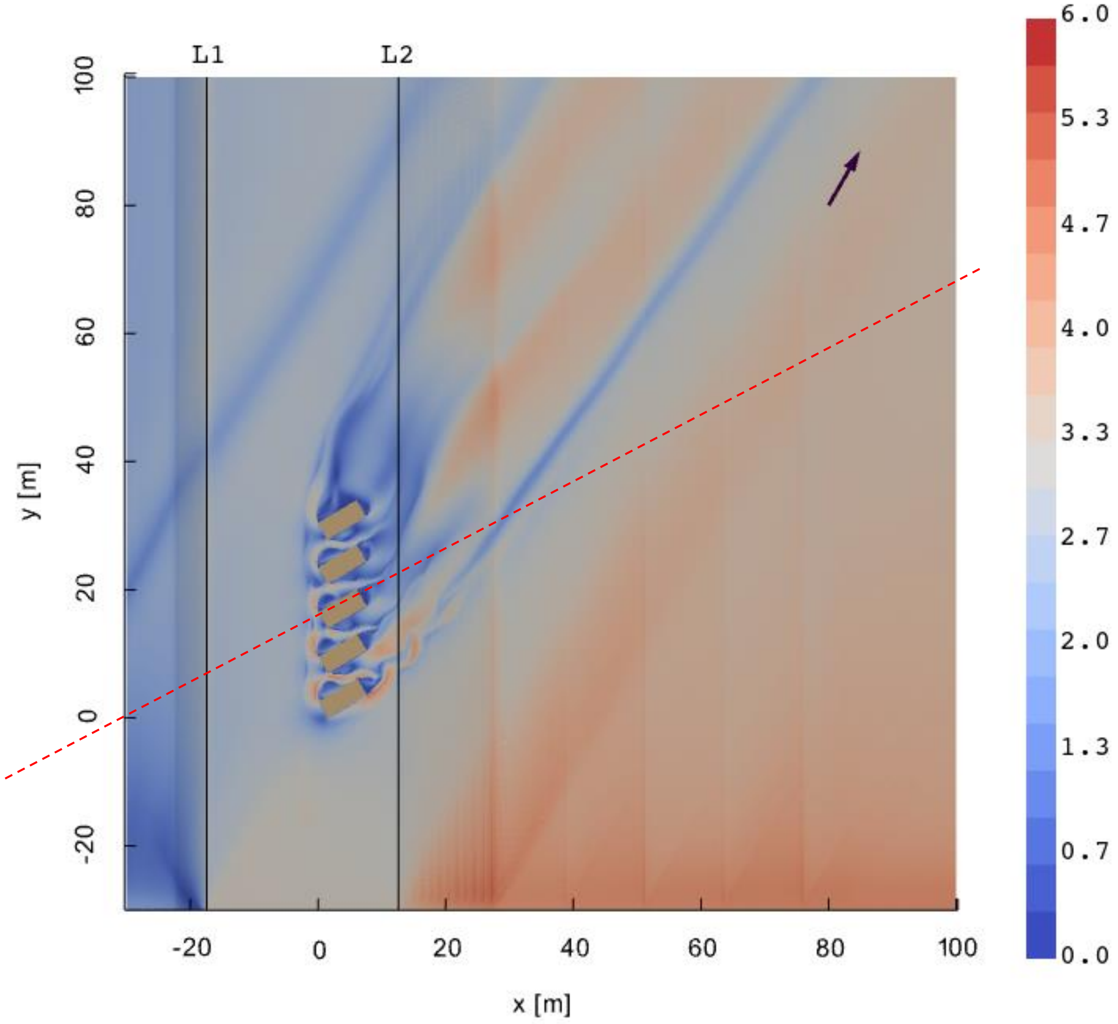
Influential parameters
α and ß
Optimisation
Optimal configuration
α = 1° and ß = 4°

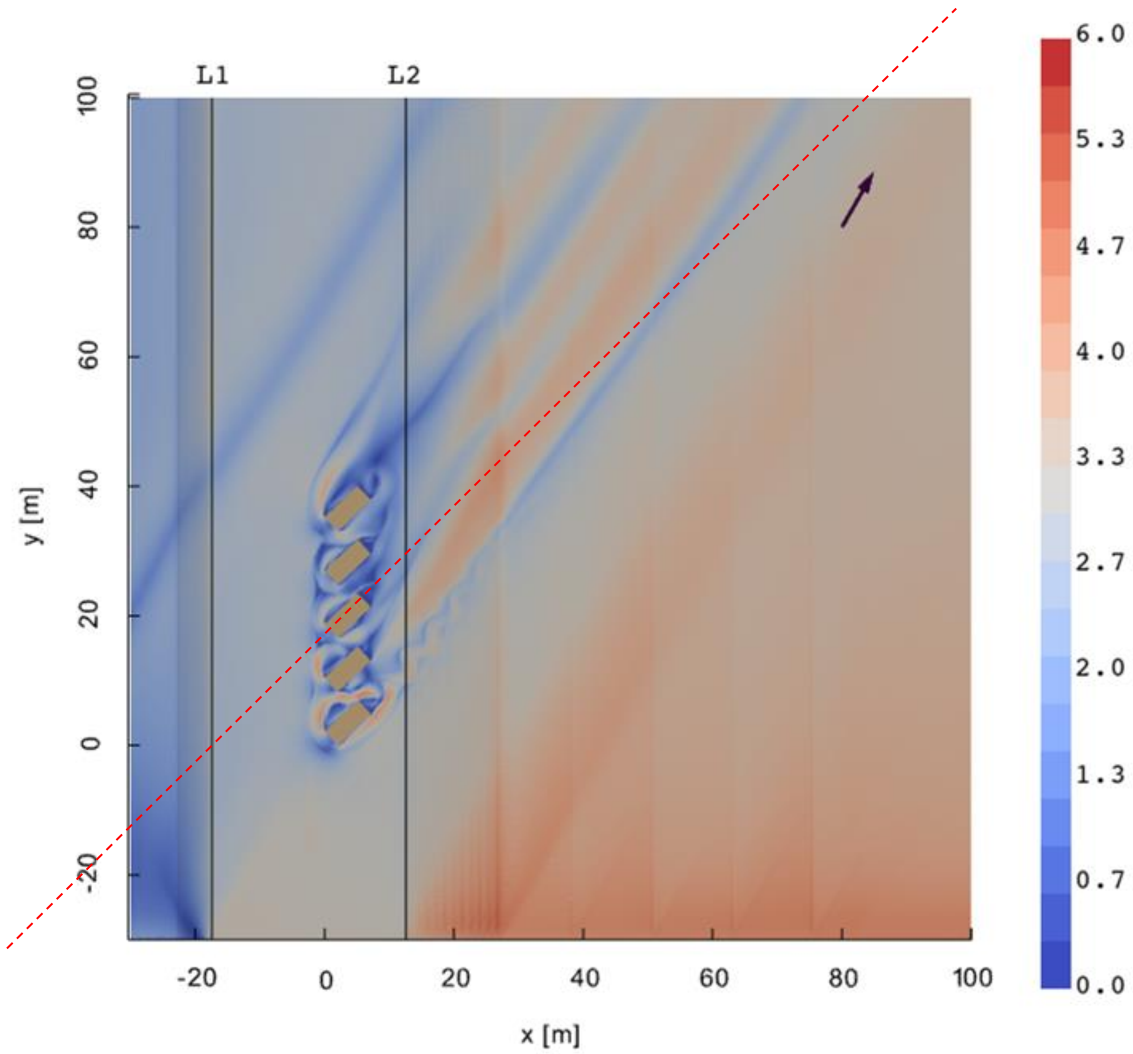

Universal kriging
1e−5
90
80
70
60
50
40
30
20
10
0
β
0
20
40
60
80
α
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0
−6.5
Sample 1
Sample 2
Sample 3
Sample 4



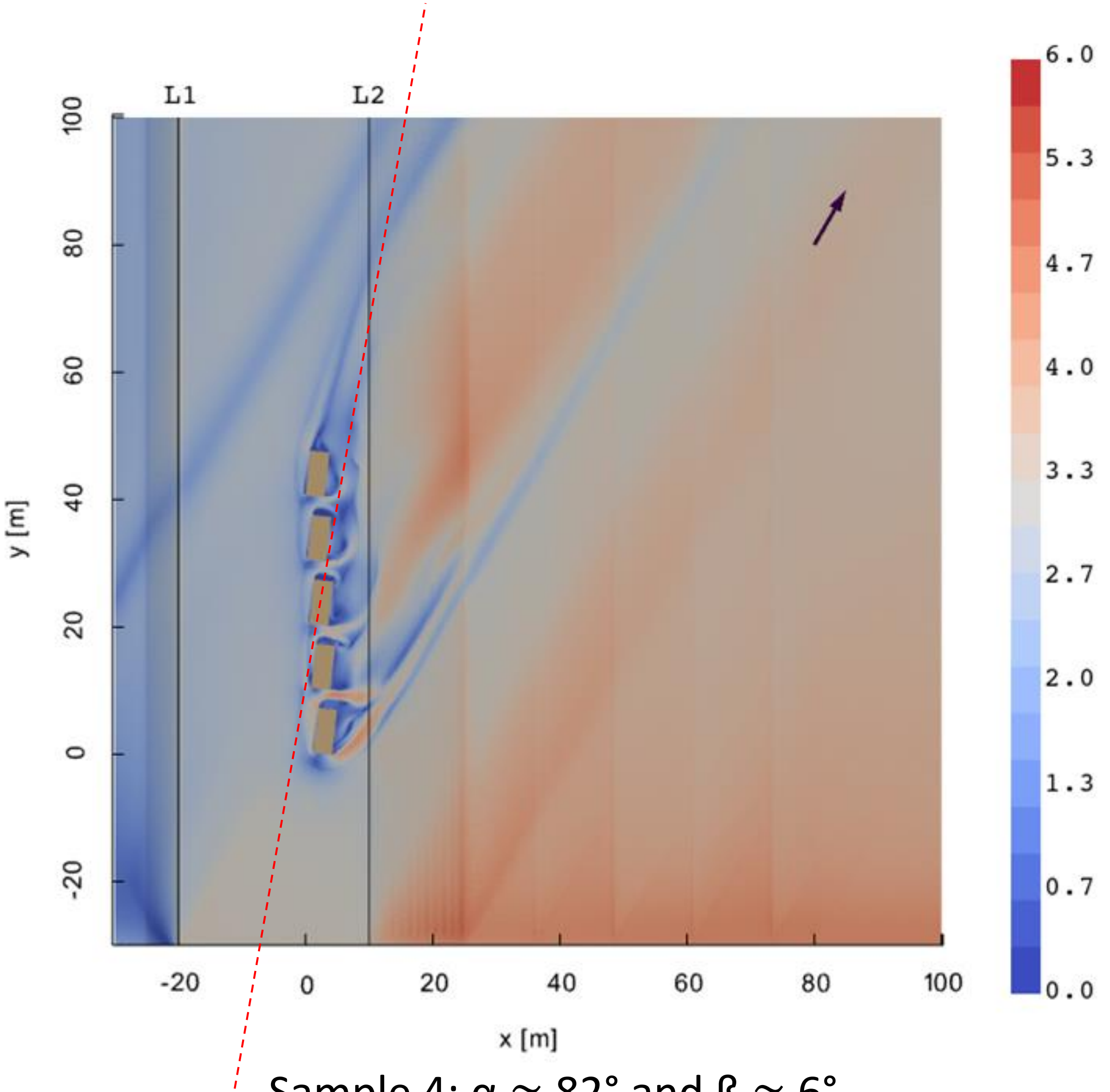
Sample 1: α ≈ 1° and ß ≈ 3.8° (Best-performing sample)



Sample 2: α ≈ 30° and ß ≈ 0.5°

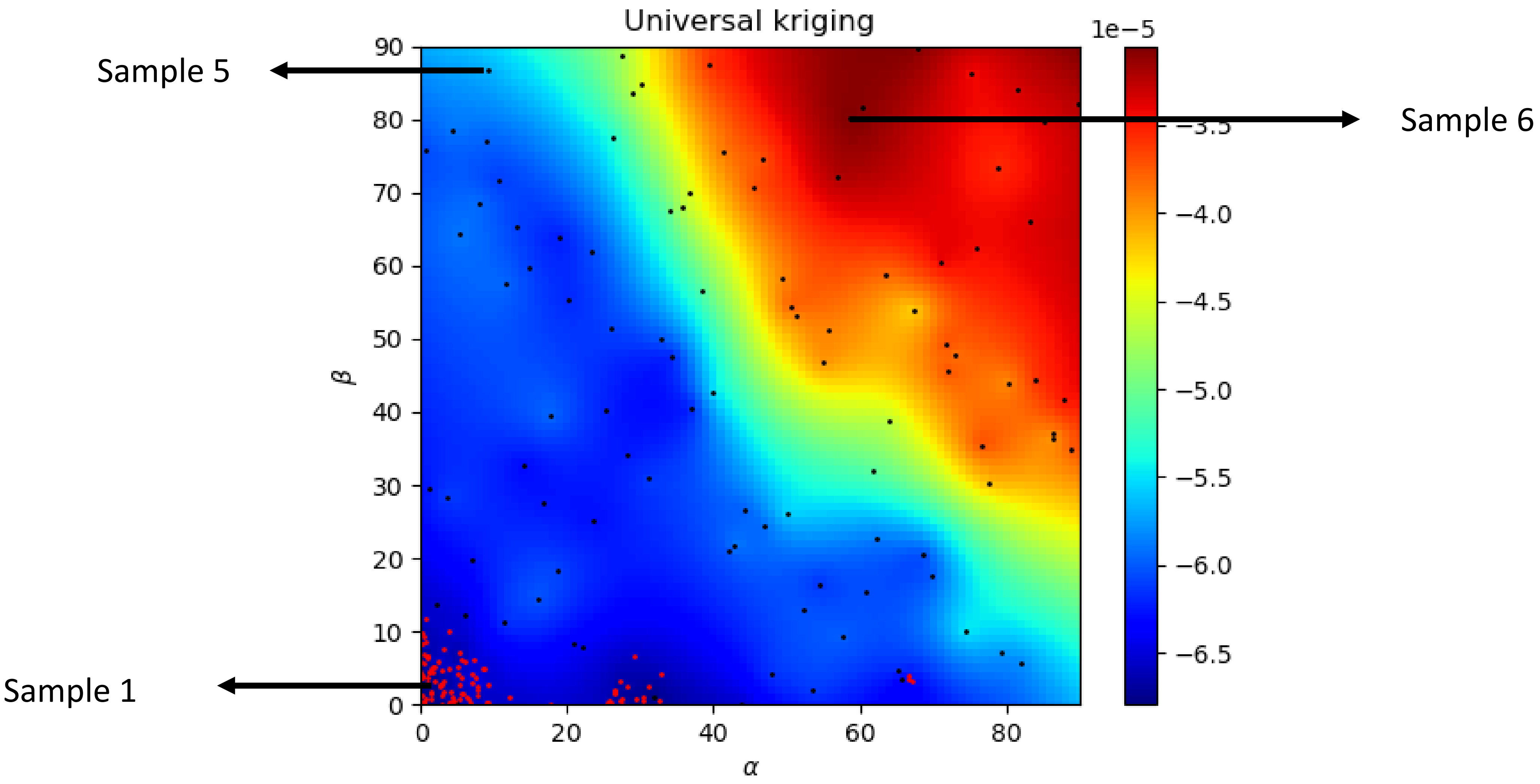


Sample 3: α ≈ 44° and ß ≈ 0°

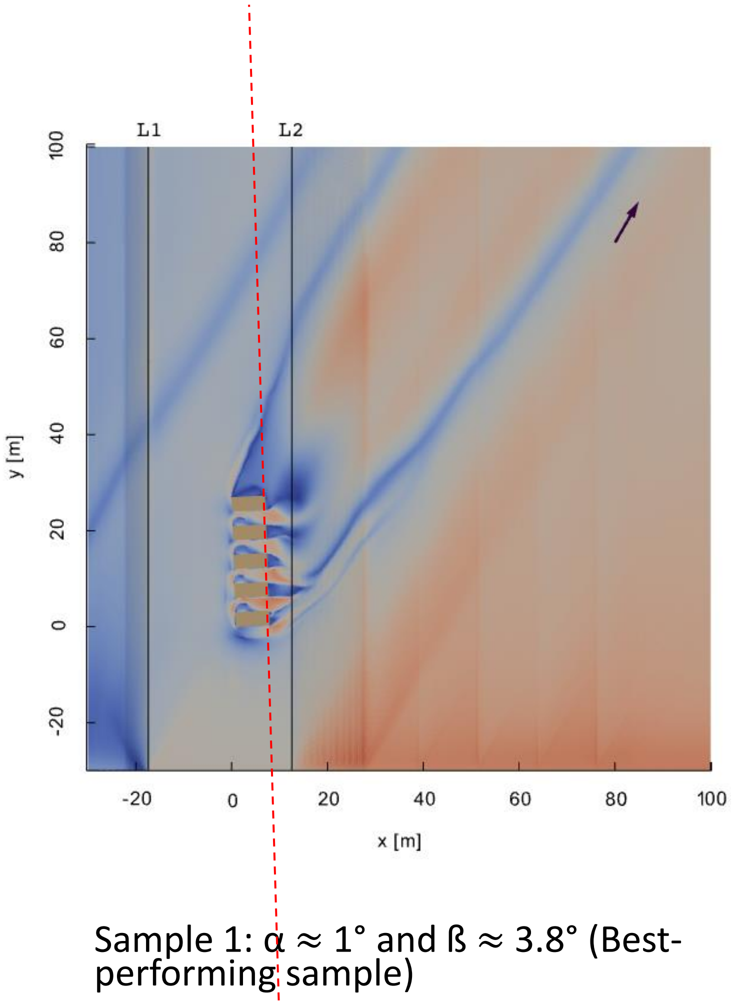


Sample 4: α ≈ 82° and ß ≈ 6°

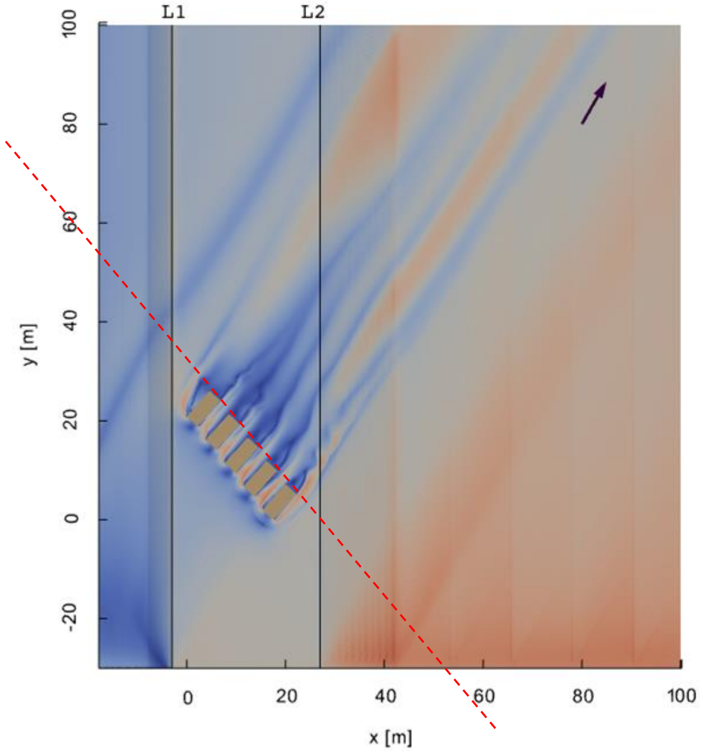
Design criteria 1:
α should be defined in a way that the houses are not parallel to the dominant wind direction, reducing wind-facing gaps



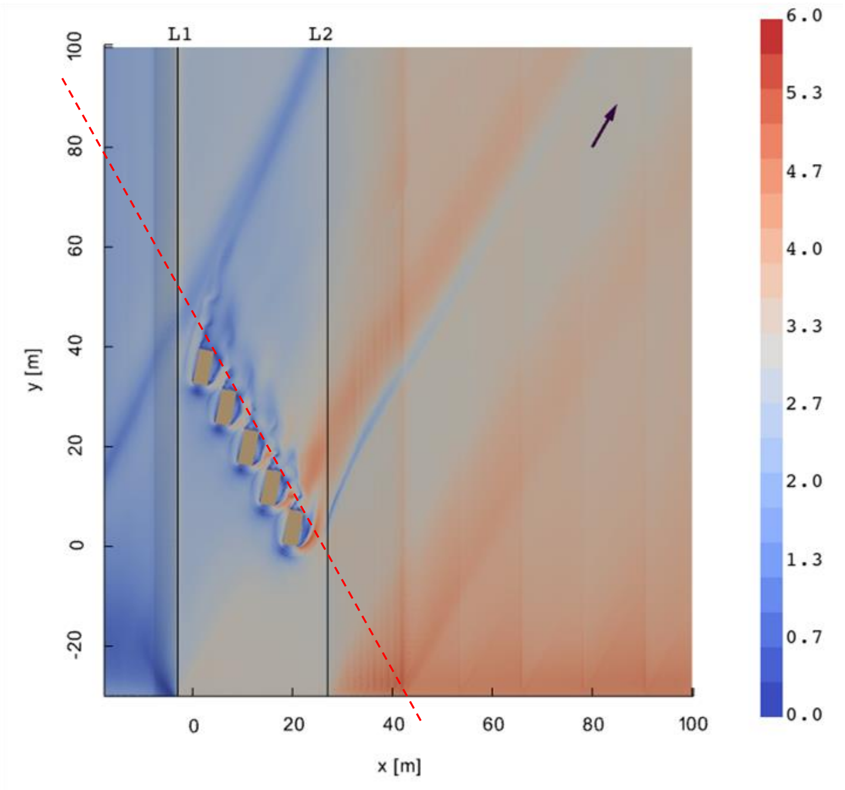
Universal kriging
Sample 5
Sample 6
Sample 1
β
α
1e−5
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
−4.0
−4.5
−5.0
−5.5
−6.0
−6.5



Sample 1: α ≈ 1° and ß ≈ 3.8° (Best-performing sample)



Sample 5: α ≈ 9° and ß ≈ 87°



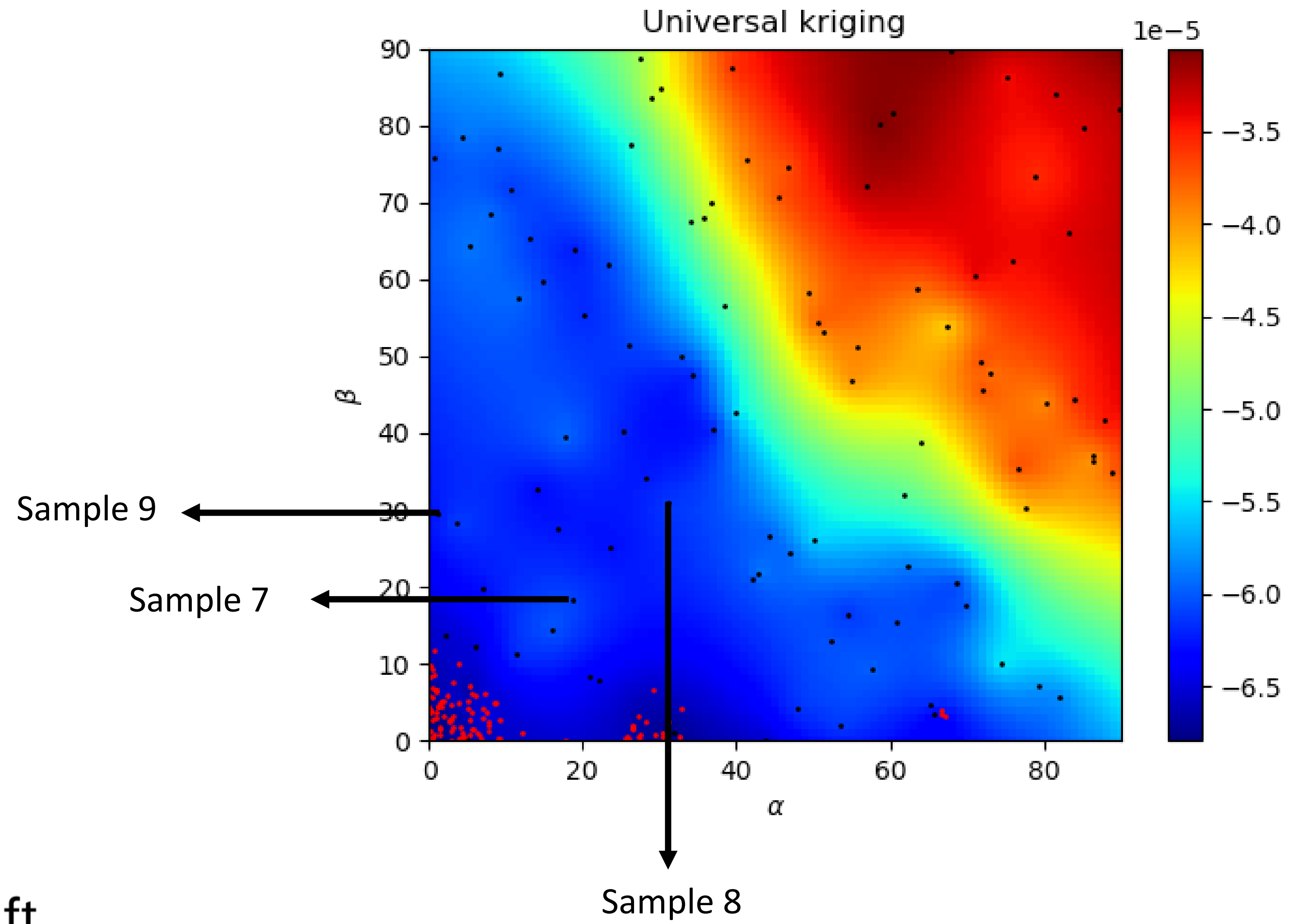
Sample 6: α ≈ 59° and ß ≈ 80° (Worse-performing sample)

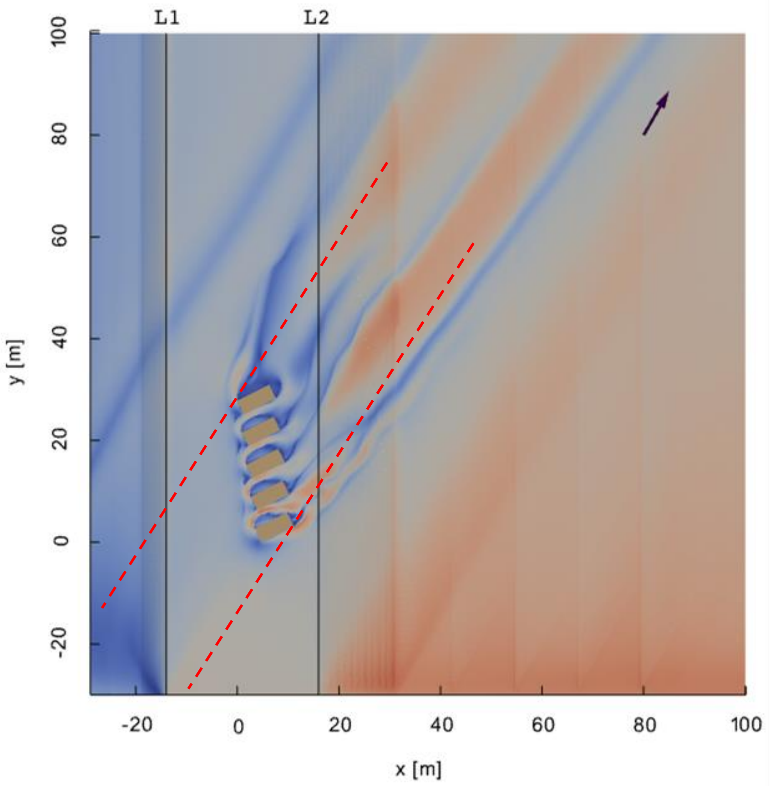
TU Delft

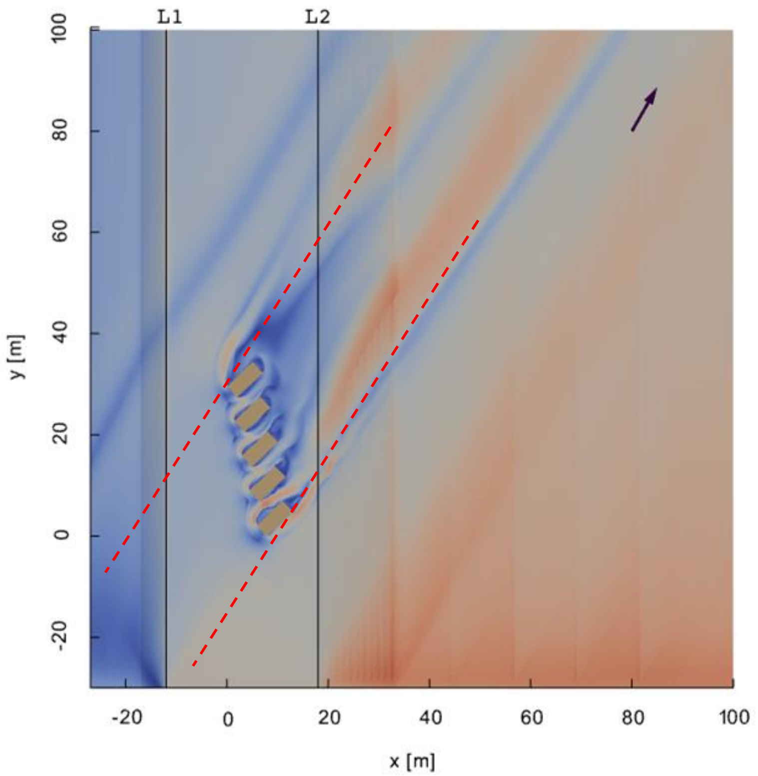
Design criteria 1:
α should be defined in a way that the houses are not parallel to the dominant wind direction, reducing wind-facing gaps

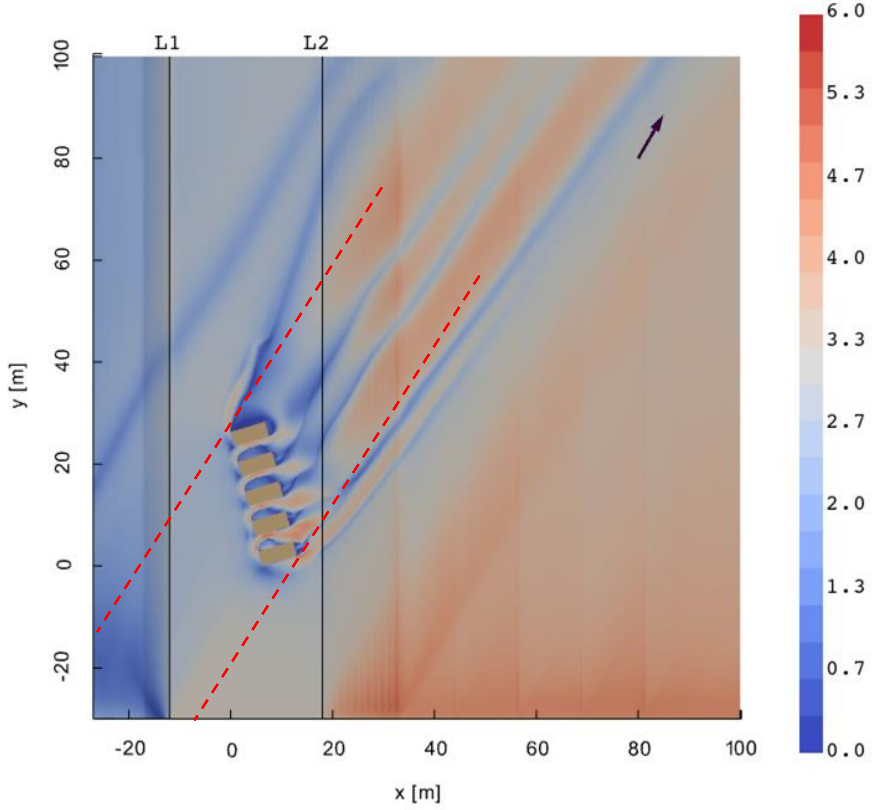
Design criteria 2:
α should also allow for enough overlap between the houses

Design criteria 3:
β should keep the configuration as consistently close to the dunes foot as possible


Universal kriging
1e−5
90
80
70
60
50
40
30
20
10
0
β
0
20
40
60
80
α
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0
−6.5
Sample 9
Sample 7
Sample 8







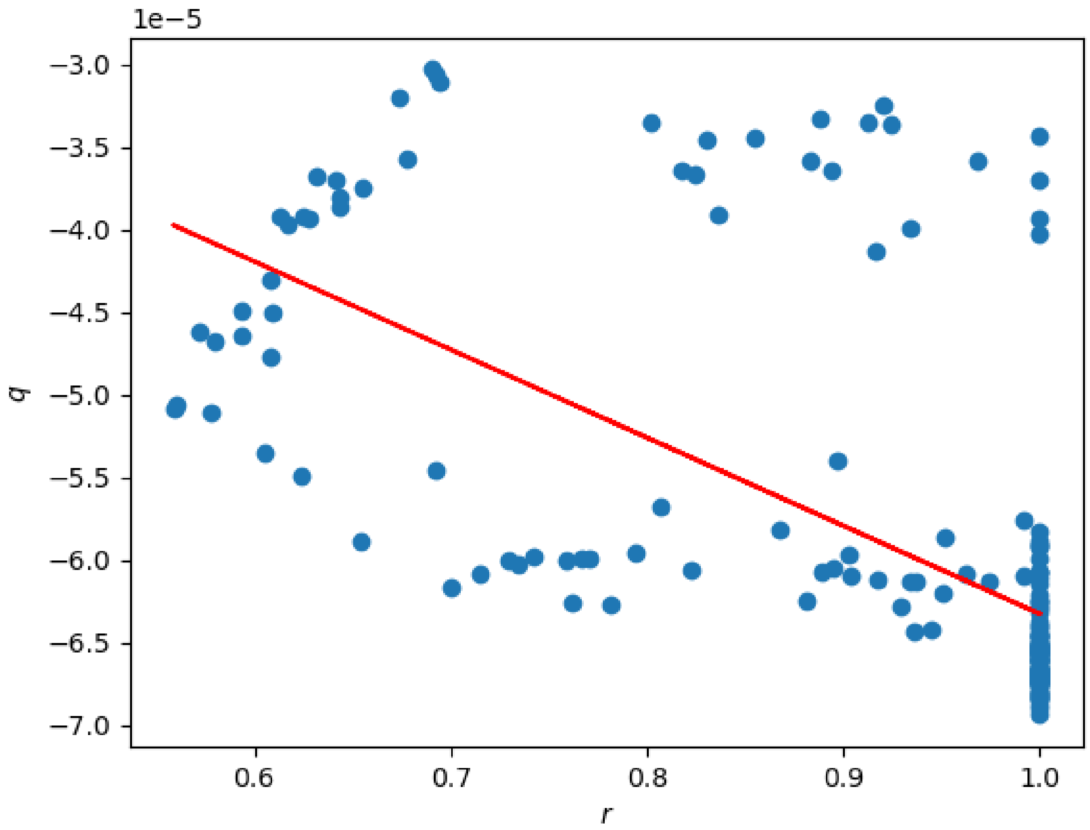
Sample 7: α ≈ 19° and ß ≈ 18°

Sample 8: α ≈ 31° and ß ≈ 30°

Sample 9: α ≈ 4° and ß ≈ 28°

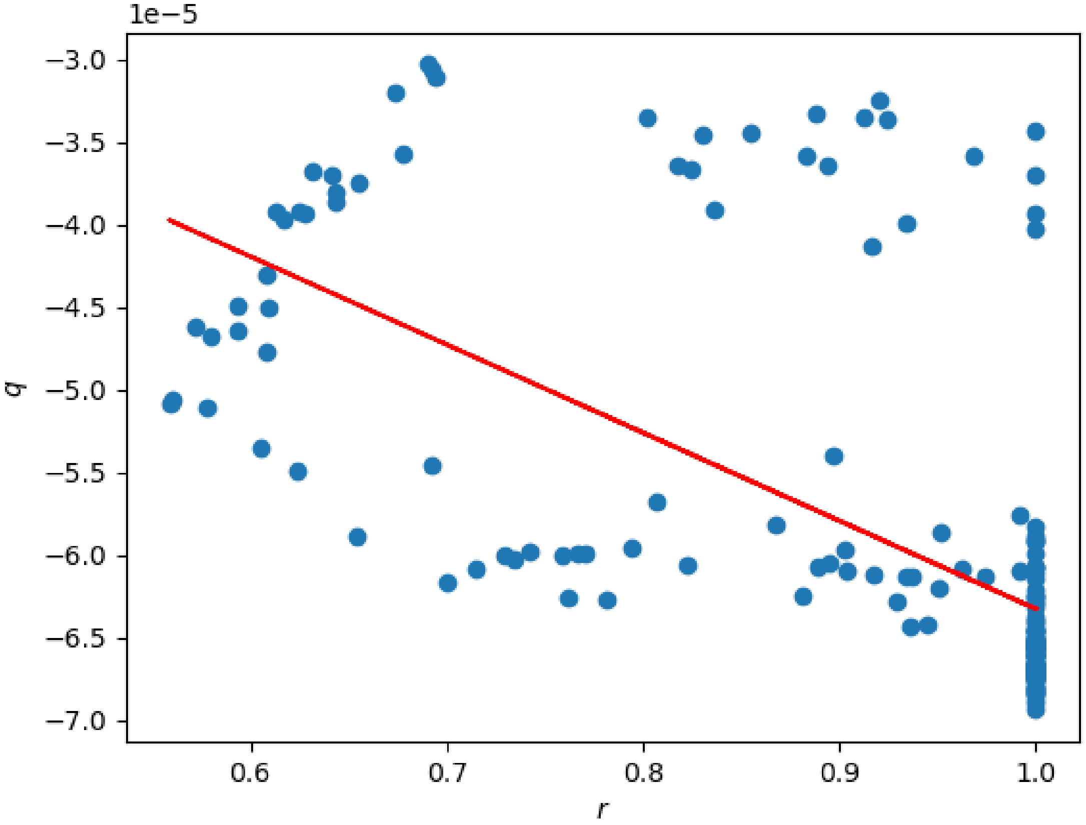
About 10% increase in the wind-facing surface

Wind-facing Surface

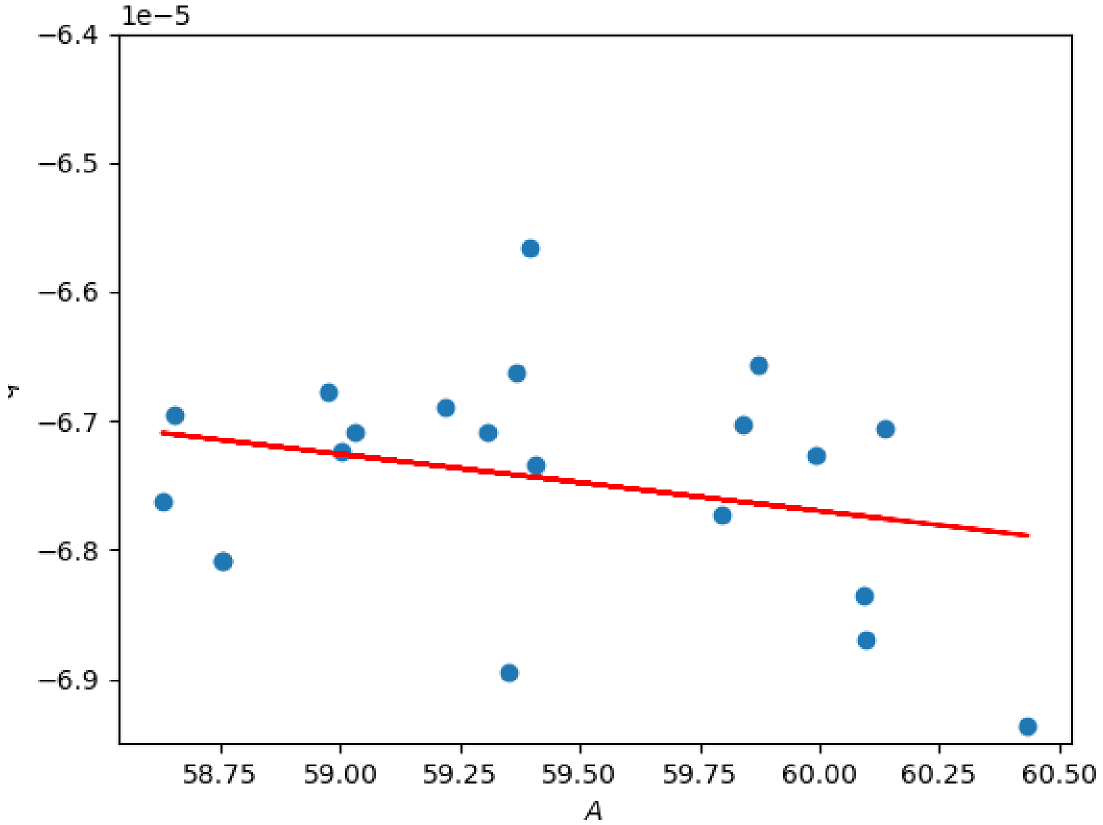


Ratio of surface with no gaps to total surface

Wind-facing Surface



Ratio of surface with no gaps to total surface



Surface with r = 1, α < 3.8°, ß < 3.8°

Design criteria 1:
α should be defined in a way that the houses are not parallel to the dominant wind direction, reducing wind-facing gaps

Design criteria 2:
α should also allow for enough overlap between the houses

Design criteria 3:
β should keep the configuration as consistently close to the dunes foot as possible

Design criteria 4:
When all three above criteria are respected, the wind-facing surface should be maximised.

Interpolated optimum

Surrogate model (100 samples):

optimum configuration: α = 0° and β = 0°

Surrogate model and first-generation (200 samples):

optimum configuration has α = 1° and β = 4°

Surrogate model and 5 generations (594 samples):

optimum configuration has α = 1° and β = 3°

Design criteria

- α should be defined in a way that the houses are not parallel to the dominant wind direction, reducing wind-facing gaps
- α should also allow for enough overlap between the houses
- β should keep the configuration as consistently close to the dunes foot as possible
- When all three above criteria are respected, the wind-facing surface should be maximised.

Limitations

- The mesh in refinement boxes for some cases presents inconsistent cell sizes
- A few assumptions have been made in setting up the model, such as simplifying the cross-section of the Dutch coast, not accounting for moisture and humidity, and not accounting for vegetation on the dunes.
- Having integer domain variables could have reduced the time for convergence for the optimisation.

Recommendations

- Geometry:

Test with different inter-distance between the houses to increase sedimentation behind the houses.

- CFD:

Create a response surface using LHS to account for the 12 wind directions for more than just the optimum configuration

- Optimisation

Try other optimisation algorithms such as the Ant Colony Optimisation

Thank you

References

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